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Design of Long Range UAVs using Computational Fluid Dynamics

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ABSTRACT

Unmanned aerial vehicles (UAVs) have been common in many different fields of use in recent years, and long-range UAVs have potential in a variety of application spaces from delivery to reconnaissance to emergency response. This study focuses on potential design of long-range UAVs and computational fluid dynamics (CFD) simulation of different wing designs. We used Autodesk CFD for simulation and 42 trials of different speeds (from 10 to 200 km/h for both fixed wing and swept wing design) were done. We conclude that swept wing design would have 9% more range compared to fixed wing under the same conditions. Thus adapting the design should help when designing new UAVs.

Introduction

Both civilian and government use of unmanned aerial vehicles (UAVs) are common in recent years. Different types of UAVs are being used in various scenarios. However, certain situations require UAVs to accomplish multiple different objectives. Problems may arise when UAVs designed for specific tasks are unavailable. The necessity of a multi-purpose UAV is crucial in many situations, such as reconnaissance, disaster response, communication relay, or cargo logistics. This study will focus on simulation of different type of wings and overall design of the UAV with the following goals:

1. Have a range of 200-400 kilometers with a maximum flight time of 4-6 hours.
2. Ensure that the length and width of the aircraft must not exceed 5 meters and the weight should be under 100 kilograms.
3. Be able to communicate with ground with cellular network or satellite, the operator should also be able to see the UAVs view from the control terminal.
4. Be able to take off and land with a relatively short runway.

These goals were selected as representative design criteria for a long-range UAV. Our goal is to demonstrate how simulation-based analysis can be used to meet these objectives.

Other features could be included in the UAV design, however we will not discuss these in this study. Such other considerations could include:

1. Achieve auto control while in the air and in poor signal conditions with the help of sensors and GPS.
2. Feature a modular design with a pod that could be changed based on the tasks and also be able to eject in an emergency.

Certain systems designed for autonomous UAVs have been achieved, including the automatic execution of a mission [1], autonomous recharge, refuel, or switching of batteries [2].

Studies of UAV-sized jet engines and their performance using different fuels was performed in [3]. Their results indicate that diesel fuel can be an appropriate power source for these engines.

Design Options

Our design goal is to produce a drone that requires long range and long endurance in the air. Therefore, a fixed wing design would closely suit the need. But there are also many different variants, such as vertical takeoff and landing (VTOL), tilt rotor, tilt wing, or tilt body.

A VTOL design would require little space for the UAV to take off and land. While VTOL aircrafts have the advantage of vertical landing, achieving this can be complex. Factors such as thrust vectoring, power of the engine, and balancing the fuselage need careful consideration. Overcoming these challenges could be more demanding compared to conventional aircrafts.

Both tilt rotor and tilt wing are part of the VTOL aircraft. They all have the benefits of short takeoff and landing (STOL) and VTOL. However, they may encounter reliability issues mentioned above along with the overall structure integrity (e.g. axis connecting either the rotor or the wing could be subject to snapping and breaking). Thus, a fixed wing design would be more reliable than the designs above.

Range

Fuel cell would be the best choice for reaching the desired range. Compared to high density lithium batteries, diesel fuel or gas, fuel cells have 60 times higher energy density but suffer from low fuel efficiency [4]. Given the size and mass of the UAV, fuel cells would still have better energy density than lithium batteries and could reach the desired range [5].

Communication

Cellular and Satellite communication can be used to facilitate this progress. Cellular modules are commonly available, with prices that could be as low as 20 dollars. It also has large bandwidth which allows better video transmission and lower latency [6]. Problems with cellular modules is that range and altitude could be severely limited when there is a limited number of cellular towers in a certain area. Satellite modules solve the problem of connectivity, where it could be available almost anywhere. However it is hard to find and the price is usually much higher than the cellular. The communication quality would also be severely limited as there is limited bandwidth and also comes with rather high latency and interference since there is a long distance between the satellite and the UAV.

Design Choices / Trade Study

In this study we consider two designs: a fixed wing and a swept wing. Both designs have a wingspan of 12 meters. The fixed wing design has a width of 1.5 meters. The swept wing has a 13.5-degree sweep and a tapered wing with the wing root measuring 1.5 meters and the wing tip measuring 0.81 meters. The total wing area for both wings is 350824 cm^2. The geometry of the designs are shown in Figure 1. These wings were chosen because 1) fixed wings are the most common wing type, and 2) swept wings are common on higher speed aircraft. The dimensions of the wings were based on the considerations that our aircraft would have a small footprint (determining the wing width and wingspan), and the shape of the sweep was based on ranges found for this wing type from open-source documentation of wing geometries.

