Research Article

Design and Analysis of Hybrid Fixed-Wing Type Flying Robot

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Received 17 June 2022; Revised 16 July 2022; Accepted 22 July 2022; Published 8 August 2022

Academic Editor: Kalidoss Rajakani

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With the advent of disruptive technologies, unmanned aerial vehicles have seen substantial growth over the past few years. The market for flying robots is increasing drastically, and they are getting used in various sectors. This paper is aimed at discussing the novel design of a hybrid fixed-wing type flying robot in which both fixed-wing and rotary-wing concepts are combined so that stable flight with vertical takeoff can be possible. Our design proposes a compact structure that can be efficiently used in indoor applications. We have also discussed its structural analysis, the model’s stability, the CFD analysis, and the vibrational analysis of the designed structure. The objective is to design an effective compact flying robot system that will be used for medical applications and need to carry a payload of a minimum of 2 kg with good aerodynamic performance. The aerodynamic model required for a hybrid fixed-wing type flying robot has been developed, and the static stability of the model has been evaluated in the paper.

1. Introduction

As demand for intelligent systems increases, the domain of flying robots is booming. Flying robots can also be classified as drones, unmanned aerial vehicles. Flying robots are systems capable of vertical takeoff and landing with no human intervention. The endorsement of the technology of flying robots made a jump from the fad stage to the mega-trend stage because of the small takeoff distance, and substantial lift and airflow will be generated. Boon et al. [3] showed in his paper a comparison between fixed-wing and rotor-type flying robots. Fixed-wing type flying robots have better wing stability, good endurance, and longer flight time. These robots were used in aircraft and for outdoor applications.

2. Literature Survey

Tayli et al. proposed a design optimization model for fixed-wing aircraft. In their paper, they have represented an efficient design to enlarge the use of fixed-wing aircraft because of the small takeoff distance, and substantial lift and airflow will be generated. Boon et al. [3] showed in his paper a comparison between fixed-wing and rotor-type flying robots. Fixed-wing type flying robots have better wing stability, good endurance, and longer flight time.
applications. Multicopter types are easy to take off and land, and they are getting used in wide applications presently. One demerit of rotary-wing is its flight time as it gets discharged after a short journey. A blend in the concept of fixed-wing and rotary-wing flying robots to build a hybrid system has also been an area of concern in the last few years. Bell-Boeing V-22 osprey [4], Harrier GR7 [5], and Convair XFY-1 [6] are some examples of hybrid flying robot which combines fixed-wing and rotary-wing concepts. Gunarathna and Munasinghe [7] developed a quartered fixed-wing hybrid flying robot with excellent performance in takeoff and landing autonomously. Siddhant Panigrahi et al. [8] proposed the design and detailed inspection and evaluation of a hybrid VTOL tilt-rotor UAV for enhanced performance. Harikrishnan [9] discussed in his paper about strength and efficiency of tiltrotor vertical takeoff type by copter UAVs. Gress et al. [10] discusses the steadiness and strength of VTOL aerial vehicles with propellers at an angle. By going through various research papers, it was found that hybrid flying robot is a budding area of research where further research is conducted to achieve a stable design and enhanced efficiency. Some of the pioneer research work in the hybrid flying robot has been commercialized like Bird’s Eye View Fire Fly6 [11], X plusOne [12], and Martin UAV V-Bat [13]. Almheiri et al. [14] proposed a composite aerial vehicle that is a mixture of fixed wing and rotor concepts for medical applications. Haider et.al [15] developed a design of a hybrid fixed-wing tricopter, and the control system and hardware parts were discussed in the paper in detail. We have also reviewed research papers on different flying robots used for medical applications [16] as well as challenges faced by flying robots in the area of energy optimization, obstacle avoidance, etc. [17, 18].

