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*Review Article*

# A Review on Vertical Take-Off and Landing (VTOL) Tilt-Rotor and Tilt Wing Unmanned Aerial Vehicles (UAVs)

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The Vertical Take-off and Landing (VTOL) unmanned aerial vehicles (UAVs) with the tilt-rotor mechanism also known as hybrid UAVs have a lot of challenges in designing and controlling concerning their use in harsh weather for surveillance and access to remote areas. This review paper presents a review of the preliminary design of hybrid aircraft and control systems. The tilt-rotor mechanism and tilt wings of a hybrid UAV are analyzed. The paper provides an outline of technical advances in UAVs in hybrid configuration concerning their constraint analysis, propulsion sizing, and design evaluation. Furthermore, the flight dynamics modeling is described with the control system and dynamics of the hybrid UAV. This paper lists various software for simulations and analysis such as SOLIDWORKS and CATIA for CAD modeling, MATLAB and SIMULINK for mathematical modeling and flight control, and XFLR5 for stability analysis of aerofoils, wings, and planes. In addition, certain control strategies are executed and scrutinized in terms of the theory, the linearity, and the implementation of the model.

## 1. Introduction

In the aeronautics industry, numerous models with VTOL capability have been developed and tested successfully, whereas in the Radio Control (RC) aircraft designs, not many of these projects have been successful. Most of them were able to achieve taking-off and vertical landing which bounds the functionality of the aircraft in one way or the other. Achieving a scaled-down model of aircraft which has VTOL capabilities that can cruise for an extended range, is feasible. The UAVs have created a foothold in the areas of E-commerce; medical transportation such as organs, blood, and medicines; the military for observation and search & rescue operations, and Science for remote monitoring, research, and analysis. Thus, being able to develop a hybrid that can hover as well as cruise would be very beneficial.

Using machine learning, various autonomous modules and sensors provide vision to the UAV, making its control more accurate and stable. However, UAVs also encounter problems such as limited endurance, range, and stability against truculent weather. The fixed-wing UAVs require launching devices or runways for landing and take-off thus requiring heavy infrastructure, usually unavailable in cities and compact remote areas. Thus, researchers can aim at building an autonomous fixed-wing UAV with VTOL capability. The hybrid of fixed-wing planes and quadcopters can effectively glide with a minimum thrust-to-weight ratio during the cruise, thus increasing its efficiency, range, and flight time. In this review, several parameters are considered in the design of the VTOL UAV, as shown in Figure 1.

Specific requirements of both e-commerce and military in aerial unmanned vehicles along with the increase in the density of unmanned aerial vehicles have led to a new configuration of aircraft, termed transitional aircraft (TA). TA configuration takes advantage of both merits of a fixed-wing aircraft, which includes high speed, endurance, and range, and of VTOL aircraft with which comes hovering capability and precise low-speed flight response, which is extremely helpful in remote areas as well as places with less space for landing. TA includes UAVs with the tilt-rotor mechanism also known as hybrid UAVs, Figure 2; despite the availability of knowledge of both types of aircraft, there are a lot of challenges for designing and controlling. At present, there is no generic methodology for designing and controllability most hybrid UAVs. It varies according to the application and configuration of the design. VTOL capabilities in a UAV, despite having a lot of issues, outweigh the complexity. Additionally, this design is more failproof, making it more reliable than other configurations, making it suitable for use in harsh weather for surveillance and access to remote areas.

In this paper, the preliminary design of hybrid aircraft, the control systems, tilt-rotor mechanism, and tilt wings of hybrid UAVs are analyzed. The paper provides a summary of technical advances in UAVs in a hybrid configuration that use the integrated features of TA, technical details, and features associated such as constraint analysis, propulsion sizing, and design evaluation. Furthermore, the flight dynamics modeling, stability analysis, and control system of the hybrid UAVs are analyzed using several simulation tools such as SOLIDWORKS and CATIA; MATLAB and SIMULINK; XFLR5 for stability analysis of aerofoils, wings, and planes; and ANSYS FLUENT for CFD analysis of the aircraft.

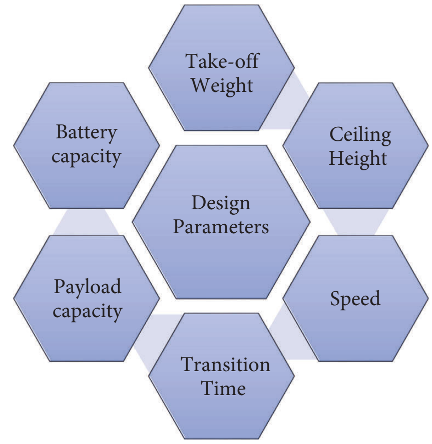


Figure 1: Design parameters of VTOL UAV studied.

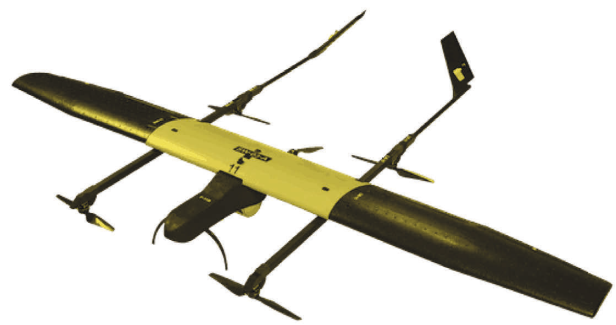

Figure 2: Hybrid VTOL UAV (courtesy: https://www.ideaforge.co.in/drones/switch-uav/).

Figure 3: The proposed dual-nacelle tilt-rotor concept for an aerial vehicle [1].

## 2. Tilt-Rotor VTOL UAV

Heslinga et al. presented a thesis on the design, analysis, and realization of UAVs with a dual-nacelle tilt-rotor, as shown in Figure 3. The UAV aims at carrying low payloads while emphasizing pace and stability. Thrust is produced by a couple of propellers that can rotate about the longitudinal plane, thus producing thrust vectoring. This enables the UAV to stably manoeuvre through a clogged environment without losing any significant speed. The Newton–Euler method and a nonlinear PD controller were developed, applied, and verified on MATLAB Simulink for spatial trajectory tracking. The project also tested two prototypes, successfully showcasing hovering and agility [1].

Szczepański and Ciopcia et al. investigated the tilt-rotor properties of a fly-by-wire steering design focusing mainly on hybrid UAV concepts. They looked into two major concepts, namely, a fusion of the steering system and the transitional state between propeller-driven lift and smooth gliding. They concentrated more on the kinematics and mechanics of the tilt-rotor assembly. The likely increase in degrees of freedom along with their impact on the pace and directional stability of the UAV was investigated. Aerodynamic force lift ($F_L$) and drag ($F_D$) are generated by airflow around the wing, as shown in Figure 4. They can be described as follows:

$$F_I = \frac{1}{2} * \left(C_L * \rho * S^* v^2\right),$$
$$F_D = \frac{1}{2} * \left(C_D * \rho^* S^* v^2\right). \tag{1}$$

Coefficients $C_L$ and $C_D$ can be defined in the following approximate, analytical form:

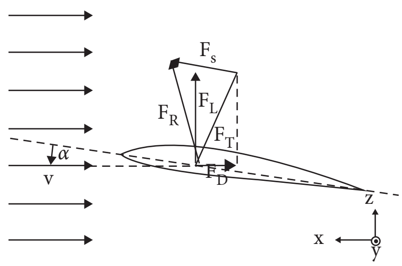


FIGURE 4: Distribution of forces in the wing during flight [2].

$$C_L = k^* C_L * \alpha + C_{L0}^2,$$
$$C_D = k^* C_D * C_L^2 + C_{D0}. \quad (2)$$

In addition, an efficiency report was also added by the team to improve energy savings and reduce the minimal thrust requirement while cruising. Two plots were generated, one describing the lift coefficient versus drag coefficient and the latter depicting the lift coefficient versus the angle of attack of the fixed-wing in the hybrid UAV, as shown in Figure 5 [2]. It was observed that the identified curve and simulated curve followed the same trend.

Ubair et al. designed a tilt-rotor mechanism through Creo 2.0 which could be used in VTOL applications. They also performed necessary experiments to test out the control of the UAV using the rotor. In addition, the control system includes novel mathematical modeling that enables a seamless transition from lift-off to cruise without any change in the flying altitude. Their design is comprised of three rotors, of which only the front two propellers have 90° rotation and are thus used for providing thrust in a cruise condition. The variation of position, velocity, and acceleration of the UAV with time is depicted in Figure 6 [3].

Vishwath et al. investigated the stability of a tilt-rotor UAV. They have built a UAV with twin BLDC motor-powered propellers that were placed close to the center of gravity. Tilting the thrusters with servos tilts the associated thrust vector. The thrusters could be rotated 90°. The tail is designed in such a way that it can counteract any disturbances occurring in the horizontal plane or vertical plane. Servos are used to tilt the whole tail that consists of horizontal and vertical stabilizers. To define the stability, this research work considered the contribution of the wing, fuselage, and tail, which together will define the longitudinal stability of the aircraft. The hybrid UAV also contains a fixed rectangular wing. To obtain wing contribution, the following formulae can be used:

$$C_{m_{0_w}} = C_{m_{ac_w}} + C_{L_{o_w}} \left( \frac{x_{cq}}{c} - \frac{x_{ac}}{\bar{c}} \right),$$
$$C_{m_{\alpha_w}} = C_{L_{\alpha_w}} + C_{L_{0_w}} \left( \frac{x_{cg}}{\bar{c}} - \frac{x_{ac}}{\bar{c}} \right). \quad (3)$$

Here, $Cm_{0w}$ is the coefficient of pitching moment at zero angles of attack of the wing, $Cm_{acw}$ is the coefficient of pitching moment about the aerodynamic center of the plain, $C_{Low}$ is the coefficient of lift at zero angles of attack of the wing, $x_{cg}$ is the distance between the center of gravity to wing's leading edge, $x_{ac}$ is the distance between aerodynamic centers to leading-edge, $\bar{c}$ is the chord length of the wing, $Cm_{\alpha w}$ is the slope of the curve plot between coefficients of pitching moment with the angle of attack of the wing, and $CL_{\dot{\alpha} w}$ is the slope of the curve plot between coefficients of lift with the angle of attack of the wing. The aerofoil utilized by them is the bell A821201 [4].

*2.1. Design, Methodology, and Analysis.* The Georgia Tech Research Institute has performed research on the rotor that would be powered by solar energy. The photovoltaic conversion method that requires an electrolyzer and closed-loop fuel cells are touted alongside laser energy transmitted from satellites and other space platforms, as shown in Figure 7. The mechanical advantage of the rotor is between 30% and 35%. Since the energy is sustainable and the rotor mechanism is highly efficient, the UAV provides an option for potential infinite flight time at high altitudes. This proposal is aimed to establish a new solution for telecommunications due to the increased congestion. These UAVs would function as miniature satellites inside the atmosphere [5].

Escalante et al. have proposed an aircraft with a tilt-rotor configuration to enhance the transition phase from one flight mode to another while combining the ducted-fan for increasing flight performance. Computational tools such as XFLR5 and ANSYS FLUENT were used for the preliminary design and verification of fixed-wing. Experiments were also conducted by his team for finding the lift system requirement. Simultaneously, the performance of the confined rotors was compared with the free ones and it was observed that there is a 20% increase in the lift generated at full thrust using a ducted-fan. The developed experimental prototype was allowed to perform vertical flight tests in outdoor environments, which achieved successful take-off and landing, as shown in Figure 8 [6].

Rawal and Abhishek from IIT Kanpur has proposed a new coaxial tilt-rotor design with the development of equations of motion for its analysis in airplane mode, helicopter mode, and transition mode. The paper is based on the structural modeling, performance study, and transition analysis of a hybrid coaxial tilt-rotor system. The design is capable of converting to a thruster from a lifter between vertical and forward flight conditions. Rotor dynamics is evaluated using rigid blades having only a flap degree of freedom. Dree's model is used for inflow measurement. The paper consists of two parts. The first part compares the proposed vehicle with a conventional coaxial helicopter. Second part analyses the transition phase in a quasi-steady manner. Finally, improvements in the maximum cruise velocity, range, endurance, and rate of climb are shown [7].

Gascó has submitted the thesis on a new and original dual-axis tilt quadrotor that extensively uses gyroscopic effects, aerodynamic forces, moments, and servo-meter dynamics to investigate an increase in efficiency compared to a conventionally actuated quadrotor. The mathematical design and model of the new actuator suite were developed to take advantage of the gyroscopic features that helped to improve the performance. The thesis shows a 20% increase

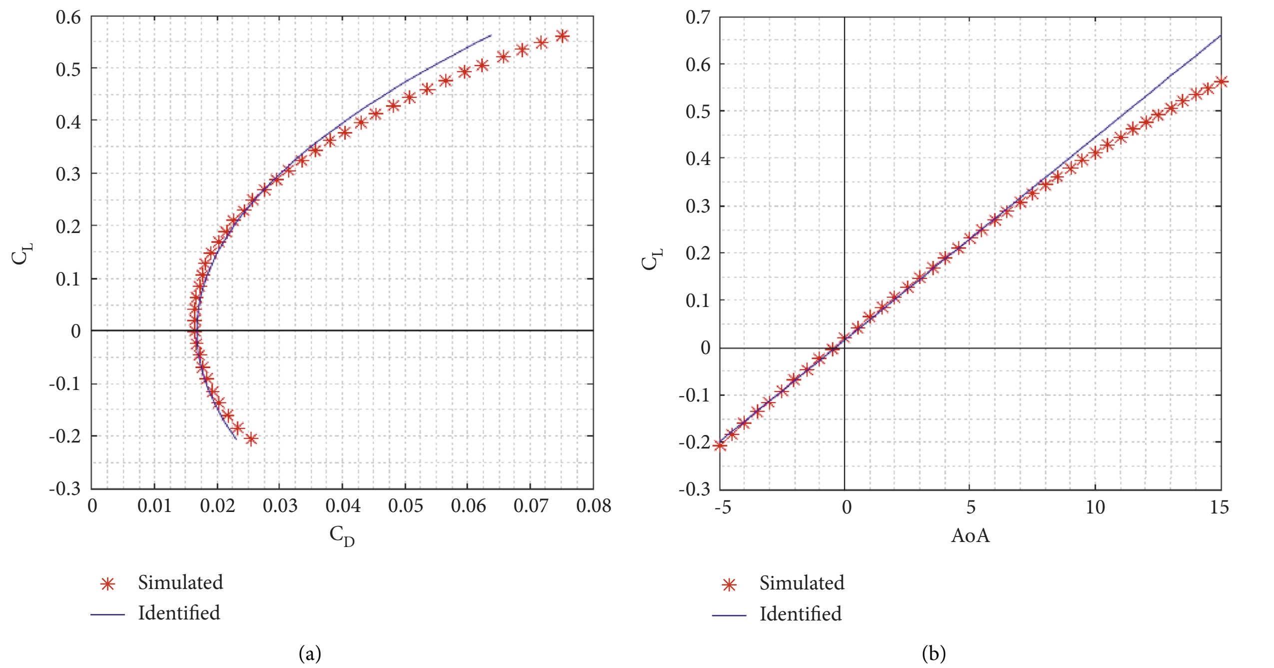


Figure 5: Characteristics of the sample airplane based on simulation and MSE identification: $k_{Cl} = 0.0429$, $C_{L0} = 0.160$, $k_{Cd} = 0.1487$, and $C_{Ld.} = 0.167$ [2].