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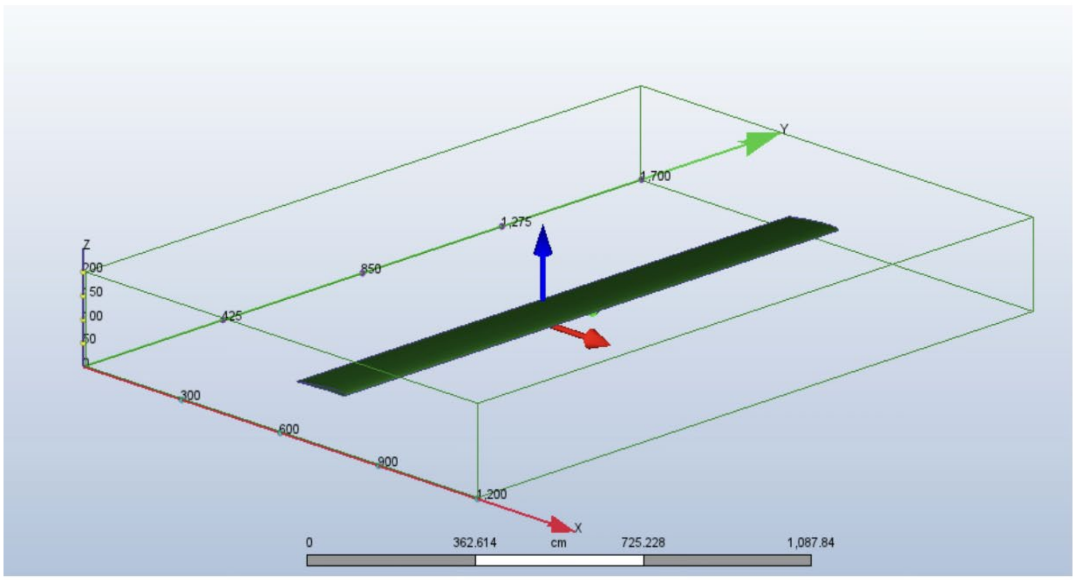
Method

To study both designs, Autodesk Fusion 360 is used to model the two different airfoils, and Autodesk CFD is used to simulate both airfoils operating at different velocities. Each simulation computed the steady flow around the given wing design. The simulations were run to convergence, with most calculations requiring 400-500 iterations to ensure the accuracy of the result. Given that our UAV is expected to perform at low altitudes, the computational fluid dynamics (CFD) calculations were performed with the incoming air at room temperature, and pressure/density of air evaluated at sea level.