After going through various research works done in the area of fixed-wing type aerial vehicles, rotary type UAVs, and hybrid type aerial vehicles, we found that hybrid kind of aerial vehicles can be beneficial for indoor applications. The main research gap that we found after going through various papers is to develop a compact design of aerial vehicles which can be used efficiently in indoor applications as most of the designs proposed conventional large structures of fixed wing aerial vehicles. All research papers have talked about the merits of combining the fixed wing and rotary wing concept. But in our paper, we have tried to develop a compact type hybrid fixed-wing design and also, we have tried to change the traditional design of fixed-wing to a more attractive wing with good aerodynamic stability. We have tried to use bird wing structures in fixed-wing type aerial vehicles. In our paper, we have discussed the design and analysis of a hybrid fixed-wing type small flying robot that would be utilized for indoor applications in the medical field. Considering the good stability of fixed-wing type flying robot and for vertical takeoff and landing multicopter arrangement can help as our main purpose is to build a flying robot for indoor application where vertical takeoff landing by motor and propeller can be the best option because of limited space.

### 3. Hybrid Fixed-Wing Type Flying Robot Design

A hybrid flying robot is a combination of fixed-wing type and rotary-wing design for autonomous takeoff and landing of flying robots. According to the US Department of Defense (DoD), small size UAVs have lengths varying from 50 cm to 1 m, and wingspans will vary from 1 m to 2 m. Maximum gross takeoff weight varies from 0 to 20 lbs. Taking the standard data into consideration, the fixed-wing type design was made which had a wingspan of 1.7 m, and the overall length of the flying robot was 70 cm and had a payload carrying capacity of 2 kg. The material for the fixed-wing structure will be carbon fiber. For vertical takeoff, two-propeller rotors were used which is a general bicopter arrangement. Depending on the payload capacity, we have chosen a motor with 2000 kV and 9 inch propeller length for rotor propeller arrangement. The limitations of bicopter and fixed-wing type flying robots can be eliminated by developing hybrid fixed-wing flying robots where the advantage of both bicopter and fixed-wing type flying robots is considered. The disadvantage of fixed-wing flying robots that are runway is required for taking off which is not possible in the indoor environment and in the case of rotary-wing type, it follows VTOL but its stability is less; so, when we combine both fixed-wing and rotary-wing, we come up with VTOL system with better stability.

#### 3.1. Wing Structure

The wing design is one of the vital parts of a flying robot that determines the flight capability of the aerial vehicle. The wing mechanism design of the flying robot to create thrust and weight was identified as the primary concern [19]. The wing structures used in flying robots are rotary-wing, fixed-wing, and flapping wing structures. Rotary-wing structures get the ability to fly by balancing the force generated by the rotor attached to them. The major challenge in rotating wing design is energy consumption, but they are the most widely used type of flying robot in form of quadcopters, bicopters, hexacopters, etc. [20]. Fixed-wing flying robots generate lifting force, and the propeller is rotated using a motor to produce thrust for flight. They have a high payload carrying capacity and have longer flight hours [21] as well as their design is stable as compared to other wing structures. The flapping wing mechanism is a bioinspired model used for UAVs and flying robots. The complexity of flapping wings [22] is more as compared to fixed-wing flying robots. The fundamental concept is to convert rotary motion generated by motors to flapping motion. Here, we have tried to combine both fixed-wing and rotary-wing concepts to have a stable flying robot system with vertical takeoff and landing.

#### 3.2. Bicopters

Bicopters are rotary-wing type designs for flying robots. It comprises two motor and propeller arrangements to create thrust for generating lift for aerial vehicles. Bicopters are controlled by generating thrust through tilting of propeller arrangement in a calculated manner [23]. An American Bi-copter V-22 Osprey is an aerial vehicle with a tilt-rotor system for taking off in an upward direction. The
aircraft was tested and found with good stability as they use cyclic pitch control [24] for flight dynamics as general bicopters are less in use because of stability issues. As cyclic pitch control mechanisms are complex and for small flying robots, it would increase the overall cost. Keeping this context in view, we have tried to design a hybrid flying robot without increasing the complexity of the model.