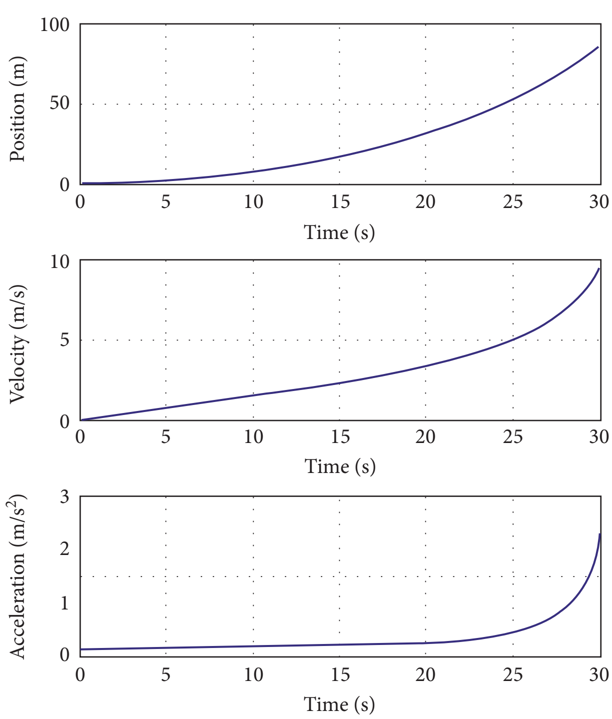


Figure 6: Variation of position, velocity, and acceleration with time [3].

in the efficiency of the new actuator suite concerning the conventional actuated quadrotor. Successful demonstration of the first flight test, rig tests, and a qualitative approval of the Simulink model were shown [8].

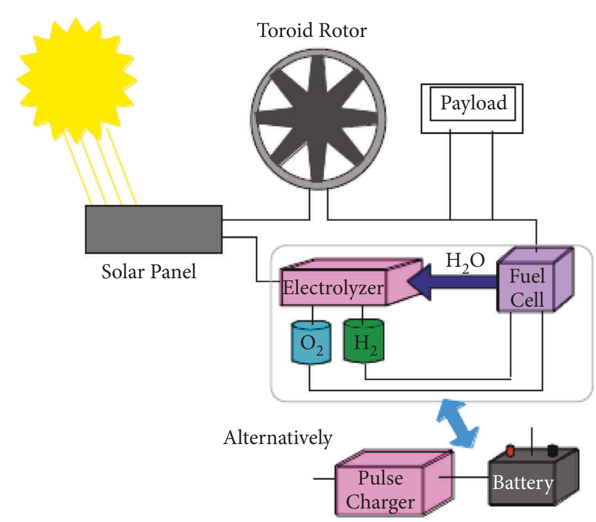


Figure 7: Power system layout [5].

Flores et al. have described the modeling, design control, and hardware execution of a tilt-rotor aircraft. The vehicle was aimed to achieve high-speed cruising capacity on a conventional plane with the hovering capacity of a helicopter by using four-tilting rotors. The Newtonian approach was established for deriving the dynamic model for both vertical and horizontal flight modes. A non-linear strategy was also evaluated at the simulation level to control the two modes, as shown in Figure 9. A low-priced digital signalling processor consisting of an Embedded Flight Control System (EFCS) was designed and modeled to achieve high altitudes with autonomous stabilized flight. A quad-plane experiment was

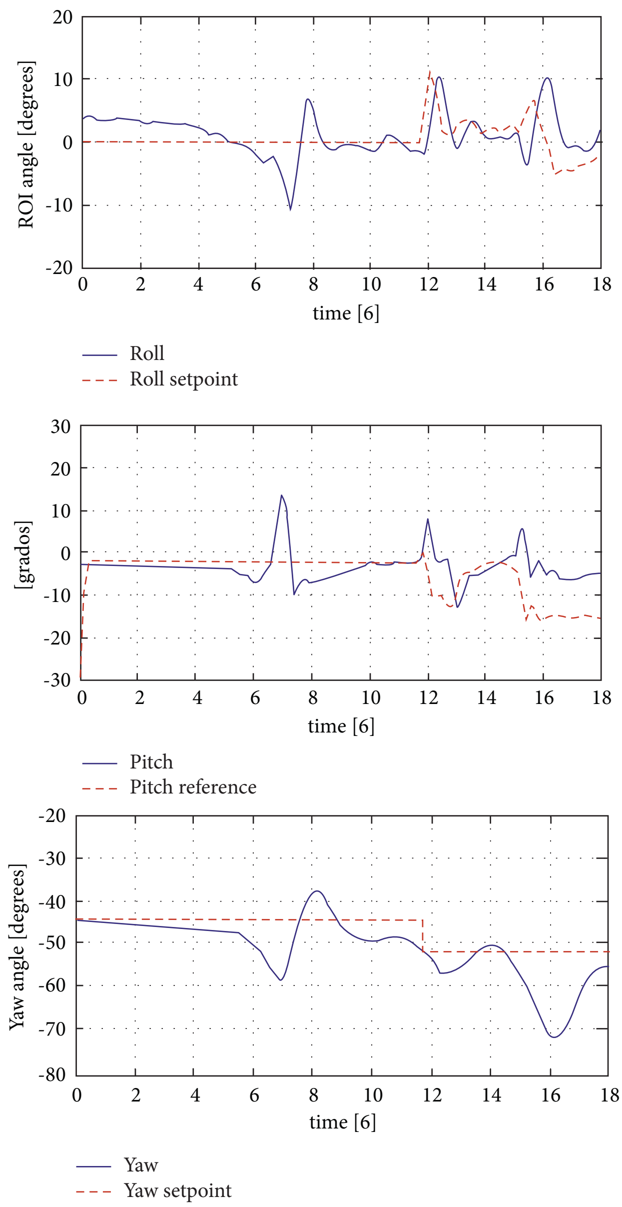


Figure 8: Flight test tracking result of the vehicle’s attitude [6].

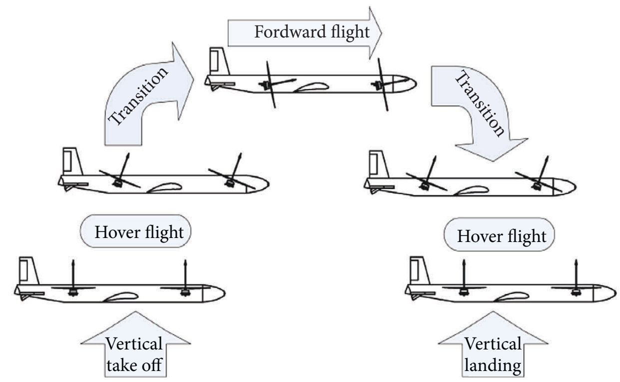


Figure 9: Operational transition [9].

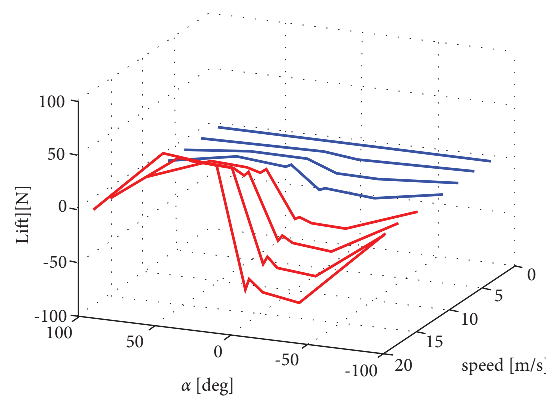


Figure 10: Lift values for different velocities [9].

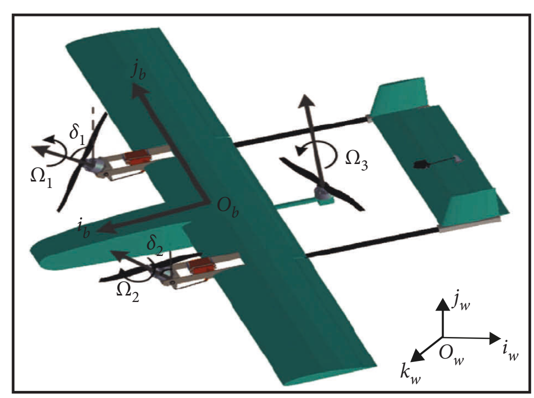

Figure 11: The body frame and geodetic frame [10].

developed to control vertical flight. Finally, the longitudinal dynamics are derived at hover and forward flight mode, as shown in Figure 10 [9].

Chen et al. have presented a tri-rotor-copter concept UAV with dual flight modes—namely, the rotor mode and the fixed-wing mode, as shown in Figure 11. The complex UAV contains a multiple-input, multiple-output, non-affine, multiple-channel cross-coupling, and non-linear system. However, they did not develop a navigation model due to the complexity and costs involved. Instead, they developed a method that would allow the UAV to navigate through a preplanned flight path in autonomous conditions. This makes the UAV unsuited for unpredictable environments. Their test flight was successful in producing satisfactory results [10].

Liu et al. have investigated the various control technique platforms, dynamics modeling, structural features, and flight control methodologies. A wide range of tilt-rotor UAV types from dual-copter types to quad-copter types was discussed. Some established models such as AKITSR TWUAV and TR-60 UAV were studied for operational issues and possible technical difficulties. In addition, a summarized study of the tilt-rotor kinematics was presented. Linear, nonlinear, and intelligent algorithm control methods were studied by them, thus establishing the pros and cons of the same. They established that non-linear systems would have to focus on the robustness and stability of the system during the transition state for a successful flight. Meanwhile, in algorithm-controlled UAVs, the emphasis is placed on path planning and flight mode planning [11].

Junaid et al. have proposed an actuation concept to improve the UAV characteristics of a quadcopter. They developed a UAV that showcased a marked increase in aggressive manoeuvering and mobility in congested environments. The tilting mechanism was established using two 3D-printed servo motors. The dynamic modeling was based on the Newton–Euler formulation, and the equations were developed using the Maple software. The simulation was conducted on the MATLAB Simulink platform, and the flight control duties were bestowed on the APM flight controller. The input angles were provided through RC control, and GPS was used for feedback on the position of the UAV, as shown in Figures 12 and 13 [12].

Ganesh and Subramanya have created a prototype VTOL UAV consisting of a quadcopter design with four tilt-rotors and a fixed-wing. The NACA 0012 aerofoil was preferred by them for low-speed conditions. A BLDC motor of prop 1145 was preferred by the team. A KK gyro system with an Atmel Mega644PA microcontroller was trusted for flight control. A 2800 mAH battery is used to power the control system. After successful flight testing, the flight could handle a payload of 900 grams at a height of 100–150 feet [13]. Jagdale et al. have investigated the basic physical mechanisms, requirements, numerous types, functions, and applications of VTOL vehicles in the current world. A comprehensive comparison of the Yakovlev Yak-38, the Bell Boeing V-22 Osprey, Lockheed XFV-1 the Hover-eye micro-UAV, and the Harrier is provided by the team. They have explored both the manned and unmanned sections of VTOL vehicles [14].

Jo and Kwon have successfully manufactured a hybrid UAV using their design process that has been termed the VTOL development process. Instead of depending upon wind tunnels for testing their aircraft, the team has turned towards Computer-Aided Engineering (CAE) software, as shown in Figure 14. For a successful flight control of VTOL, the team banked on FW (Firmware) coding. The UAV is designed for both completely autonomous and manual control from the ground. The latter can be performed through a GCS (Ground Control Station). The UAV can carry more than 3 kg of payload and a horizontal flight speed of 108 km/hr. They also contain a built-in LTE module for destinations with increased range. The prototype was tested, and satisfactory results were obtained in the form of flight time, hovering tolerance, pitch angle, bank angle, etc., [15].

Maxim et al. have proposed a new sizing methodology for the design of electric UAVs. They have investigated a hybrid UAV concept powered by five fixed rotors. The UAV contains four rotors for vertical lift required for VTOL applications and one rotor for providing thrust during flight. Their design philosophy is built on constraint analysis as the source leading to the mass analysis of the UAV, which then leads to geometrical requirements [16]. Bibek et al. have investigated the concept of blended wing design in VTOL UAVs. Their design was created using the CATIA CAD software. The design proposes to have two rotors for VTOL functions on either side of the wing. A microcontroller capable of handling six channels is used to control the propellers and servo motors. A lithium-ion battery will be used to power the UAV. Although the work does not result in the manufacturing of the prototype due to its complexity, the concept of the blended wing is unique and can be utilized in upcoming research work [17].

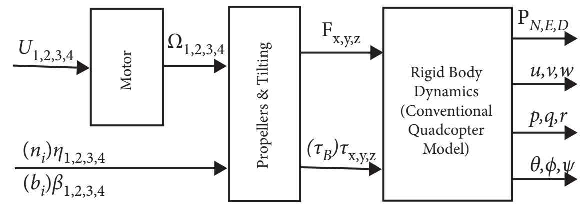

Figure 12: Dual-axis tilting quadcopter modeling diagram [12].

Abd Rahman et al. stated that UAV markets have been fully developed to perform in numerous applications. Although UAVs have their restrictions in the range of flight, endurance, and manoeuvrability. Traditional aircraft can manoeuvre for a longer range and have more endurance but need a take-off area. On the other hand, multi-rotors have high manoeuvrability, but they cannot be utilized for long-range flights as speeds are lower and consume higher energy. A hybrid UAV gives the ability to travel fast to a further distance. This paper talks about the dissimilarities between rotorcraft UAVs and forward wing UAVs. The answer for the dual uses is a hybrid vertical take-off and landing aircraft [18]. Many more research novelties are explored by scientists and researchers. A few of the innovations relevant to the present work are listed in Table 1.