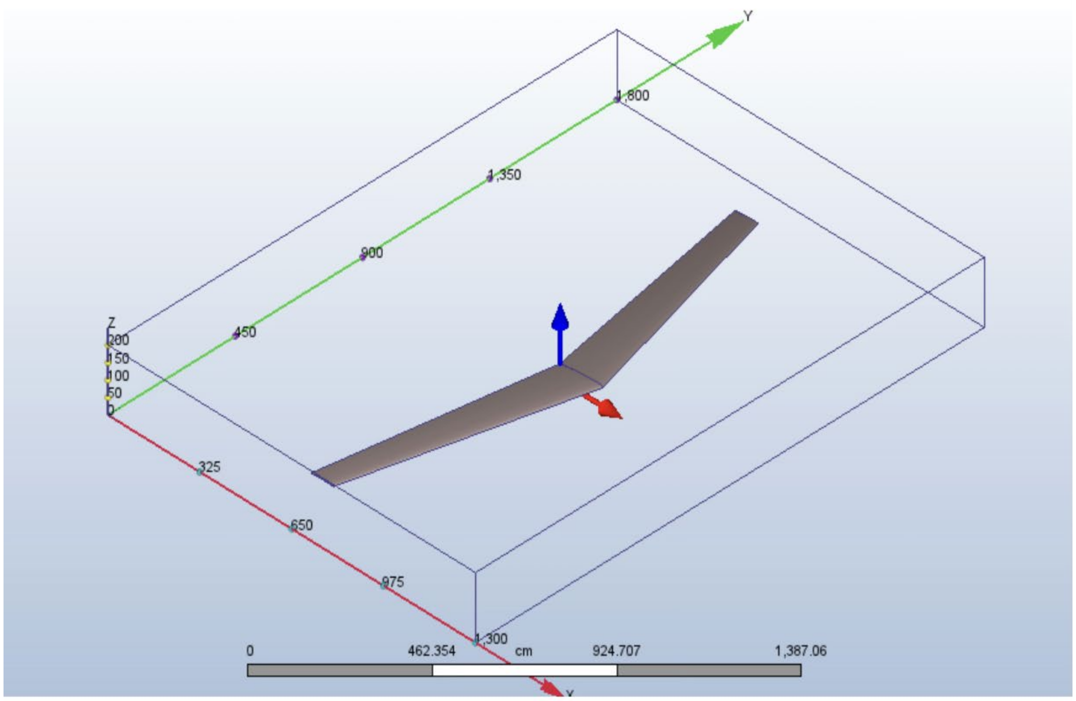


Figure 1. The Autodesk models of the two wing designs. The top panel shows the fixed wing, and the bottom panel shows the swept wing design. The direction of flight is indicated by the red arrow, and the lift direction by the blue arrow.

To find the ideal speed for the highest lift to drag ratio, simulations are conducted at airspeeds ranging from 10 km/h to 200 km/h, with increments of 10 km/h of airspeed for each airfoil. In total, there were 42 CFD simulations that needed to be performed to span this range (21 for each of the two designs). The lift and drag coefficients are recorded at each air speed and are used to calculate the lift to drag ratio. The results are listed in Table 1 and plotted in Figure 2.

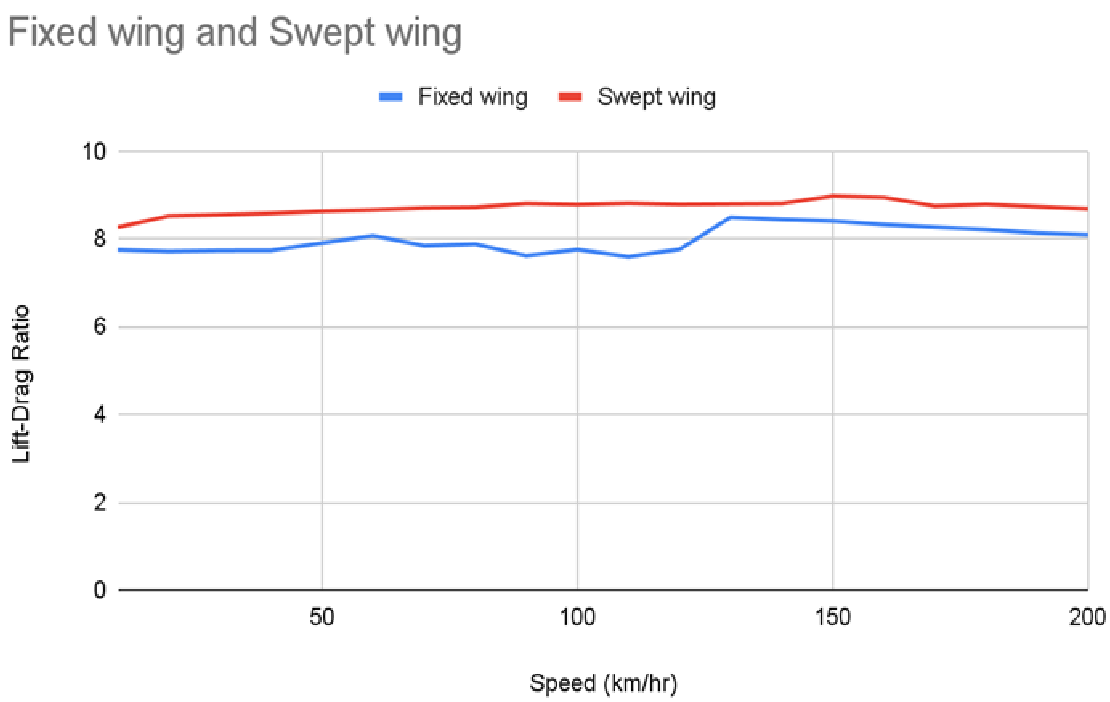
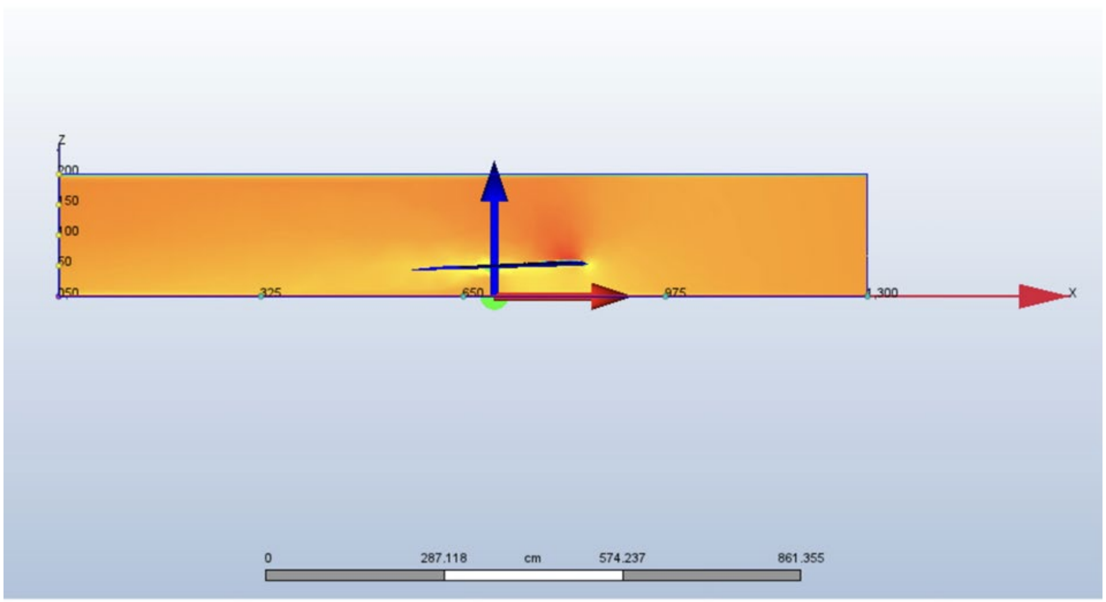


