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Research paper

Smart variable pitch propeller system for unmanned aerial vehicles

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Abstract

This paper aims to develop a closed-loop control system for maximum efficiency of variable pitch propeller systems, which utilize mechanical mechanism to change the pitch of the rotor blades in a full size plane, while this system cannot use in a small size plane, specifically, for battery powered unmanned aerial vehicles (UAV's), the system seeks to maintain the optimal angle of attack of the propeller so as to maintain the maximum efficiency of the propeller throughout all stages of flight. The variable pitch propeller is controlled by a micro-controller and is governed by the relative airspeed of the propeller. When applied to UAV it results in an over-actuated control system. This article proposes an experimental model for a variable pitch propeller, in which thrust and power consumption are optimized. The proposed novel approach is analyzed and discussed, while the efficiency of the variable pitch propellers is being evaluated by extended simulation and experimental results.

Keywords: *Arduino Speed Controller; Control System; UAV Power Consumption; Unmanned Aerial Vehicles; Variable Pitch Propeller System.*

1. Introduction

UAV's are currently being utilized in many different sectors by governments, industries and individuals. The ability to launch, operate and retrieve UAV's safely, quickly and cheaply in comparison to manned systems is paramount to the growth of the industry. Electric powered UAV's are increasing in popularity due to advancements in batteries, however, they generally have shorter flight times and range when compared to larger systems with combustion engines. A standard fixed pitch propeller, which is common with battery-powered UAV's, will only achieve maximum propeller efficiency for a single relative forward velocity [1 - 4]. Variable pitch propeller systems however are able to maintain the optimal angle of attack for the propeller throughout a large range of relative forward velocities [5], [6]. By maintaining this optimal angle of attack the propellers are able to work with maximum efficiency throughout all stages of flight. This ability to operate with maximum efficiency throughout all stages of flight would benefit smaller battery powered UAV's, as it would allow for longer flight times and increase their operational range.

Although variable pitch propeller systems are common on larger manned aircraft they are often a type of variable pitch propeller that is referred to as constant speed propellers and are governed by hydraulic pressure that is dictated from the RPM of the combustion engine. Although these systems are effective they cannot be integrated into an electric powered UAV. This means that in order to adopt a variable pitch propeller system, which is designed to increase propeller efficiency on a small battery powered UAV; a new system must be developed [1], [2], [7].

Recently there has been research centered on passive variable pitch propellers for UAV's. These work to maintain the desired angle of attack using a balanced mechanical system, which relies upon counterweights and the aerodynamic lift of the propeller [8], [9]. Researchers have also experimented with variable pitch propellers attached to quadcopters. However, these have tended to focus on the agility and acrobatic performance of the quadcopters rather than the efficiency of the propeller [10], [11]. An active variable pitch propeller that is designed to maintain the optimal angle of attack for the maximum efficiency of the propeller would differ from the passive variable pitch propeller due to the involvement of a control system, which would include an actuator and microcontroller.

One of the main issues identified in the development of this system include the creation of a closed loop control system. In order to develop such a system, a firm understanding of the background theory was required. This included researching momentum theory, blade element theory, and vortex theory in order to develop sufficient mathematical models. Therefore, the aim of this paper is the development of a new closed-loop control system for active variable pitch propeller systems for UAV's.

2. Theory background

The analysis of propeller performance can be accomplished using one or more of the following theories: momentum theory, blade element theory, and vortex theory. In this article the analysis of propeller performance depended upon momentum theory.

The principle of momentum theory is that any aerodynamic propulsive device produces a thrust by imparting a change in momentum flux to a specified mass of air (Newton's second law). The basic momentum theory analyses the effects of this change in momentum, the work done on the air, and the energy imparted to the air. Unlike the blade element theory, it does not take into account the geometry of the blades. Instead the momentum theory assumes a large number of blades of infinite thinness, which is modelled as an infinitely thin disc. The momentum theory does not provide a means to predict propeller losses due to blade skin friction, rotational motion, or mutual blade interference, nor does it account for any geometry parameters other than disk area. Although it is simple to apply, this theory must be combined with some other analytical tool to be of use to the designer [1 - 4].

Unlike the momentum theory, blade element theory analyses the performance of the propeller. As a propeller is quite simply a rotating air foil, it is possible to divide the blade into a number of chordwise segments. Blade element theory simply states that by summing the contribution of all segments of all blades we can analyses the performance of the propeller [4].

If we refer to Fig. 1 we can see that as a propeller rotates with a constant RPM we have a vector equal to ωr. If there is airflow over the propeller we have the vector V, which then gives us the resultant velocity of the propeller Vr.

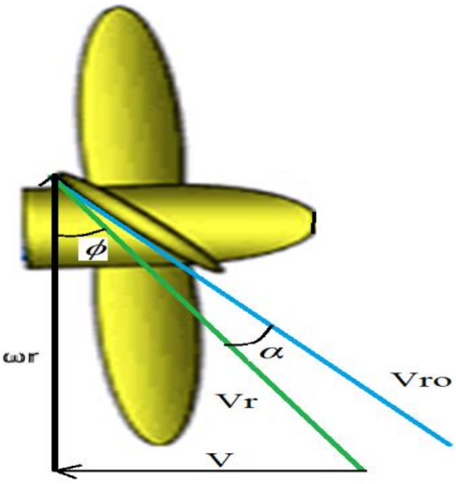

Fig. 1: Blade Element Theory Diagram.