*2.2. Modelling and Prototype.* The first configuration is more intricate in comparison to others as it is more difficult to optimize the flight during the transition from the vertical direction to the horizontal direction or vice versa, which can cause it to overshoot and go out of balance causing a loss in attitude. However, it makes VTOL more efficient and stable overall while keeping it lightweight. In wing design, as shown in Figure 15, weight estimation is used for finding wing loading ($W_l$) using the following equation:

$$W_1 = \left(\frac{\text{Weight}}{S_y}\right)(S_w = \text{Wing Area}). \quad (4)$$

For wing design, wing loading is more paramount than the empty weight and the lowest value needs to be taken to reduce stress on the wing during the flight. Wingspan ($b$) is calculated using the Aspect Ratio (AR).

$$\text{AR} = \frac{b_w^2}{S_v}. \quad (5)$$

A typical AR is between 6 and 8, and a higher AR enables the aircraft to safely glide even at low speed, making it easy to do so in the event that the motor fails. For calculating the chord of a wing ($C_w$), for ease of manufacturing, a rectangular wing is considered.

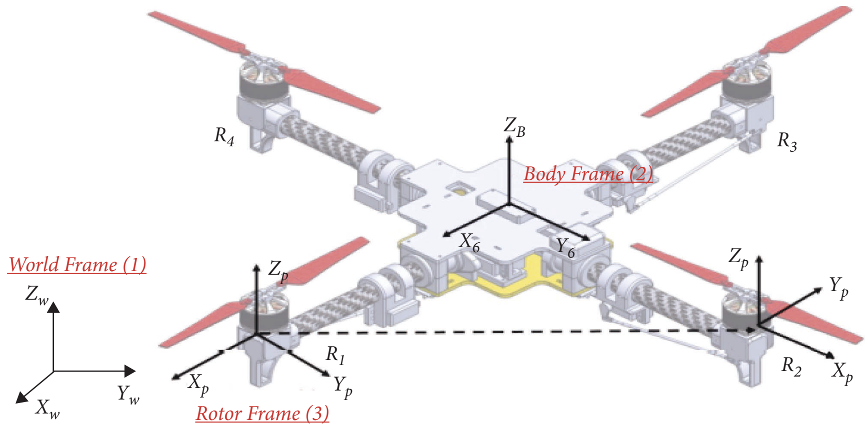


Figure 13: Rotor numbering and reference frames [12].

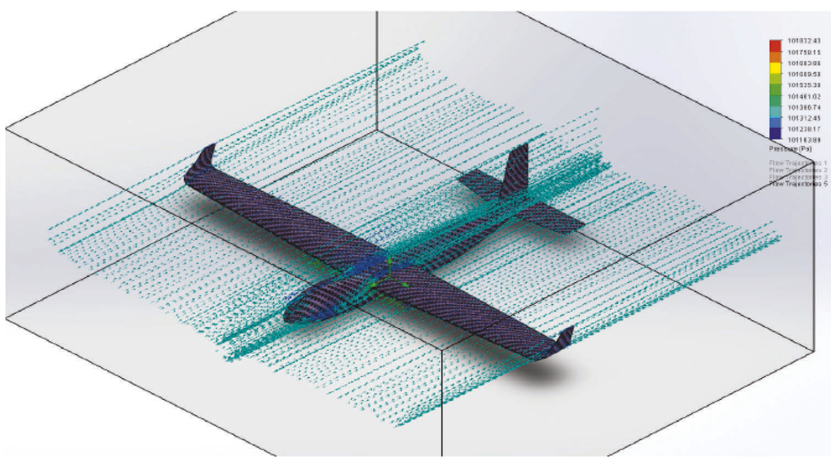

Figure 14: CAE simulation analysis [15].

$$S_y = b_y * C_V. \tag{6}$$

In tail design, the sizing is similar to the calculations that were done in wing design, with a horizontal configuration for the tail with an elevator for controlling the pitching moment and not a vertical tail to reduce the complexity of the UAV control. In fuselage design and material selection, the fuselage design does not have specific calculations, the frame's aerodynamic shape can be improved by covering it accordingly with light material to make it more aerodynamic, and it has an exposed unit used to store battery, GPS unit, and power distribution board. Material selection is a critical parameter for the design of a UAV, and light material is preferred to reduce the empty weight. No specific electronic design is required. The electronics include brushless motors, a control module that is Pixhawk, radio frequency modules, and a battery charger. One of the most widely used techniques in industrial control system application is PID control that is an error-based system with a control loop that processes variables, and it is accurate and stable as a controller. It can be used to regulate temperature, pressure, speed, etc.

The first fully fabricated and functional prototype was used to collect data for stabilization, and iterations were done accordingly to make it more stable at various altitudes, Figure 16. The three modes are hovering, transition, and cruise in front flight mode. The graph represents the time of flight to be about 60 seconds, which gives you vibration levels in three axes of the flight in different stages. The vibration did fall significantly below 60 m/s, and it was concluded that more PID tuning was needed to reduce the vibration and a camera is needed for in-flight monitoring and other purposes, as shown in Figure 17 [18].

*2.3. Research Method and Optimization.* Win et al. have aimed for the aircraft configuration in VTOL mode, and the manoeuvrability test is analyzed using the aerodynamics equations in the mathematical model. In this exploration, the KK 2.1 flight modulator was utilized for the VTOL phase and airplane phase. The initial task is to build up the VTOL mode, and the next task is to successfully convert the VTOL phase to the airplane phase. In this research, they have indicated the structure and execution of the VTOL airplane by drawing out the mathematical model of the VTOL airplane as shown in Figure 18. Then VTOL UAV was tested effectively in both manual and programmed flight operations [19].

Table 1: Research innovations carried out by various teams on VTOL-UAV.

| Team | Innovation carried | Software/technique used | Remarks |
|---|---|---|---|
| Paul Heslinga et al. | UAVs with a dual-nacelle tilt-rotor | MATLAB simulink | Aims for a low payload with pace and stability. Two prototypes were tested successfully |
| M Ciopcia et al. | Tilt-rotor properties on a fly-by-wire | Lift-drag mathematical model | Worked on steering system combined with transitional state along with efficiency report |
| Ubair Ejaz Butt et al. | Tilt-rotor mechanism | Creo 2.0, mathematical modeling | Test of control of UAV using a rotor |
| N.C. Ajay V et al. | Stability of a tilt-rotor UAV | Prototyping with BLDC motors, servos, mathematical modeling | Analyzed contribution of the wing, fuselage, and tail for stability |
| Carlos A. et al. | Aircraft with tilt-rotor configuration with ducted-fan | XFLR5 and ANSYS FLUENT | A 20% increase in the lift at full thrust was reported. |
| Naman Rawal et al. | Coaxial tilt-rotor design | Structural modeling with performance study and analysis, Dree's model | Enhancements in maximum cruise velocity, range, endurance, and rate of climb reported |
| Pau Seguí Gascó | Dual-axis tilt quadrotor | Mathematical design and model, Simulink | 20% increase in the efficiency of the new actuator suite |
| G. Flores et al. | Hardware execution of a tilt-rotor aircraft | EFCS | Longitudinal dynamics are derived at hover and forward flight mode |
| Chao Chen et al. | Tri-rotor-copter concept UAV | Mathematical modeling | Tested the flight successfully |
| Liu Zhong et al. | Investigations on tilt-rotor UAVs ranging from dual copter to quadcopter | Investigations of models, features, and algorithms | Concluded that focus should be on robustness and stability |
| Ali B Junaid et al. | Actuation concept for quadcopter UAV | Maple software, MATLAB simulink, 3D printing, and mathematical modeling | Developed UAV with aggressive manoeuvering for congested environments |
| Shishir G et al. | Prototype VTOL UAV quadcopter with four tilt-rotors and a fixed-wing | Prototyping | Successfully carried a payload of 900 grams at 100–150 feet |
| Daeil Jo et al. | Manufactured own hybrid UAV | CAE software, prototyping, FW coding | A prototype was tested successfully and can carry a 3 kg payload |
| Bibek D et al. | Blended wing design for VTOL UAVs | CATIA CAD software | The concept of the blended wing is unique; however, no prototype was made and tested |

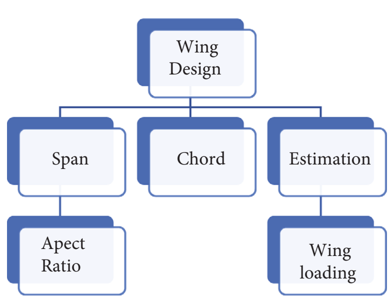

Figure 15: Designing of UAV wing.

Saharudin had performed an analysis in structural for sizing the wing section of UAV. Mission parameters and the mission profile of hybrid tilt-rotor UAVs are also scrutinized. The structural analysis comprised calculating the shear forces and uniform distributed load on the wing of a hybrid tilt-rotor UAV. Wing design simulation was also done in Solidworks and CATIA. It is used for validation of the wing design and its structural integrity. Finally, the conclusion stated that the hybrid tilt-rotor UAV has more endurance, range, and manoeuvrability, is more economical and functional, and is a highly prospective area for academic research [20]. Puspita et al. have designed and manufactured a hybrid VTOL unmanned aerial vehicle that was based on the SLT philosophy. SLT (Separate Lift and Thrust) comprises two sets of motors among which one set is used for vertical movement, while the other set is used for horizontal movement. This philosophy is said to offer the best solution during the transition. A tail boom was added to negate the


Figure 16: Final prototype.

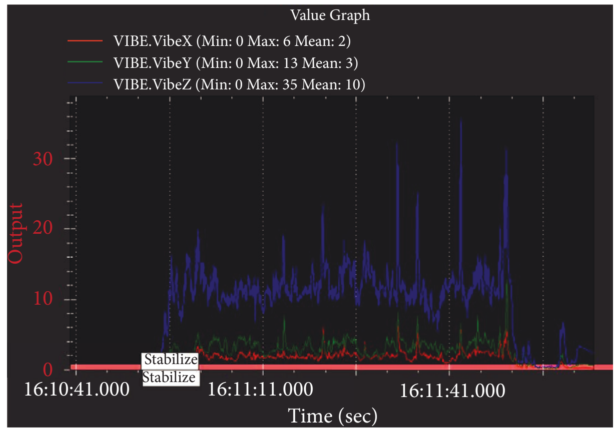


Figure 17: Vibration in three axes [18].

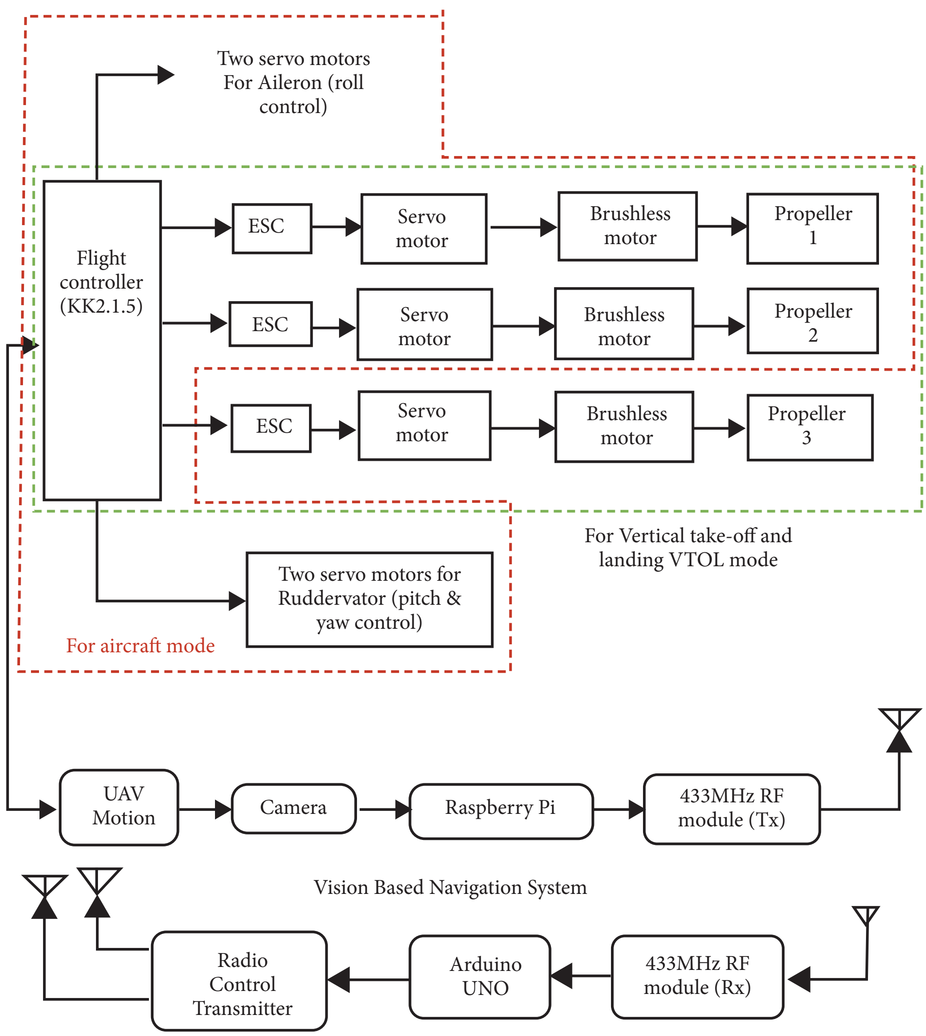


Figure 18: Block diagram of the VTOL aircraft system [19].

moments caused by the wings. The PTC Creo Parametric software was used for CAD modeling. Furthermore, analysis was performed with the help of XFLR-5 and ANSYS (CFD). The UAV managed an impressive thrust-to-weight ratio of 2.13 during the hovering phase. The design enables a maximum payload of 1 kg. MATLAB Simulink aided them in understanding the transition phase from take-off to hovering. The team opted for composites of reinforced glass and carbon fiber for manufacturing the UAV. The UAV was tested for both static structural tests and flying [21].

Thomson aimed his research on the application of VTOL tilt-rotor aircraft with offshore oil support capability. The tilt-rotor concept used in army bell XV-15 aircraft in NASA is evaluated. The discussion and analysis of the concept are done on the XV-15 aircraft model. The comparison of tilt-rotor aircraft and an advanced helicopter is done based on relative cost per comparison mile. Benefits to operators in terms of economic, operational safety, reliability, and passengers are described extensively. A comprehensive study of XV-15 aircraft and its program description is also done. The tilt-rotor has many advantages over helicopters in the conventional sense such as lower cost and greater safety, providing more range, endurance, and more controllability. Results in the tilt-rotor program provide a good stable projection and vote of confidence. A tilt-rotor is expected to be available for civil use in remote areas. The graphs on fuel efficiency, effectiveness in terms of cost, between sixteen-seat and forty-seat aircraft, fuel consumption comparison, speed comparison, and ride quality comparison were also provided, as shown in Figure 19 [22].