Figure 2. Lift to drag ratio (dimensionless) for the two wing designs as a function of the airspeed. Throughout the range of speeds considered, the swept wing has a superior lift to drag ratio.

Table 1. Lift-Drag ratio for both designs as a function of speed

Speed (km/h)	Fixed wing L/D Ratio	Swept wing L/D Ratio
10	7.747	8.260
20	7.712	8.519
30	7.731	8.546
40	7.735	8.580
50	7.904	8.629
60	8.072	8.658
70	7.842	8.699
80	7.878	8.714
90	7.615	8.803

100	7.755	8.779
110	7.591	8.809
120	7.760	8.782
130	8.489	8.793
140	8.439	8.803
150	8.402	8.974
160	8.323	8.944
170	8.264	8.744
180	8.210	8.784
190	8.133	8.729
200	8.090	8.679



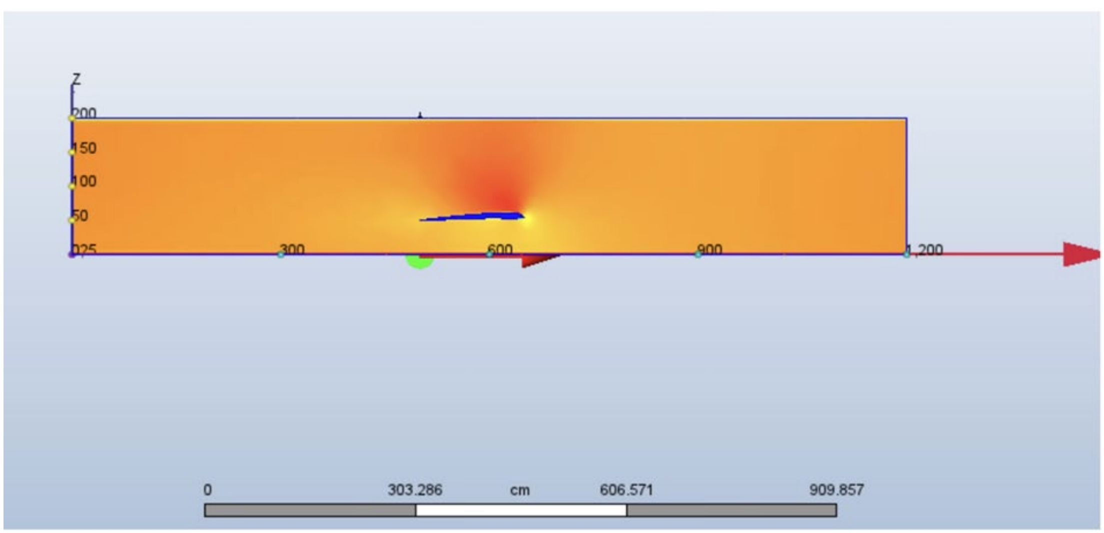


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Figure 3. The velocity magnitude for the 100 km/h airspeed case for the swept wing (top) and fixed wing (bottom). Results are shown at the wing midplane; the flow is moving from right to left in the figure. We observe a more concentrated area of high velocity magnitude in the swept wing design relative to the fixed wing.