3.3. Stability and Control of a Bicopter. Bicopter design consists of the main body with propellers at the end. Propellers here rotate in the opposite direction so that they can create a couple that can counteract each other and, hence, eliminates net yaw in either direction. Yaw for bicopter is controlled through the controller with different speeds. To generate the total yawing force speed of one propeller, it has to change relative to the other propeller. Roll in the flying robot is achieved by differential thrust control, which varies the thrust of one motor concerning the other. The stability issues in the bicopter are due to yaw accompanied by a roll, which shows that it cannot pitch up and down. To solve these issues, tilt rotors are used which will help to raise or decrease the gradient depending on the direction in which the motor is tilted [25, 26].

Here in this paper, we have used a tilt-rotor propeller and fixed-wing design to achieve stability of the flying robot as well as we can achieve vertical takeoff and landing. The kinematic and dynamic model for the fixed-wing flying robot is discussed below along with its CAD model and analysis results.

4. Modeling of Hybrid Fixed-Wing Flying Robot

In this section, we have discussed the kinematic and dynamic model for hybrid fixed-wing flying robots developed. Further in this section, we have discussed the conceptual drawing developed for the hybrid fixed-wing flying robot using CAD software and a mathematical model for checking the stability of our model. While designing the flying robot, we have taken into consideration its frame or body design and wing structure design. The body has to be taken in such a way that it should be able to support the wing structure and should have the payload carrying capacity. In the design of wing structure, we have taken standard aerofoil structure design but the overall aesthetic of the wing was made similar to the wing of a bird which can give better aerodynamic stability to our structure. Selection of propeller will help in vertical takeoff and landing. Considering all these parameters, mathematical model for the flying robot was developed.

4.1. Kinematic Model for Fixed-Wing Flying Robot. The kinematics of a flying robot deal with its position, velocities, and forces acting on it. To describe the force and motion of a hybrid fixed-wing flying robot, a total of 12 variables are required [27]. Here, we have defined three displacement parameters which can have varying values with their velocity, angle, and angular velocity, respectively, as shown in Table 1 below.

A transformation matrix has been built which will have \( y, \theta, r, a, \) and \( \beta \) values that determine the angles used for a moving state UAV. \( y \) is the yaw angle, \( \theta \) is the pitch angle, \( r \) is the roll angle, \( a \) is the attack angle, and \( \beta \) is the sideslip angle. The transformation matrix between the main frame co-ordinate system and airflow coordinate system [28] is as follows.

\[
O_{fa}, X_{fa}, Y_{fa}, Z_{fa} = 
\begin{pmatrix}
\cos \beta \cos \alpha & \sin \beta & \cos \beta \sin \alpha \\
-\sin \beta \cos \alpha & \cos \beta & -\sin \beta \sin \alpha \\
-\sin \alpha & 0 & \cos \alpha
\end{pmatrix}
\begin{pmatrix}
P_f, X_f, Y_f, Z_f 
\end{pmatrix}.
\]

4.2. Dynamic Model for Fixed-Wing Flying Robot. In the dynamic model, 12 states of UAV physical parameters are decided. The 12 coordinates are determined with the help of the base system, i.e., \( O_{fa}, X_{fa}, Y_{fa}, \) and \( Z_{fa}, P_x, P_y, \) and \( P_z \) represent displacement and velocity conditions. \( y, \theta, \) and \( r \) represent the Euler angle which defines the angle position of the aerial vehicle, and \( s, t, \) and \( v \) represent the change of state. The calculation done here is based on Newton’s second law [29].

\[
F_e = \frac{d(mv)}{dt}, \quad (2)
\]

\[
T = \frac{dHm}{dt}, \quad (3)
\]

where \( F \) is the accumulation of external forces, \( m \) is the mass of UAV, \( T \) is the accumulation of torques, and \( H_m \) is the angular momentum.