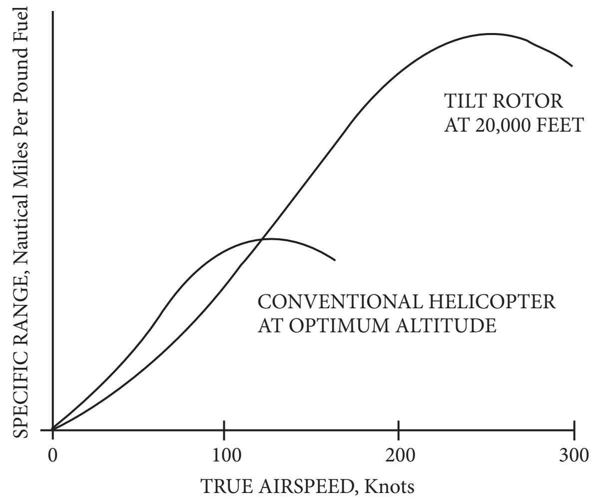


Figure 19: Fuel efficiency [22].

Dündar et al. worked to simplify the design procedure and performance analysis concentrating on the energy consumption of an FW VTOL UAV. Low take-off weight and high aerodynamic performance are the dominant factors taken into consideration while designing the vehicle. Repetitive iterations are done for the sizing process according to weight and selected aerodynamic analysis, as shown in Figure 20. Critical performance characteristics such as weight, lift coefficient, aspect ratio, wing sweep, taper ratio, aerofoil selection, wing sizing, and control surfaces are calculated and compared to standard models using Simulink in the MATLAB software. COG is used to calculate the static stability concerning the neutral point. In various flight conditions such as take-off and landing, momentum theory is implemented for vertical flight while maximum endurance is evaluated through the cruise flight. Performance calculations of electrically powered FW VTOL UAVs are done using various parameters such as maximum power, and the power required for take-off, landing, and climbing. Drag calculations are performed in level flight to evaluate the drawbacks of the multi-rotor system including propellers providing the vertical flight. Finally, a comparison of VTOL FW having multi-rotors and only FW is done in terms of endurance, as shown in Figure 21. It is concluded that FW with a multi-rotor system having four propellers is more efficient than the VTOL FW concept. Thus, VTOL FW UAV was successful to do the vertical take-off and landing with its four vertical engines and one horizontal engine. It has a 4.7 kg total take-off weight and a 2-meter long wingspan and can fly at a maximum fineness ratio with 72 km/h cruise speed [23].

Saeed et al. presented a technical outline of a hybrid UAV with recent advances in his paper. His paper also provides a review of the dynamic modeling, control, and design of the UAV. The FW UAV and VTOL UAV have their limitations such as payload, flexibility, and endurance. Thus, the hybrid UAV is proposed for inducing the beneficial features. A comprehensive study of convertiplanes and their subtypes is also done. Wing tilting, tilt-rotor, and fixed dual rotor system are mentioned in the subtypes. Various flight control models are discussed, implemented, and compared on the basis of linearity, as shown in Figure 22. Control laws are termed on the basis of linear and non-linear models that are based on the dynamics of the hybrid UAV. The review paper is informative to researchers influenced by hybrid UAV development [24].

In this research study, the author is focused on iterative methodology, as shown in Figure 23, to optimize the process by sizing and resizing an electric fixed-wing UAV. Table 2 shows the comparison of different aircraft schemes, thus elucidating the advantages of FW VTOL to conventional aircraft.

The process for sizing has two parts: The first part computes the requirements of the design to get the basic parameters of the aircraft design being optimized. The second part involves resizing for the next iteration, and integrated analysis is done on initial sizing. The mass calculation of all the components of UAVs, battery capacity calculation, FW constraint analysis and updated geometry sizing are amalgamated into fixed-wing electric VTOL UAV-integrated analysis. The analysis of the feasibility of performance constraints is done using constraint analysis. Wing loading and power loading are imperative factors that are found in this analysis. The available data is used to derive several new empirical equations. The total mass equation is

$$\text{MTO} = \frac{(\text{MVTOL propulsion} + \text{MFW propulsion} + \text{M payload})}{1 - (\text{MF batt} + \text{MF struct} + \text{MF subsyst} + \text{MF avion})}. \tag{7}$$

The general equation for the battery mass fraction is then

$$\text{MF battery} = \frac{tP}{\text{MTO Espec}\,\eta\,\text{batt fusable}}. \tag{8}$$

Here, $t$ is the duration of a given mission segment and $P$ is the required power.

The total mass and battery capacity are calculated using the analysis of the mission for fixed-wing and VTOL hybrid UAVs. Many iterations are done to conclude the final design

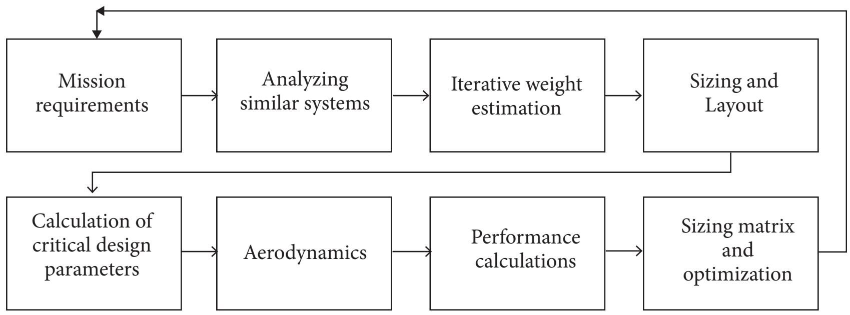


FIGURE 20: The design methodology [23].

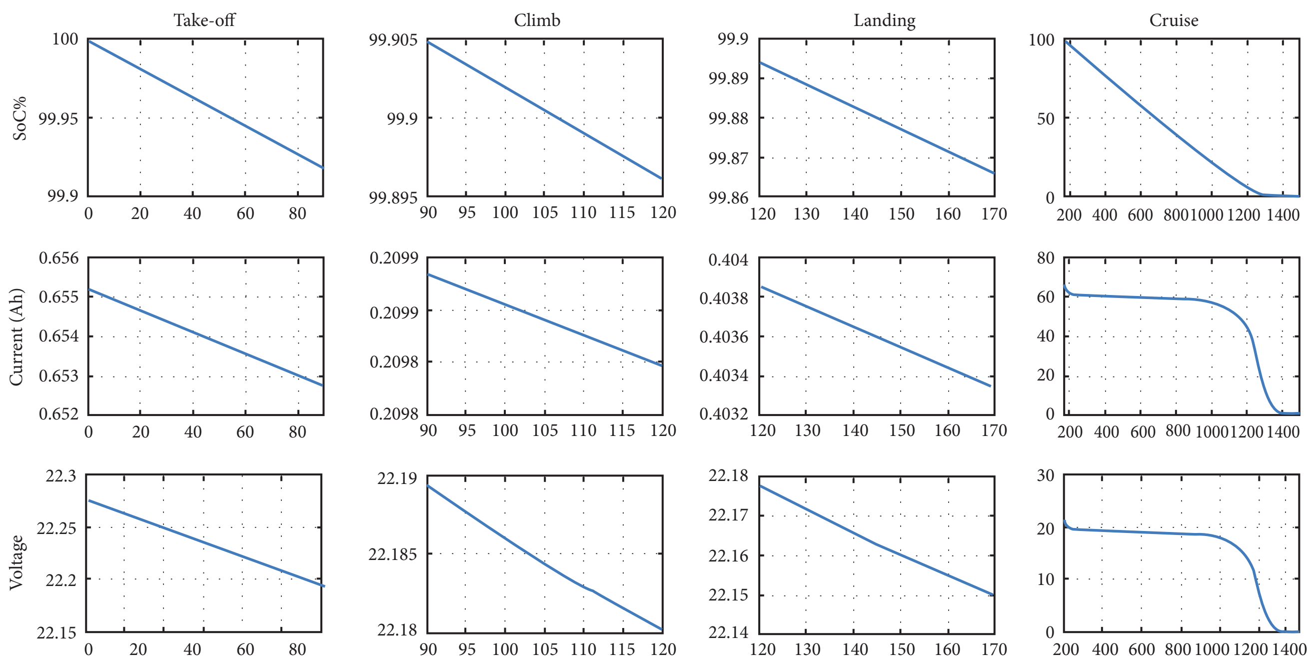


FIGURE 21: General results during missions [23].

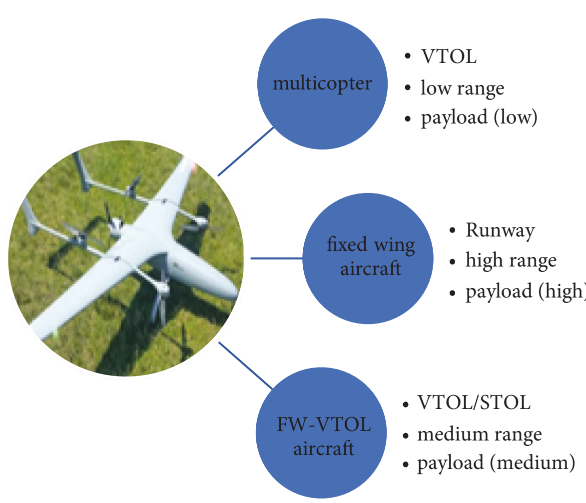


FIGURE 22: UAV configurations.

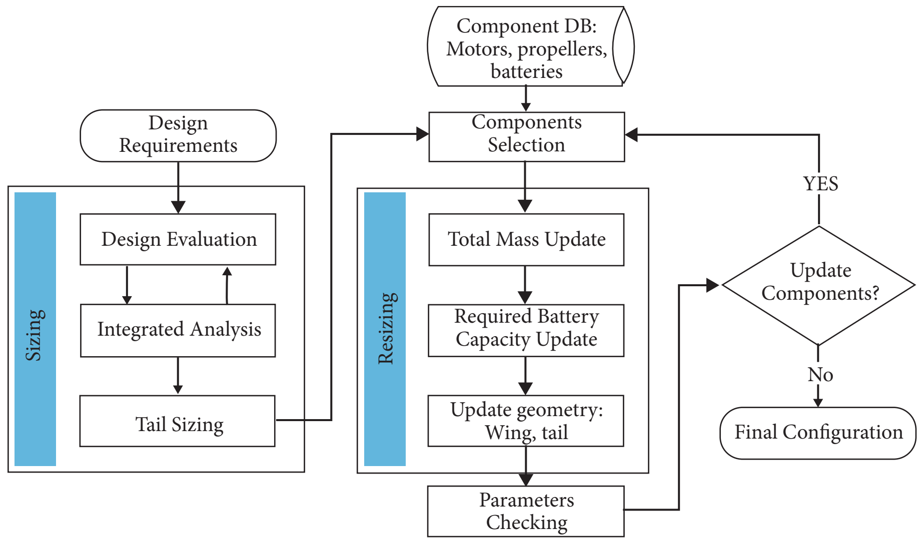


Figure 23: Fixed-wing VTOL electric UAV preliminary sizing/resizing process [25].

Table 2: Comparison of different aircraft [25].

| | Multicopter | Fixed-wing aircraft | FW-VTOL aircraft |
|---|---|---|---|
| Take-off/landing | VTOL | Runway, catapult | VTOL/STOL |
| Hovering | Yes | No | Yes |
| Maneuvering | Very agile | Medium | Medium |
| Stability | Unstable | Stable in forwarding flight | Stable in forwarding flight |
| Range, endurance | Low | High | Medium |
| Forward speed | Low | High | High |
| Payload | Low | High | Medium |
| Control system | Propeller RPM change | Control surface deflection | Both |

while selecting the actual components of the propulsion system. An in-depth analysis is also done on a 3.5 kg fixed-wing electric UAV in the paper [25].

## 3. Tilt Wing VTOL UAV

A. R. Serrano et al. looked into the complications of both air force aircraft UAVs and the increase in commercial aircraft consisting of shorter runways. These limitations lead to a path of discovering a new category of aircraft known as transitional aircraft (TA). It incorporates advantages of both a fixed-wing airplane and vertical take-off and landing. Appropriate data is available on both of the modes, but there is no generic methodology for designing TA, a lot of challenges in the selection of TA configurations, as shown in Table 3. A major issue is regarding the mutual aerodynamic interactions that occur during the transition flight phase when the aircraft changes the flying mode from hovering mode to cruising mode. Thus, transitional aircraft are capable of flying in both of these modes. These aircraft have different characteristics from vertical take-off and landing to flying at low velocities. In addition, flying in different directions produces complicated manoeuvers. The performance of the aircraft is increased in terms of range, endurance, payload carrying capacity, and maximum forward velocity in comparison to other conventional UAVs. In addition, the TA helps in reducing transition time, enhancing stability, and reducing dead weight for optimizing the flight conditions, which improves the aircraft usage in all kinds of aircraft flying modes, as shown in Figures 24 and 25. Hence, this paper focuses on providing a proper solution to the design methodology and mathematical formulation of a transition aircraft. A design chart is produced for developing optimum design parameters such as power values, rotor disc loadings, aircraft weight, wing loadings, and engine sizing. Finally, the developed methodology was validated using XV-15 and compared to the actual sizing parameters. The results showed that the error was less than 3%. Finally, the proposed approach can be utilized to calculate optimized power requirements, wing loading, and rotor disc loadings based on actual flight mode requirements [26].

Muraoka et al. investigated the Quad Tilt Wing (QTW) VTOL UAV, which comprises tandem tilt wings with propellers attached in the middle of each wing (span-wise) and whose configurations have a high potential for hybrid UAVs. In order to perform civil UAV activities, the QTW (Quad Tilt Wing) VTOL UAV has been under development by the Japan Aerospace Exploration Agency (JAXA), which contains advanced vehicle configurations. The research aims at developing a technical foundation for QTW VTOL UAV vehicle system design including tandem wing layout, flight operation, and flight controls. The data obtained from the

Table 3: The contrast between tilt-rotor and tilt wing UAVs.

| Type | Features | Structural aspects | Manoeuvre/control |
|---|---|---|---|
| Tilt-rotor type, [20, 21] | Endurance, range, economical, functional, and manoeuvrability | Two sets of motors, one set for vertical movement, and the other set for horizontal movement | (i) Provide thrust both laterally and vertically<br>(ii) Direction can be changed using a tilting mechanism<br>(iii) Capability to manoeuvre in remote areas with increased efficiency of the aircraft in cruising forward as well |
| Tilt wing type, [26] | Range, endurance, payload carrying capacity, and maximum forward velocity | Controlled by actuators | (i) Reduced transition time<br>(ii) Enhanced stability<br>(iii) Reduced dead weight for optimizing the flight conditions to improve the aircraft usage in all kinds of aircraft flying mode |

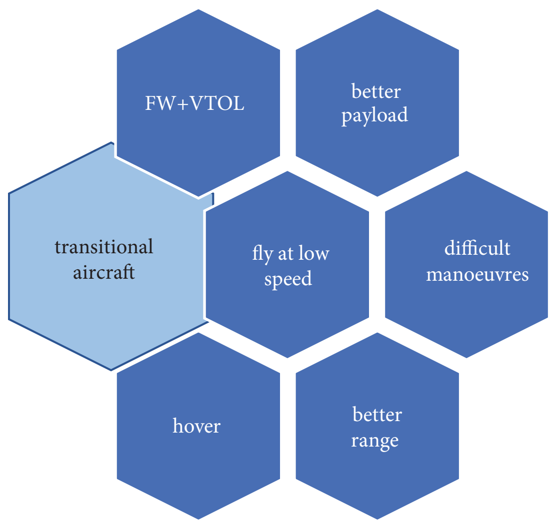


Figure 24: FW-VTOL electric UAV sizing process.

wind tunnel tests of the QTW UAV was used to create a nonlinear flight simulation model with six degrees of freedom. The plan was to use the model for the analysis of flight characteristics, namely, trim, transition schedule, stability, and controllability. The analytic aerodynamics model and mass properties model integrated the QTW's powered-lift and configuration features, as shown in Figure 26 [27].