The fixed wing design has a noticeable lower lift to drag ratio compared to the swept wing design. While the swept wing design has an average lift to drag ratio of 8.71, the fixed wing design only has an average of 7.98. The optimal speed of the fixed wing design is about 130 km/h, and the swept wing design is about 150 km/h. Figure 3 compares the profile of the velocity magnitude for the two cases.

Results

Using the CFD data collected above, we can estimate the range of the UAV with either of the wing designs. Assuming that the drone has a mass of 60 kg and it is carrying a payload of 40kg, also given that diesel fuel has an energy density of 45.3 MJ per kilogram and small turbojet engines only have 15% efficiency. The weight of the fuel would be around 80 kilograms and the maximum speed for a four hour flight range would be around 170km/h and 180km/h respectively.

Using a similar calculation, we can determine the maximum distance that the UAV can travel on a single tank of fuel. The swept wing has over 9% larger maximum distance than the fixed wing, as shown in Figure 5. The formula is as follows:

Fuel density * Fuel mass / [L/D ratio * (Battery mass + Payload mass + Mass of the UAV) * velocity of the UAV * Time] = Range (Hr)

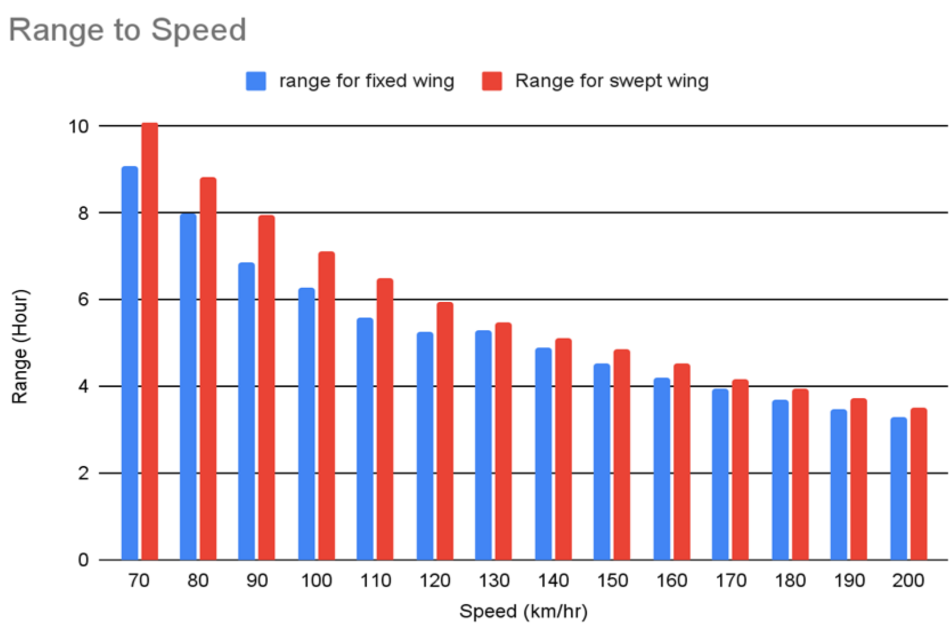

Figure 4. The range in time as a function of speed for the two different wing designs. For a swept wing, the target of a 4 hour flight time can be achieved at approximately 170 km/hr, while the fixed wing requires a speed closer to 160 km/hr.

Figure 5. The range in kilometers as a function of speed for the different wing designs. Given the small change in the lift to drag ratio over the different flight speeds, the distance that can be traveled is nearly constant. The average range is 648 km for the fixed wing and 707 km for the swept wing.

Conclusion and Future Work

Design options and simulations have been done on potential designs of a long range UAV. Based on the analysis the swept wing design has a longer range than fixed wing. However, the UAV must operate at a speed higher than 70 km/hr to function. Future study can be conducted with different variations on wing designs and fuel cells with higher energy density while being stable. Constructing the potential design may be possible in the future.

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