By expanding these two formulas according to the characteristics of the fixed-wing flying robot, the dynamic model can be obtained as follows [28, 29].

\[
\begin{pmatrix}
u_1 \\
u_2 \\
u_3
\end{pmatrix} = 
\begin{pmatrix}
-ta3 + vu2 \\
-vu1 + su3 + \frac{1}{m} F_x \\
-su2 + tu1
\end{pmatrix}, \quad (4)
\]

where \( F_x, F_y, \) and \( F_z \) denote forces generated in flying robots in alignment with the base system. When the flying robot has a motion concerning the airflow, then the
where \( C_1 \) (\( \alpha \)), \( C_2 \) (\( \beta \)), and \( C_4 \) (\( \alpha \)) are coefficients of lift, drag, and moment, respectively. As per plane of symmetry analysis in lateral direction, impact of aerodynamics is connected with rudder (E2), aileron steering gear (E3), the angular velocity of yaw (\( \gamma \)), the angular velocity of roll (\( \alpha \)), and angle of sideslip (\( \beta \))[28, 29].

\[
l_u = \frac{1}{2} \rho V^2 A C_1(\alpha, t, E_1),
\]

\[
d_x = \frac{1}{2} \rho V^2 A C_2(\alpha, t, E_1),
\]

\[
w_1 = \frac{1}{2} \rho V^2 A C_3(\alpha, t, E_1),
\]

where \( \rho \) is the mean aerodynamic chord length, \( \rho \) is the density of air, \( A \) is the flying robot wing area, \( C_1 \) is the coefficient of lift, \( C_2 \) is the coefficient of drag, \( C_3 \) is the coefficient of the moment, and \( E_1 \) represents a signal for the elevator. For fixed-wing flying robots, angle of attack for the aerial vehicle is generally very small due to which linear relations can be taken for aerodynamic parameters.

### 5. CAD Model Developed for Hybrid Fixed-Wing Flying Robot

The conceptual drawing for hybrid fixed-wing flying robots was developed using CAD software, i.e., CREO software, by taking reference from standard small flying robots already in commercial use and also given in various research papers. The model comprises the main body, fixed-wing structure, and two tri-rotor propellers with the motor attached to the body structure. Figure 1 shows the conceptual model of a hybrid fixed-wing flying robot developed in CAD software. Table 2 below shows the geometric quantities for the conceptual design of hybrid fixed-wing flying robots.
which are taken as reference from standard approved designs of flying robots. Considering our requirements, dimensions are modified [32].

6. Mathematical Model for Checking the Stability of Fixed-Wing Flying Robot

Here are the following features of the fixed-wing flying robot:
- Wing span: 1.7 m
- Chord length: 0.33 m
- Width of wing: 0.245 m
- Width of the fuselage: 0.35 m

The area of the wing is calculated as:

\[ \text{Area of wing} = \text{span} \times \text{width} = 1.7 \times 0.245 = 0.4165 \text{ m}^2 \]

The aspect ratio is defined as the square of span and area of the wing:

\[ \text{Aspect ratio} = \left( \frac{1.7}{0.4165} \right) = 4.09 \]

The taper ratio is defined as the tip chord/root chord ratio:

\[ \text{Taper ratio} = \mu = \text{tip chord/root chord} = 1 \]

The mean aerodynamic chord is defined as the average length of the chord:

\[ \text{Average aerodynamic chord} = c = \frac{2}{3} X c r \left( \mu^2 + \mu + 1 \right) = 0.245, \]

\[ (18) \]

\[ X_{ac} = c/4 = 0.245/4 = 0.06125. \]

\[ X_{cg} = 0.125, X_{cg} > X_{ac}, \text{wing is stable.} \]  \[ (19) \]

The wing is stable if the centroid of the flying robot (Xcg) is greater than the mean aerodynamic chord centroid (Xac).

7. Simulation Result

The conceptual drawing developed in this project needs to be validated through the structural and modal analysis, which is conducted using ANSYS software. Structural analysis will check the structural stability of the model, and modal analysis will check the change in mode shape because of its natural frequency generated due to the own weight of the model, as well as the computational fluid dynamic analysis that was conducted to calculate the lift force and the airflow velocity and the vortex created near the model developed was studied.

7.1. Structural Analysis for Fixed-Wing Model. Structural analysis of hybrid fixed-wing flying robots was done in ANSYS software. A load of 2 kg is applied to the flying robot; then, it was found that deformation values were 3.0729 × 10^{-5} m which is very less, and the equivalent stress generated is 0.045 N/mm^2 which is also very less than the compared yield strength of carbon fiber that is 3500 N/mm^2. The equivalent stress also known as von Mises stress is considered the maximum safe stress beyond which the structure can fail according to failure theory [33]. As equivalent stress is less than the maximum yield strength of carbon fiber, we can consider our design to be safe.