Greater lift characteristics at both the front wing and rear wing of the UAV are thanks to the wing-propeller duo. Minor flow interference between the wings is produced. The wing tilt angles, body angle of attack, flap angle, and power influence the aerodynamic coefficient. The immersion of the wings in the propeller slipstream results in lift generation even during hovering at zero wind conditions. Yaw control can be established using the flaperons that could also function to produce axial forces. The mass parameters, namely, the center of gravity, inertial moment, and inertial product, depend on the tilt angle of the wing, as shown in Figure 27. Total aerodynamic forces and moments are computed by summation of wing-body components, control components, dynamic components by aircraft rotational motion, and tail wing components. The tilt angle schedule against airspeed is based on the trim analysis of each wing from the simulation model. A QTW vehicle dynamics simulation model was created to ascertain the prediction of flight characteristics, which was one of the major issues in VTOL designs. In addition, a vehicle flight control system is an important component to achieve safe and efficient VTOL operations. The research done here can be used for further prototyping and feature development including a high-level auto flight control system with guidance and navigation as well as a fast and cruise-efficient propulsion system [27].

*3.1. Modelling, Design, and Analysis.* Amiri et al. postulated the UAV's usefulness in everyday life, thanks to the advancement in aerodynamic studies, CFD, propulsion & sensors. As UAVs become more diversified, there occurred the demand and requirement for the efficient performance of additional tasks on a single airframe. VTOL airframes play a crucial part here to meet these diverse demands of the task application. A more compact and controllable UAV is needed. A gyroscope that does not rely on a moment of the arm can be a powerful tool for the control system of such UAVs and would not depend on the geometry of the vehicle. The limitation of helicopters in a close environment and


Figure 25: Types of UAVs [26].

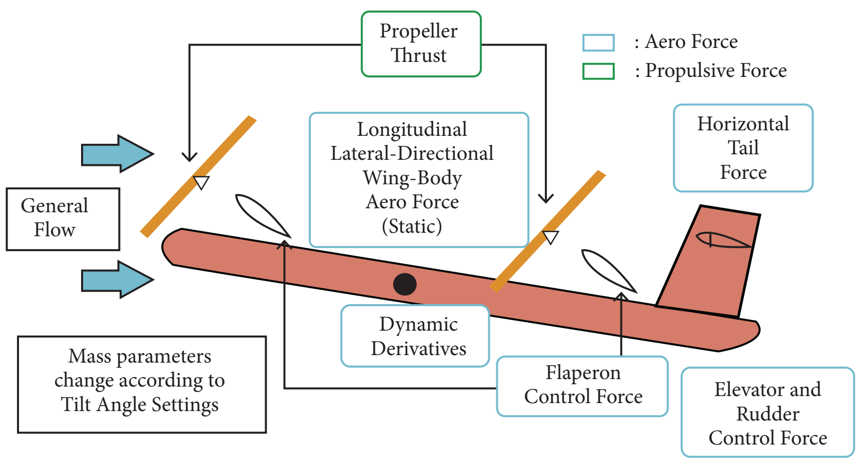


Figure 26: Aerodynamic and propulsive force model [27].

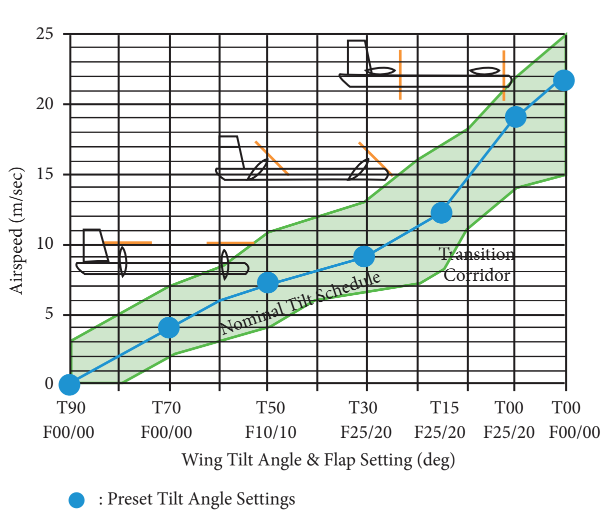


Figure 27: The plot of tilt angle vs airspeed [27].

forward speed has been a problem, but the introduction of tilt-rotors has the promise to be a game-changer for UAVs. Tilt rotors that hold the ability to provide thrust both laterally and vertically and whose direction can be changed using a tilting mechanism gives them an advantageous capability to manoeuvre in remote areas with increased efficiency of the aircraft in cruising forward as well. The paper shows a prototype on which simulations were done to find pitch and yaw moments that affect the stability of the UAV and talks about the lift fan OAT (Oblique Active Tilting) mechanism and its capability to provide pitch, roll, and yaw moments, as shown in Figure 28. The results of the simulation showcase the output as angles, while the input was propeller speed as signals and for several pitch angles, as shown in Figure 29. The OAT mechanism is seen to be more advantageous than just stability control, and the lift fan OAT mechanism has the capability of being efficient and provides high cruise speed and high manoeuvrability in tilt-rotor aircraft [28].

Figure 28: Prototype of dual-fan VTOL with lateral and longitudinal rotor Fans at 90° [28].

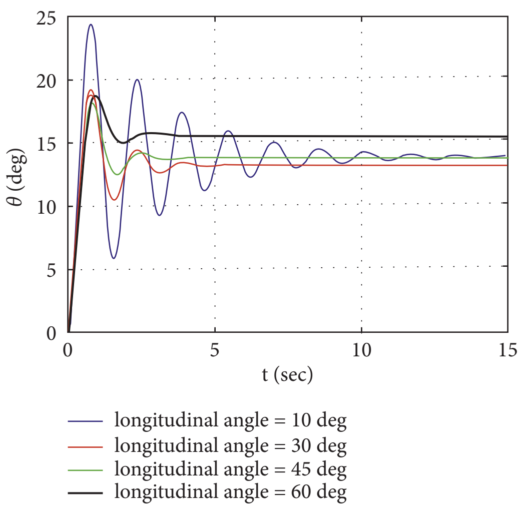


Figure 29: Feedback of control of the vehicle pitch with proportional controller term equal to 1 for different longitudinal angles [28].

Elfeky et al. postulated that quadcopters have become a focus of research in UAVs and have many applications for commercial and military purposes. QRAV (Quadrotor Aerial Vehicles) can perform VTOL and can be used for effective transport for the military and hostile environments. Tilt wing VTOL aircraft was designed and tested for feasibility, but various problems occurred to performance and controllability. A quadcopter is a well-researched type of VTOL due to its simple design and high agility. The conventional quadcopter has six degrees of freedom, three orientations, and three positions. Quadrotors are often underactuated, which results in two translational motions that are coupled with two rotational orientations, but they had limitations in terms of efficiency and high-speed motion for the cruise. A new concept of quadrotor design is introduced in this paper with four rotors and each rotor having two axes of tilt about the frame increasing the total number of inputs from six to twelve (six orientations and six rotational). This mechanism is controlled by actuators that increase the complexity of the system and have undesired aerodynamic effects, as shown in Figure 30. However, the advantages in terms of stability and controllability outweigh the complexity and undesired effects mentioned.

The PID system is used for controlling this intricate system to reduce the effects and undesired issues in the UAV and make the flight more optimal and control the angle of tilt and system according to the flight or mission progression. The main advantages are that every rotor position and orientation can be controlled independently, giving it superior manoeuvrability compared to other designs; the free inputs help to maintain optimal flight even if a gust of wind or extreme conditions are present. The system is more fail-safe as if one motor malfunctions, still the flight can be controlled accordingly with the high degree of freedom of this mechanism. This paper shows that the mechanism gives a big boost to manoeuvrability and agility of the quadcopter and enhances the fault tolerance of the UAV, and it can even work on two opposite rotors too in control. Thus, giving it an edge over other designs in terms of efficiency, fail-safe system, and robustness [29].

Anh et al. presented a tilt tri-UAV configuration, providing both performances of the conventional airplane and VTOL capability of a helicopter combining the advantages in a single configuration. Newton–Euler equations combined with aerodynamic formulae were utilized to create the mathematical model. For controllability, a neural network-based, non-linear PID control is used to stabilize the altitude in the trajectory during take-off and transition. A low-cost ultrasonic sensor is used for the measurement of height for 3-10 m and IMU (Inertial Measurement Unit) that consists of a gyro and accelerometer, and orthogonal magnetometers are used for the embedded system for control of the tri rotor aircraft. During hover, the propellers in both rear and front produce enough thrust to lift and balance each other accordingly. During the transition, there is an increase in velocity. However, zero longitudinal acceleration is soon reached with a reduction in the front motor's RPM and frictional drag. Although the value is low, it is enough to create lift; during the transition, the rotor speed gradually increases as it rotates and reaches a cruise speed where it has enough momentum to continue the horizontal flight. The plane stabilizes itself accordingly to facilitate the condition of flight. The paper demonstrates a basic control strategy and how it can achieve a longitudinal path and be implemented in reality, as shown in Figure 31 [30].

Aditya and Yash have presented a review paper based on various configurations of VTOL UAVs and their advantages over conventional aircraft. They can either be unmanned

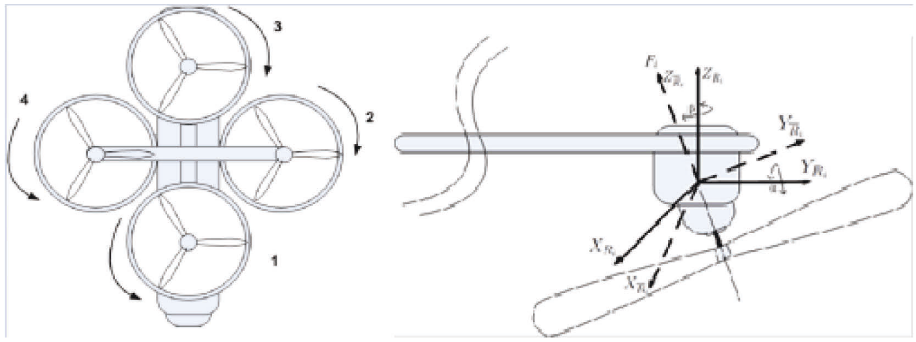

Figure 30: Rotor position tilt angles of rotors [29].

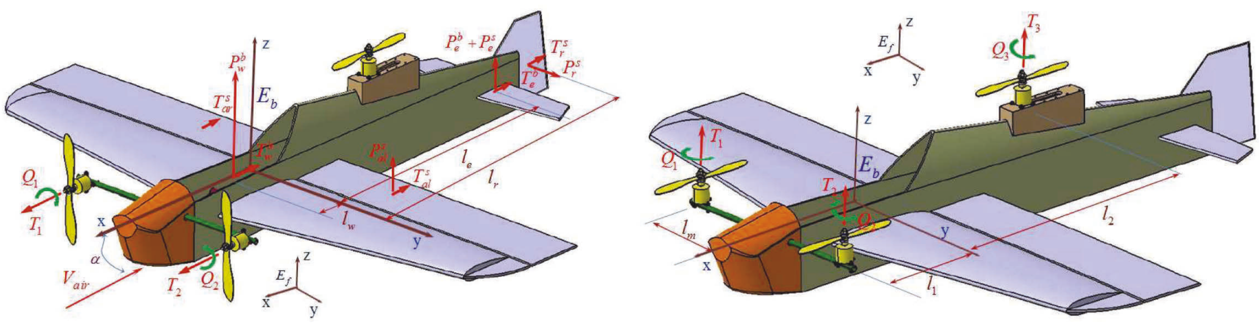

Figure 31: Horizontal flight vertical flight [30].

types or manned types in various scales and sizes. They started with insights about the early inventions of the VTOL such as Harrier, V-22 Osprey, and Yak-38 Forger. Then, the paper shows the comparison and advantages of the VTOL UAVs of a smaller scale such as dual copters, tri-copters, quadcopters, and hex-copters. In addition, advancement in VTOL has led to research for hoverbikes. Various applications of these vehicles are provided. The conclusion states that the octocopter is more suitable for aerial photography. For small-scale applications and high lifting capacity, *Y*6 and *X*8 configurations can be used in the coaxial motor configuration, as shown in Figure 32 [31].

Muhammad and Sasongko have established the analysis of flight dynamics and tilt-rotors in a VTOL aircraft during the transition stage, as shown in Figure 33. The forces and moment equations in the longitudinal plane of the motion are used to derive the model of the aircraft. The UAV's flight characteristics are studied with the help of airplane dynamic response, during the conversion phase from hover to level flight, to understand the control system design phase. The simulations are done on the MATLAB Simulink software, as shown in Figure 34. The nacelle angle and rotor thrust control are held on the subsystem "tilt-rotor." Two simulations are carried out, namely, the transition phase from longitudinal lift to lateral cruise flight phase as well as the conversion phase from lateral cruise to vertical flight phase. It can be concluded that a successful stable system can be obtained with the use of the longitudinal flight dynamic model of the tilt-rotor aircraft. However, it still requires some fine-tuning through upgrades to the control system. There is a further need for corrections and improvements to the dynamic model to obtain a more accurate and precise quantitative representation of the system [32].

Finger et al. have investigated the requirements of an electric propulsion system for VTOL UAVs. Payload carrying capability and endurance capability have been considered the hallmark of an aircraft. Their analysis does a lot of experimentation in wing sizing, engine sizing, and hybrid opportunities (in terms of fuel). A supplementary electric propulsion system has been suggested depending upon the flight requirements. Three missions have been defined with the first one focusing on a small payload but with increased endurance (10 kg payload, 8 hours endurance). The second one focuses on carrying a medium payload (50 kg) with a short endurance time (3 hours), while the third one is aimed at carrying the heaviest payload (100 kg) for a mid-range capability (5 hours). Other factors that were considered to be important in the mission were lift drag ratio, hover time, and surplus thrust factor. The paper demonstrates the various sizing possibilities depending upon the configuration requirements, which can be viewed as futuristic concepts to drive down cost, as shown in Table 4 [33].

*3.2. Modelling, Prototype, and Analysis.* Sandilya have presented a tilt quad rotor aircraft having features of both fixed-wing UAVs that have low energy consumption with higher operational speed and rotary aircraft with VTOL capabilities. A 3D modeling of a tilt quad rotor RC aircraft was done successfully and was fabricated to prove the concept, as shown in Figure 35.

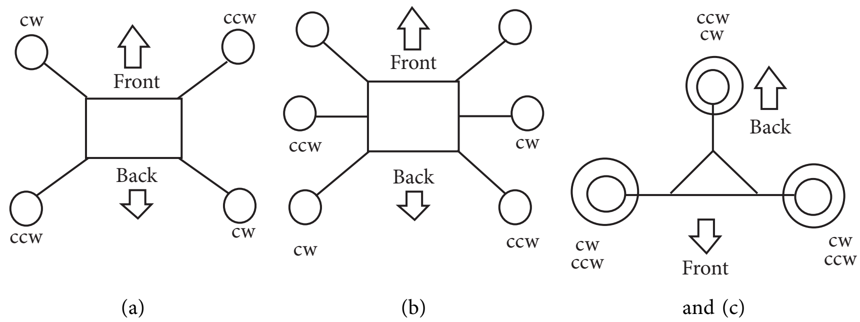


FIGURE 32: (a) $X$ configuration, (b) hex-copter configuration, and (c) $Y6$ configuration [31].

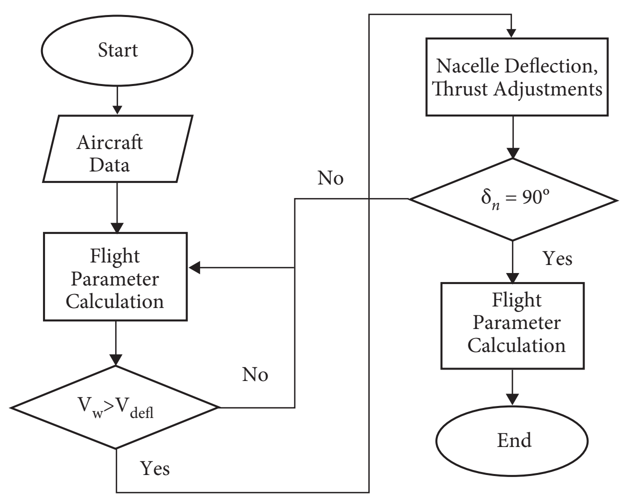


FIGURE 33: Flowchart for nacelle angle and rotor thrust determination [32].

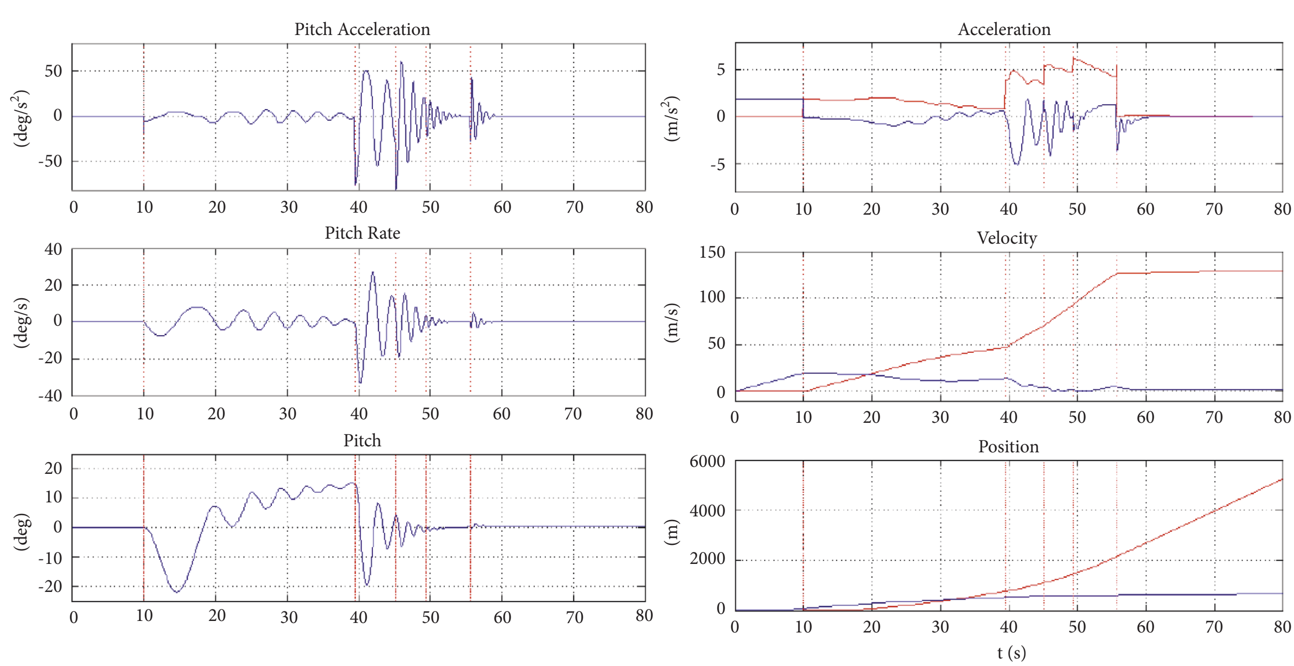


FIGURE 34: Transition mode flight parameters [32].

Table 4: Modeling, design, and analysis done by various teams.

| Team | Innovation carried | Software/technique used | Remarks |
|---|---|---|---|
| N Amiri | Simulations to find pitch and yaw moments | CFD, propulsion, and sensors | The lift fan OAT mechanism has the capability of being efficient, providing high cruise speed and high manoeuvrability |
| Mahmoud Elfeky | A new concept of quad-rotor design with four rotors and each rotor having two axes of tilt | Prototype was tested | The mechanism gives a big boost to the manoeuvrability and agility of the quadcopter and enhances the fault tolerance of the UAV |
| Duc Anh Ta | Tilt tri-UAV configuration | Newton–Euler equations combined with an aerodynamic formula for a mathematical model | Demonstrated a basic control strategy and how it can achieve a longitudinal path |
| Muhammad R | Analysis of flight dynamics and tilt-rotor in a VTOL aircraft during the transition stage | MATLAB Simulink software | Further need for corrections and improvements to the dynamic model |
| D.F. Finger | A supplementary electric propulsion system | Prototype was tested | Demonstrates the various sizing possibilities depending upon the configuration requirements |

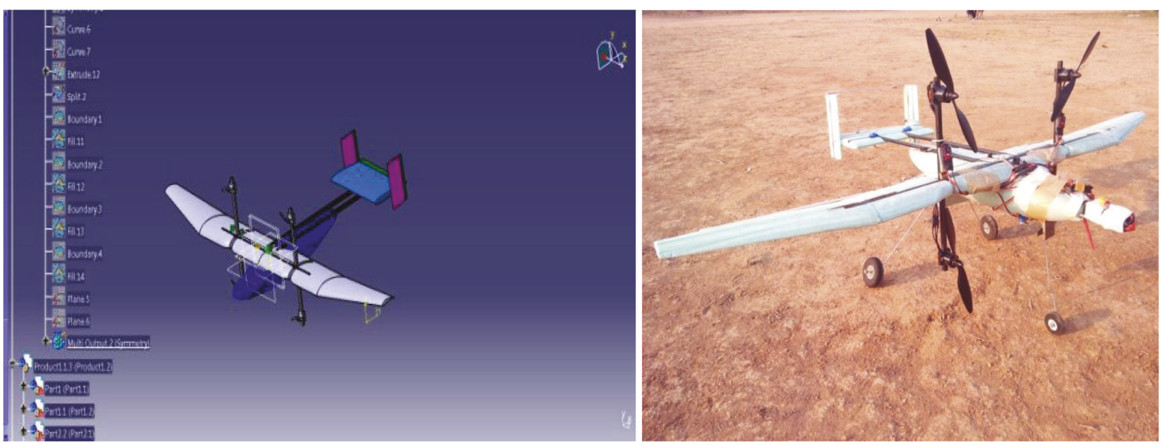

Figure 35: Tilt quad RC aircraft UAV assembly: (a) 3D model and (b) fabricated [34].

The major parameters considered in the novel concept are as follows: range (m), speed (m/s), endurance (hr), weight (kg), service ceiling (m), wingspan (m), length (m), and payload (kg), as shown in Table 5. The graphs were plotted to take two parameters at a time, and information was extrapolated accordingly. The main requirements of the novel concept UAV are as follows: VTOL feature incorporated in the design, highly manoeuverable, should be capable to carry a load of 1.5 kg, max velocity should be approximately 25 m/s, and should have high lift characteristic and high stability, as shown in Table 5.

The advantages of the UAV are energy efficiency, high manoeuvrability, energy efficiency, higher-speed control, and VTOL capability. Limitations are the cost of the UAV compared to other models in a similar configuration and higher complexity and lower efficiency due to the use of four rotors instead of one in forwarding motion, as shown in Figure 36. Further need to control the UAV using a fully autonomous system is required for a more efficient and to reach the required potential that is stated before [34].

Yu et al. presented information about VTOL UAVs and their future scope in technology worldwide. The author presents a case study on different types of VTOL UAVs actively being tested in seven counties such as South Korea, China, Japan, the United States, Israel, Switzerland, and France. One of them is a KUS TR that is a tilt VTOL developed in South Korea, as shown in Figure 37. It was made to develop the world's first commercialized aircraft. It is lighter than Tr-100 and has easy manoeuvrability. Tr-100 is VTOL smart UAV for civilians, which was developed by KARI (Korean Aerospace Research Institute), as shown in Table 6. Similarly, Aerosense is a VTOL UAV developed by Japan's SONY corporation. It is used for product delivery, patrolling, and high-quality photo shooting for aerial photography. It uses cloud technology and high-speed autonomous flight configurations. Air-Mule is developed by Tactical robotics, which is an Israeli manufacturer used for military loading applications.

Table 5: KUS-TR performance and data.

| | | | |
|---|---|---|---|
| Length | 3.5 m | Width | 5.2 m |
| Max weight | 210 kg | Payload | 30 kg |
| Engine | 55 HP | Max. speed | 250 km/h |
| Cruise speed | 200 km/h | Max. attitude | 4.5 km |
| Control (radius) | 60–200 km | Time in service | 6 hrs |
| Manufacturer | Korean air | Development nation | South Korea |

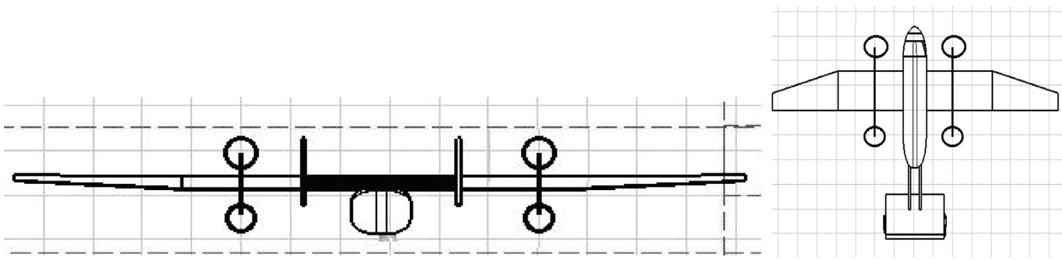

Figure 36: 2D concept: (a) In cruise mode and (b) in hovering mode [34].


Figure 37: VTOL UAV: (a) Concepts by different nations, (b) KUS TR, and (c) TR-100 [35].

Table 6: TR-100 performance and data.

| | | | |
|---|---|---|---|
| Length | 5 m | Width | 7 m |
| Max weight | 1000 kg | Payload | 100 kg |
| Engine | PWC-206 (56 HP) | Max. speed | 500 km/h |
| Fuel level | 300 kg | Max. attitude | 5 hrs. |
| Control (radius) | 200 km | Price | 30 hundred million |
| Manufacturer | KARI | Development nation | South Korea |

Thus, the author also states other aircraft, their applications, and performance data in terms of weight, cruising speed, management radius, time in service, maximum speed and altitude, manufacturer information, etc., as shown in Table 7. The other aircrafts mentioned are Airbus DS Tannan300, Wingtra, VD200, and X-plane. Thus, the author presents different VTOL technologies used in different countries such as China, Korea, Japan, the USA, etc., and summarizes a comparison report in terms of performance and applications [35].

Finger et al. posited that the power required in VTOL UAV during hover is greater than what is needed during the cruise. The power problem can be solved with a balancing electric propulsion system. The paper focuses on the initial sizing algorithm for transitioning VTOL aircraft with a hybrid-electric propulsion system. It is intended to be used for urban air mobility or air taxi for future mid-range VTOL aircraft, as shown in Figure 38. Short missions favor electric propulsion systems as this configuration reduces the complexity of hybrid. As in short-range, electric and hybrid-electric propulsion becomes more suitable.

Parameters that severely affect the aircraft mass and size are number of passengers, design range (100 km, 500 km), and propulsion are combustion, fully electric, hybrid electric, and technology level. The three methods for enabling VTOL capability of aircraft, as shown in Figure39, are as follows:

(1) Lift + Cruise (L + C)—A separate hover I in the aircraft in addition to the cruise propulsion does not contribute to lift production.

Table 7: *X*-PLANE performance and data [35].

| | | | |
|---|---|---|---|
| Length | 15.2 m | Width | 13.4 m |
| Max weight | 5450 kg | Time in service | — |
| Engine | 4000 HP | Max. speed | 741 km/h |
| Manufacturer | DRPA | Development nation | USA |

(2) Lift = Cruise (L = C)—The same propulsion in this configuration is used for both cruise and hover. Here engines are poorly matched in the cruise as they cannot be throttled back efficiently.

(3) Lift + Lift/Cruise (L + L/C)—A lift system is added to the airframe supplemented in hover by the cruise propulsion system and the most efficient system.

The L + C method is chosen as it has a more fail-safe system compared to others. Here, the initial sizing is used to determine the values of max take-off weight and wing area and thrust of a new aircraft based on the requirements. The result of initial sizing is used to model the first design, which is processed further to refine the design. A tool by the Institute of Aircraft Engineering of FH Aachen is used for the initial sizing of fully electric and hybrid-electric aircraft. The design of CVTOL is highly critical and sensitive to variation. It was observed that fully electric aircraft are still too heavy and hybrid electric provides no clear advantage over other systems, medium-range missions would allow an increase in efficiency in the hybrid electric system, but complexity might increase and steady progress in battery technology and motor technology is required for more efficient system [36].