From the results, it can be concluded that the design is safe as per structural analysis results. The figure below shows the total deformation and equivalent stress developed on a hybrid fixed-wing flying robot when a payload of 2 kg is applied to it. Figure 2 shows the total deformation generated in the flying robot by the application of a load of 2 kg, and Figure 3 shows the maximum equivalent stress developed in the flying robot using ANSYS software.

7.2. Vibration Analysis of Hybrid Fixed-Wing Flying Robot. Here we have performed free vibration analysis for the wing of the aerial vehicle using Euler's theory [34]. It was found that by mathematical calculation, we found the natural frequencies generated by the aerial vehicle and the result of which was compared with modal analysis results from ANSYS software. And the results found were matching from analysis results and mathematical calculations.

For free vibration analysis, Euler beam theory has been used in which a center offset due to shear force brings into play bending and torsional modes. For calculation, we have taken the condition that no pure torsion and bending modes exist. The equations given below are for free vibration analysis:

\[ \omega_n = (\beta_n L)^2 \sqrt{ \frac{EI}{mL^3} } \]

\[ (20) \]
\[(E\dot{Y}''')'' + \omega^2 m(x) Y(x) = 0, \quad (21)\]

\[I = \int_0^c \frac{1}{3} \left[ (Y_w - Y_1)^3 - (Y_l - Y_1')^3 \right] dx, \quad (25)\]

\[\beta^4 = \frac{\omega^2 m}{EI}, \quad (22)\]

\[T_1 = \max \{ Y_w - Y_1 \}, \quad (26)\]

\[A = \int_0^c (Y_w - Y_1) dx, \quad (23)\]

\[h = \max \left\{ \frac{|Y_w - Y_1|}{2} \right\}, \quad (27)\]

\[y' = \frac{1}{A} \int_0^c \frac{1}{2} (Y_w^2 - Y_1^2) dx, \quad (24)\]

\[K_A = \frac{1}{c^2 \tau} A \int_0^c (Y_w - Y_1) dx, \quad (28)\]
\[ K_I = \frac{1}{c^4 T^2 (r^2 + z^2)} \int_0^r \frac{1}{3} \left[ (y''' - y')^3 - (y'' - y')^3 \right] dx, \quad (29) \]

where \( \omega_n \) is the natural frequency, \( \beta_n \) is a natural angle, \( L \) is the length of wing span, \( E \) is Young’s modulus, \( m \) is the mass per unit length, \( I \) is the moment of inertia, \( A \) is the area, \( Z_u \) is the largest \( Z \) value of wing, \( Z_l \) is the smallest value of the wing, \( z' \) is the mean value of \( Z_u \) and \( Z_l \), \( K_A \) is the area coefficient, \( T_1 \) is the highest value for wing thickness, \( p \) is the largest wing camber value, and \( d \) is the wing chord length.

Frequently used airfoil value for \( K_A \) and \( K_I \) is given as \( K_I = 0.036 \) and \( K_A = 0.6 \) [34].

\[ A = K_A c t (\text{approx.}), \quad (30) \]

\[ I = K_I c t (r^2 + h^2), \quad (31) \]

\[ m = \rho X A \quad (32) \]

Natural frequencies of each mode shape = \( \omega_n f = (B_n L)^2 \sqrt{EI/mL^2} \) are as follows.

For the fixed-wing structure, modal analysis was performed in ANSYS, which determines the natural frequency of the fixed-wing type flying robot and the first four mode shapes. Modal analysis was performed using Block Lanczos solver, including prestress conditions.

Figure 4 shows the different frequency mode shapes generated from modal analysis in ANSYS software. It can be concluded from modal analysis results that the mode shape generated represented a very less deformation value; so, we can consider our design as stable as per modal
analysis for deformation under the natural frequency of the flying robot.

Figure 5 above shows the frequency distribution of mode shapes for hybrid fixed-wing flying robots using modal analysis in ANSYS. For six different mode shapes, the corresponding natural frequency value is mentioned in the above figure.

The table below shows the summary of results obtained from structural and vibrational analysis of hybrid fixed-wing flying robots using ANSYS software. The results were found to be within the safe limit.

7.3. CFD Analysis for Hybrid Fixed-Wing Flying Robot. The computational fluid dynamic analysis describes the airflow pattern, and it calculates the aerodynamic parameters like thrust force, lift and drag force, and lift, and drag coefficient. CFD analysis was done in the ANSYS FLUENT
module to find lift force, which was found to be 145 N approximately near to theoretical calculation. Figure 6 below shows the velocity contour and velocity vector distribution around the flying robot and the effect of air on the flying robot from the simulation carried out in ANSYS software.

Figure 7 shows velocity streamlines of airflow around the fixed-wing flying robots and the vortex generated near the tail portions when the flying robot will be in the air.

From the above results, it can be concluded that our conceptual design is stable and safe to withstand the load of 2 kg along with its weight, as well as the structure can resist vibration.

We have taken the different angles of attack and carried out a CFD analysis to check the coefficient of lift: the graph of which is shown in Figure 8. It shows the variation in coefficient of lift for the various angle of attack.

Further analysis was carried out to find the coefficient of lift and drag for our model. We have taken a 4 deg angle of attack and carried out 200 iterations to check the coefficient of lift and drag values. It was found that the coefficient of the lift was 0.501, and the coefficient of drag was 0.0703 as per the simulation results. Figure 8 shows the value of the coefficient of lift and coefficient of drag at different iterations.

Figure 9 shows the lift and drag coefficient generated after 200 iterations in the FLUENT environment, and the ratio of Cl/Cd was generated.

In this project, we have developed the conceptual design of hybrid fixed-wing flying robot, lift and thrust force were calculated, and results were validated with simulation results.

8. Result and Discussion

In this paper, we have tried to propose a hybrid fixed-wing flying robot design that combines the advantages of both fixed-wing and rotary-wing type aerial vehicles to build an efficient system. The results above show the structural stability of our proposed design by carrying out structural and modal analysis in ANSYS software results which are shown in Table 3. Aerodynamic analyses were carried out to check the velocity flow lines and the effect of airflow on the aerial vehicle. From the above results, it can be concluded that our design is safe as per the structural and aerodynamic analysis results. One of the major challenges for our design will be the cost-effectiveness and security and govt. regulation on the use of flying robots. Our paper can help researchers to further take up the topic of indoor application of flying robots which is currently less explored and further work can be done to come up with a more cost-effective system.
9. Conclusion

In this paper, we have presented our conceptual design of a hybrid fixed-wing type flying robot which we will use for the medical sector for indoor applications. A hybrid flying robot combines the advantage of both fixed-wing type aerial vehicles and rotary-wing aerial vehicles to come up with an efficient system. In our design, we have tried to modify the traditionally used fixed-wing design with bird wing structure but keep the fixed wing concept intact. Also, we have proposed a compact structure of a hybrid fixed-wing flying robot that can be used for indoor applications. During the literature review, it was found that less work has been done in the area of indoor application of aerial vehicles. This is the area that needs to be more explored; so, we have tried to take some steps by proposing a novel design of flying robots that can be used in indoor applications in the medical sector. The following area was explored, and the work is concluded with the following conclusion:

(i) We had developed the mathematical model, and then the conceptual design for the same was developed in CAD software

(ii) Further to validate our model, we had performed structural and vibrational analysis to check the stability of the model as well its load-bearing capability and modal analysis for the flying robot system

(iii) Also, CFD analysis was conducted to check the lift force generated by the model and the velocity streamline and vortex generated near the flying robot

(iv) It was found that the conceptual design of hybrid fixed-wing flying robot was stable and was able to withstand payload capacity as per the analysis results, and the lift force generated was sufficient for vertical takeoff as we have used two tilt-rotor propellers with the motor of 2000 kV capacity which can create sufficient thrust force to lift the flying robot structure

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the Dongseo University, “Dongseo Cluster Project” Research Fund of 2022 (DSU-20220006).

References