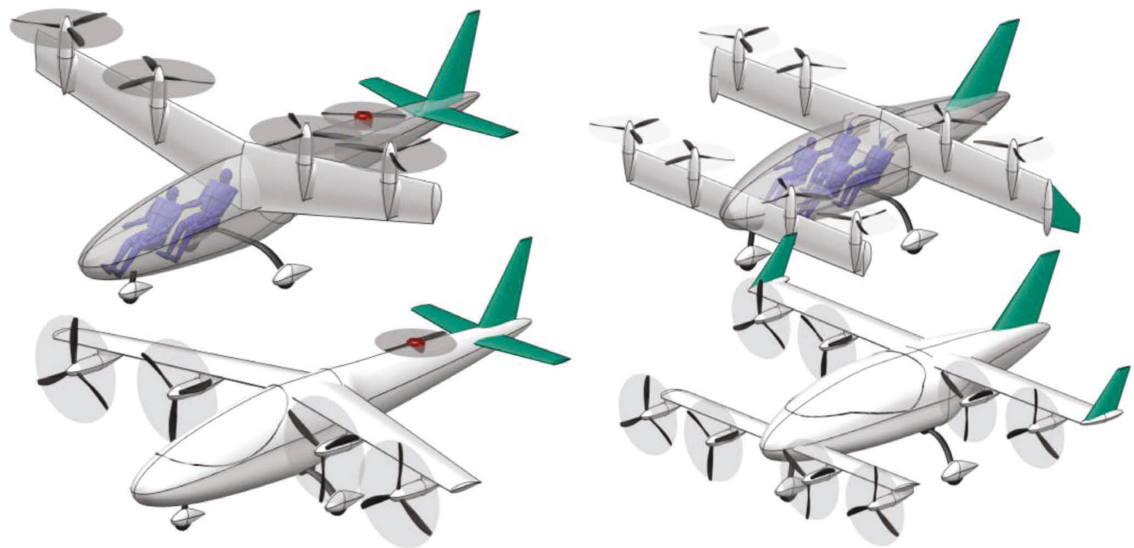

Figure 38: Hover and flight mode. (a) 2 passenger concepts and (b) 4 passenger concepts [36].

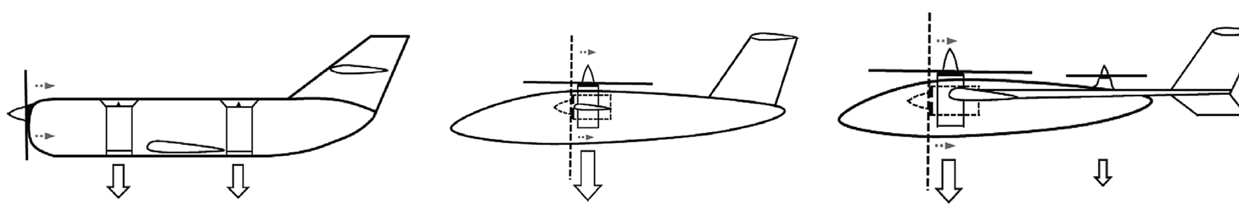

Figure 39: Methods for VTOL, (a) L+C (Separate lift engines). (b) L=C (Same engines for lift and cruise. (c) L=L/C (cruise engines support lift engines), [37].

Finger also posits that one of the biggest challenges in aviation is the design of VTOL aircraft, and this paper explains the design space for a VTOL UAV and evaluates the performance of conventional aircraft. The key variables such as cost and benefits of VTOL requirement are assessed. The first configuration has a forward motor and two vertical motors that become redundant during forwarding flight, while in the second configuration the rotors tilt horizontally and act as both hovering and cruise, but not much speed is required in UAV, leading to lower efficiency of the UAV, as shown in Table 8. In the third configuration, we deal with both horizontal and vertical motors present, thus increasing the efficiency of the UAV overall and providing better stability, as shown in Figure 40 [38].

The VTOL and CTOL configurations are gone through thoroughly in the paper and credibility that VTOL aircraft are certainly very feasible, and their design remains challenging, but the advantages are still highly beneficial, as shown in Figure 41. With technological improvement, better-performing aircraft is possible. Battery improvements will open a new field for electric and hybrid-electric propulsion, which is neglected in this paper [38].

*3.3. Research Methodology and Optimization.* Saengphet and Thumthae show a study on the design of a fixed battery-powered UAV designed to carry an Automated External Defibrillator (AED) or a payload of 1.5 kg. This has the ability not only to take off or hover but also cruise, as shown in Figures 42 and 43. This fixed-wing has the capacity for achieving high speeds with high endurance without a tilt-rotor mechanism. This type of UAV is termed a hybrid UAV. The design was initialized by considering maximum take-off weight, battery weight, and capacity estimated from the fixed-wing multi-rotor power required. The coaxial rotor, motor, SC, and battery are reviewed. The constant power method was adopted to improve the accuracy of the range and endurance of battery-powered aircraft instead of the voltage method [40].

General Requirements applied for this aircraft consist of reliability, maintainability, availability, and transportability, as shown in Figure 44. Given the small number of non-moving elements, the non-tilting rotor system was chosen as well. Transportability is the capability of the carrier or towing or folding of the wing and integration for assembling the UAV. The conceptual design consists of six sub-sections: maximum take-off weight, drag estimation, power, weight build-up, battery weight, and subsystem efficiency. The aircraft is tailless (flying wing) to reduce moving parts and flutter. It is difficult to control autonomous flight. A *Y*-6 coaxial rotor is used to increase motor efficiency, thrust, and compactness. A retractable landing gear is used to reduce drag and payload placement on top of the fuselage where the red cross symbol is situated, as shown in Figure 45.

The logarithm relation of empty weight is

Table 8: Prototyping analysis done by various teams.

| Team | Innovation carried | Software/technique used | Remarks |
|---|---|---|---|
| B. V. Sandilya | Tilt quad rotor aircraft have features of both fixed-wing UAV | 3D modeling | Further need to control the UAV using a fully autonomous system is required for a more efficient |
| Seunghee Yu | Lighter than Tr-100 and has easy manoeuvrability | Prototype built | Summarizes a comparison report in terms of performance and applications |
| D. F. Finger | Balancing electric propulsion system | Tool by institute of aircraft engineering of FH aachen | Fully electric aircraft are still too heavy and hybrid electric provide no clear advantage over other systems |
| D.F Finger | Various configurations are tested with different forward and vertical motors | 3D modeling | VTOL aircraft are certainly very feasible; their design remains challenging, but the advantages are still highly beneficial |

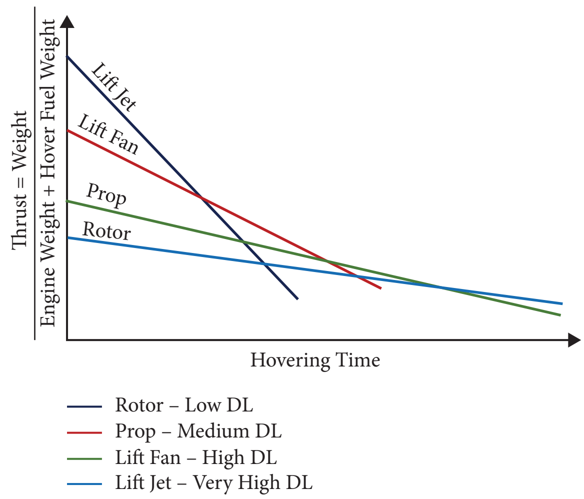


Figure 40: Hover performance of various VTOL configurations, [37].

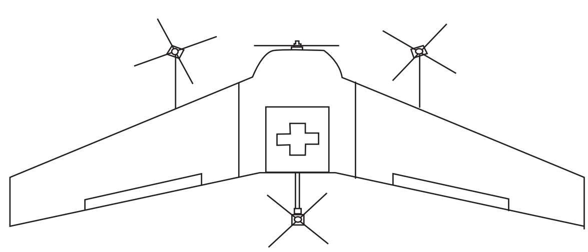

Figure 41: Concept of flying wing Y-6, [38].

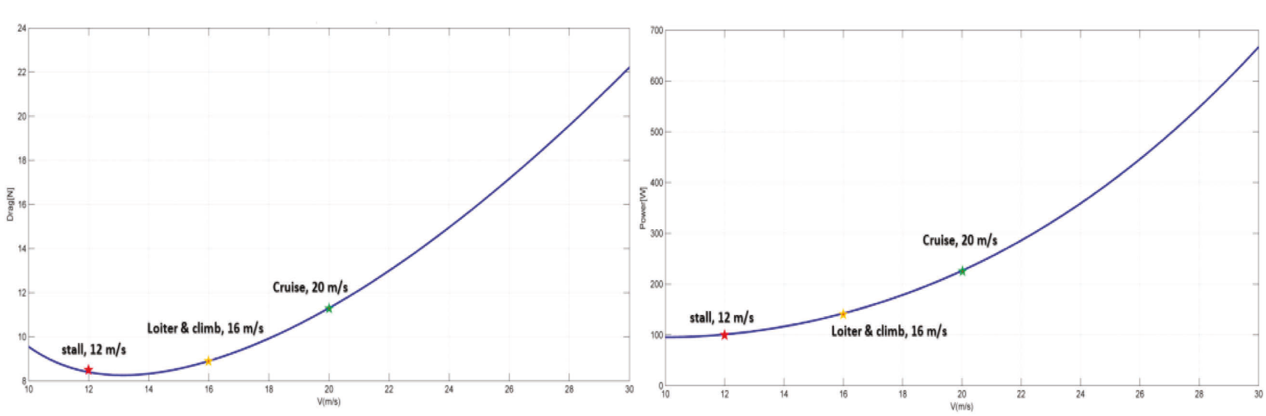


Figure 42: (a) Thrust required and airspeed. (b) Power required and airspeed, [39].

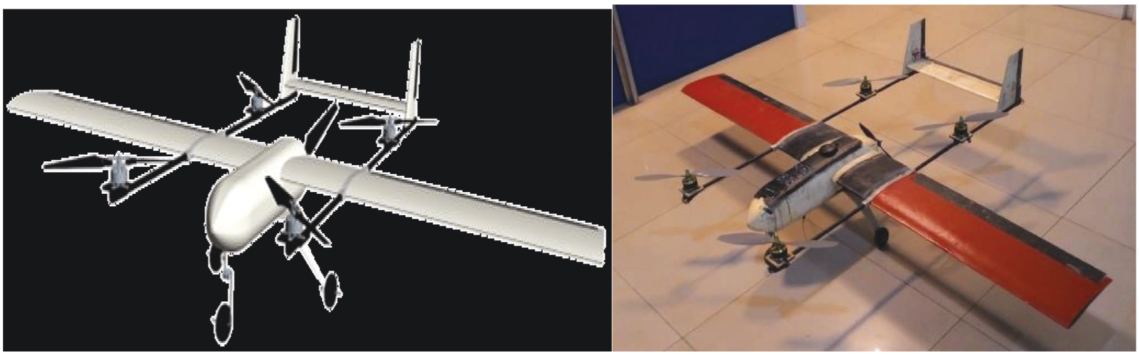

Figure 43: UAV, (a) CAD design. (b) Prototype, [39].

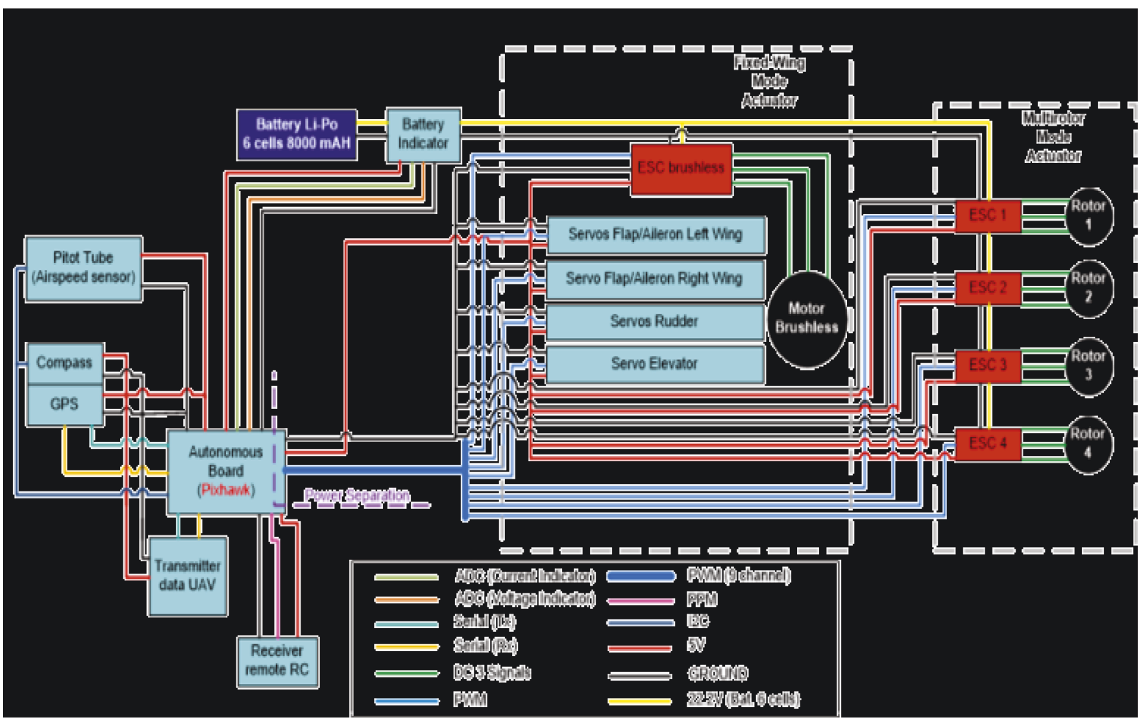


Figure 44: Power Distribution, [39].

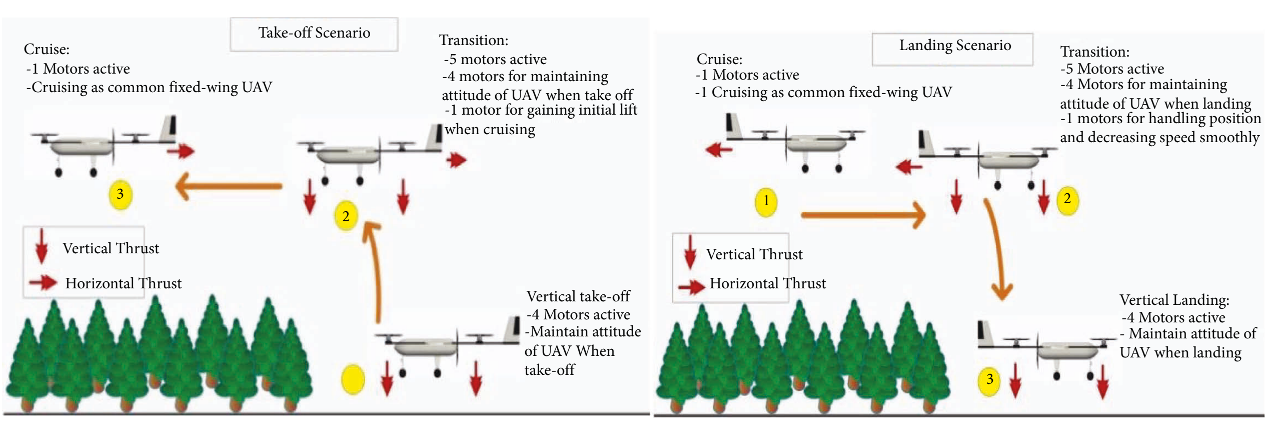


Figure 45: (a) Take-off scenario. (b) Landing scenario, [39].

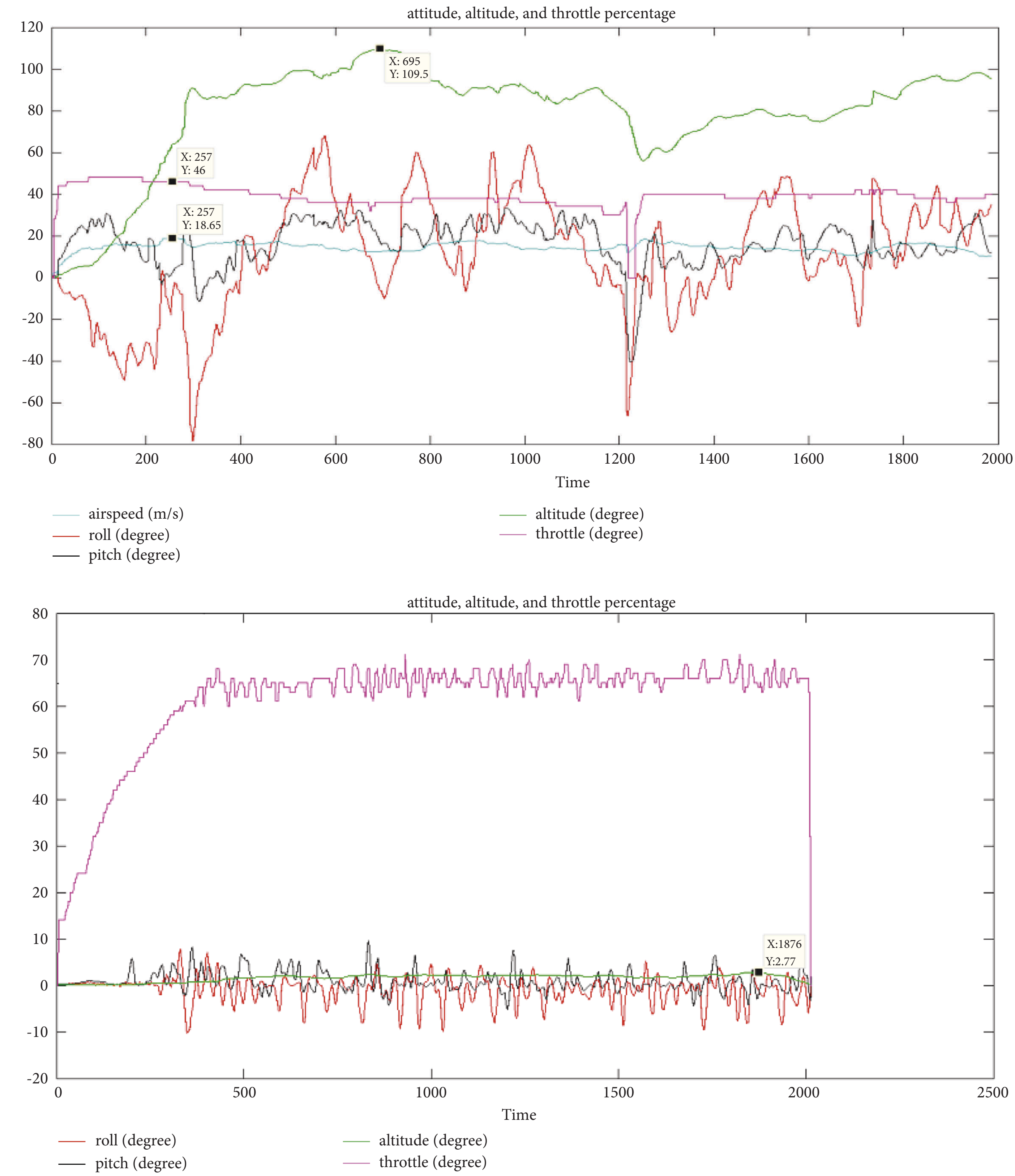


Figure 46: Flight data during, (a) transition and cruising, (b) hovering, [39].

$$W_e = 10^{-0.155+0.91\log_{10}(W_{TO})}. \quad (9)$$

The maximum take-off weight is taken as input, and it is broken up into four elements: empty weight, payload weight, multi-rotor system, and battery weight,

$$W_{TO} = W_e + W_{pl} + W_{MR} + W_b. \quad (10)$$

Since the WERs did not take the hybrid UAV weight into the database, the multi-rotor system weight was set as a part of the payload during iteration. The battery capacity is over 15000 mah, and three packages of 4 S battery of 5000 mAH were

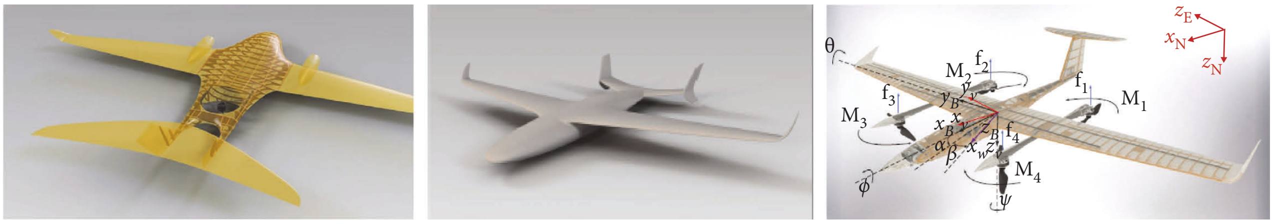

Figure 47: (a) Initial design concept. (b) Second design concept. (c) Final Design concept, [40].

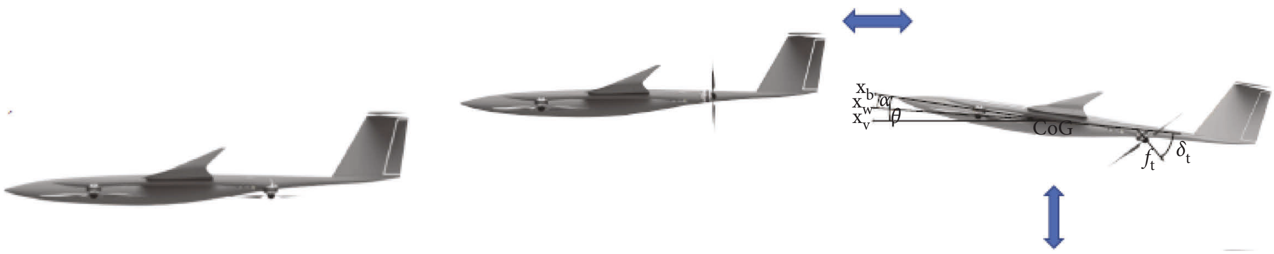

Figure 48: Second design concept, [40].

used. The maximum take-off weight is 66.69 N, and the minimum drag is 13.1 m/s. The minimum power required speed is 10 m/s, which is lower than stall speed, as shown in Figure 46.

Fixed-wing thrust and multi-rotor thrust were separated to reduce the risk of tilting rotor system failure. Flying wing with coaxial rotor propulsion in the intended platform and multi-rotors has high drag fraction. If drag is reduced, the range of the aircraft reduces the weight of the battery in the process with a reduction of power needed. Increasing take-off velocity is possible to reduce the energy consumption if optimal efficient motors are used. Stability analysis requires the aerofoil analysis of the wing and the wing geometry. The propulsive efficiency of both configurations must be investigated to obtain better range and endurance estimation [40]. Hadi et al. presented a design of avionics and control scenarios of a small hybrid VTOL UAV, as shown in Figure 47. It has combing features of both a fixed-wing UAV and a rotorcraft, providing both high manoeuvrability and high endurance. Here, the avionics, power system of the aircraft, and control system design are discussed in detail. Here, the thrust of the four motors is considered to be twice the weight of the UAV.

The power distribution, as shown in Figure 48, gives a rough diagram of the electronic setup in the UAV, with four servos used for control surfaces and ESCs to regulate the RPM of the motors. A pitot tube is used to calculate speed, and GPS is used for calibration and it is controlled by radio control.

In preliminary, only upward thrust is required to lift off to a safe attitude before transition, Figure 39(a). The control surfaces are not activated, and the forward motor is inactive. As transition begins, the forward motor is activated and the vertical motors gradually reduce RPM, the forward is fixed at 75% throttle throughout the journey till it reaches cruise speed, and the control surfaces (aileron, rudder, and elevator) add to the stability and manoeuverability now. During the landing, all four motors are active, reduce rpm gradually, and maintain altitude until it lands after transitioning from cruise flight, as shown in Figure 39. On further testing, only 46% of throttle is required during forwarding flight where the airspeed reaches 18.21 m/s and the stall speed is 12.41 m/s. The flight data, as shown in Figure 49, indicates that the aircraft can handle both modes successfully, and the transition stage has a bit of instability that can be controlled by the pilot accordingly [37].

Czyba et al. had investigated that fixed-wing UAVs with VTOL capabilities could be utilised to overcome the problem with fixed-wing that does not operate well in constrained airspace, at low speeds, and at altitudes. The paper presents the design of the UAV with VTOL capability with prototyping, mathematical models, and CFD simulations. It is designed in a hybrid platform that corresponds to hovering, transition, and spatial airframes. The CAD and the CFD analysis for specific flight modes were decided through an iterative process, as shown in Figures 41 and 42.

The article presents the design methodology for the VTOL UAV along with it the design evolution from a 3-point platform supported through a ducted fuselage propeller to a quad-rotor support in an H configuration. It is a unique configuration of four propellers or rotors faced downwards during hovering mode and fixed in the front and can be tilted in the back configuration horizontally acting as a pusher in the rear end. This configuration with parameters mentioned in Table 9 has also made strong claims to be more efficient in terms of aerodynamics. The rear motors act as thrust-vectoring engines providing vector thrust accordingly in the flight during the transition and horizontal during the transition. The proposed design is more robust against strong winds, as shown in Figure 43. CFD simulation presented that it is impossible to control the aircraft in an open-loop system. The transition is especially demanding and dangerous especially since it can stall easily at that point if not properly regulated. Overall,

FIGURE 49: Prototype of VTOL UAV, [40].

TABLE 9: Parameters of the design concept.

| Parameters | Value |
|---|---|
| Configuration | VTOL UAV |
| Wingspan | 2520 mm |
| Length | 1600 mm |
| Propeller | 16 × 8 inch |
| Max speed horizontal | 10 m/s |
| Max speed | 30 m/s |
| Wing area | 54 $dm^2$ |

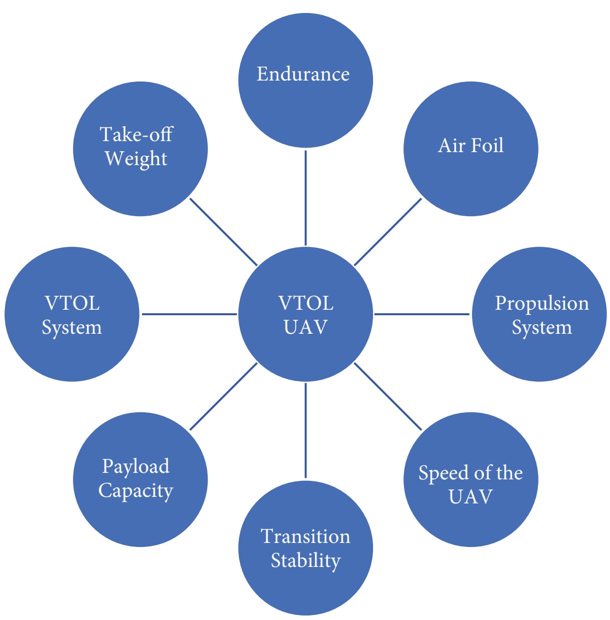


FIGURE 50: UAV iterations.

the design is well superior to other configurations available in the industry and can be used for their higher manoeuvrability and endurance [39].

## 4. Summary

The papers that have been reviewed have each focused on improving one or more factors that influence the capability of the UAV. The present, past, and futuristic concepts have been reviewed by us to present us with the data required for creating our innovative design of a VTOL UAV. In Figure 50, the various concepts and factors have been highlighted.

Since the appearance of the concept of VTOL aircraft, many different types of VTOL technologies have been developing. As we can see from the paper, a lot of problems occur in the novel concept and have been solved and still are being optimized for a more sophisticated and compact design with a good fail-safe system. Several points can be considered in future aircraft design:

(a) With increasing requirements, each technology can find its application instead of over-relying on a single technology or concept. It depends on the demand for small VTOLs for civil applications. Small low-cost VTOL technologies, such as UAVs with tilt-rotor mechanisms and tilt wing mechanisms, attract more research attention and are more thoroughly discussed. The tilt wing configuration with propellers attached span-wise in the middle of each wing has a high potential for hybrid UAVs.

(b) Greater lift characteristics are achieved at both the front wing and rear wing of the UAV wing-propeller. VTOL airframes and tilt-rotors can provide thrust both laterally and vertically that play a central part to meet varied demands.

(c) A neural network-based PID system is used to stabilize the altitude in the trajectory during take-off and transition, which makes the flight more optimal and controls the angle of tilt.

(d) The propellers in both rear and front produce enough thrust to lift and balance during hovering mode, are fixed in the front, and can be tilted in the back, while the nacelle angle and rotor thrust control are held on the subsystem.

(e) From the discussion earlier, it can be found that this novel concept of UAV can meet different demands, and they show a trend of upgradation; traditionally, it has been a tilt-rotor mechanism due to extensive research on them, and new technology could be researched to replace it too, which may be more effective and cheaper. We can do a trade-off analysis over and over again on technology features to get the optimal design of VTOL aircraft.

## Abbreviations

VTOL: Vertical take-off and landing
CTOL: Conventional take-off and landing
UAV: Unmanned aerial vehicles
TA: Transitional aircraft
PID: Proportional, integral, derivative
CFD: Computational fluid dynamics
FW: Fixed-wing
QTW: Quad tilt wing
CAE: Computer-aided engineering
RC: Radio control
GPS: Global positioning system
BLDC: Brushless direct current.

## Data Availability

All data are included in the manuscript.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

The authors gave ideas for the article, performed the literature search and data analysis, and drafted and/or critically revised the work of the paper.

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