Where:

ωr	Propeller velocity (m/s)
V	True airspeed (m/s)
V_r	Resultant velocity (m/s)
V_{ro}	Overall resultant velocity (m/s)
ϕ	Pitch angle (degrees) = Arctan (V/ ωr)
α	Angle of attack (degrees)

As the propeller imparts energy onto the air, it induces a velocity. As known, from both momentum and blade element theory that calculating the induced velocity is quite complicated, due to the fact that the requirement factors for these theories are different: in momentum theory the thrust from the propeller is required to calculate it, while in blade element theory the coefficient of lift of the propeller is required. Taking into account that by using the thrust from the propeller to calculate the induced velocity would induce a continuous loop in the system, we can conclude that this would be an impractical approach. The other option is using an equation for induced velocity from blade element theory. This requires the coefficient of lift for the propeller to be known. The effect of induced velocity for the small size and shape of the propeller can be ignored [1], [2].

The next factor that must be investigated is the angle of attack of the propeller. The maximum efficiency for a propeller usually occurs at a relatively small angle of attack; however, this is unique to each propeller and depends upon several factors such as the size and shape of the propeller. For this reason, it was decided to estimate the optimal angle of attack, □, at 4□ for the purpose of initial testing.

From Fig. 1, it is clear that by ignoring the induced velocity we can say that the optimal pitch angle is equal to,

$$\text{pitch}=\phi+\alpha \tag{1}$$

Another important concept is the advance ratio of a propeller. This is a non-dimensional parameter that allows propellers of different shapes and sizes to be compared with one another. The value of this parameter is instead reliant upon the relative airspeed of the propeller and is given by the equation.

$$J = V / nD \tag{2}$$

Where V (m/s) is the airspeed relative to the propeller, n (RPS) is the rotational speed of the propeller and D (m) is the diameter of the propeller. Even though momentum theory and blade element theory fundamentally differ, it is possible to use the principles established in both theorems in order to produce an understanding of propeller analysis.

The efficiency of the system can be calculated using an equation for propeller efficiency that was obtained from momentum theory, Eq. 3. This equation does not take into consideration any loses from the system.

$$\eta = \left(\frac{1}{2}+\sqrt{\frac{1}{4}+\frac{T}{2\rho A V^2}}\right)^{-1} \tag{3}$$

Where, T is the thrust produced (N), ρ is the density of the air (kg/m^3), A is the two-dimensional area of the propeller (m^2), and V is the true airspeed (m/s).

3. Experiment system

From Eq. 1 it is possible to see that as the true airspeed changes so does the optimal pitch angle. By setting the propeller to a constant speed and measuring the true airspeed it is possible to determine the optimal pitch angle, along with calculating the advance ratio, J. By attaching the system to a thrust stand and measuring the resultant force it is possible to calculate Eq. 3.

The system should be able to perform the following tasks:

- Read and record the relative forward air speed;
- Read and record the thrust force produced from the propeller;
- Calculate the optimal pitch angle (as shown in Eq. 1);
- Adjust the pitch angle to maintain the optimal angle of attack.

To realize these tasks, the suggested system consists of:

i) A brushless motor connected to a variable pitch propeller assembly (Fig. 2);
ii) A thrust measurement stands to measure the thrust force T. This was achieved by modifying a Turnigy™ thrust stand to interface with an Arduino Mega™;
iii) A linear actuator to control the variable pitch propeller;
iv) An airspeed sensor to measure true airspeed;
v) Perpendicular to the propeller. The brushless motor itself was powered from a lithium polymer (LiPo) battery. Arduino Mega™ microcontrollers were used to control the system.

The whole system is shown in Fig.2.

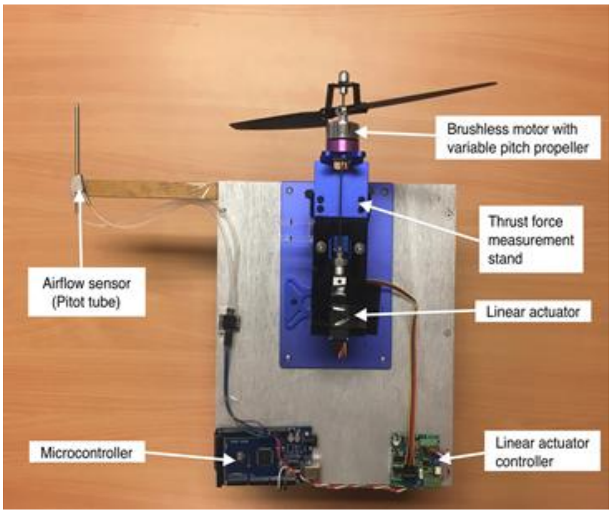

Fig. 2: Variable Pitch Propeller System.

Figs. 3 (a) and (b) show the motor and variable pitch propeller assembly. This system operates in such a way that an actuating rod, which had been inserted through the hollow shaft of the motor, is used to control the pitch of the propellers. This was achieved through the use of bearings, allowing the propellers to rotate freely about the rod, whilst a series of linkages that connect the rod to the propeller allow for a courser or finer pitch depending on whether the rod was extended or retracted, respectively. The extending and retracting of the rod was achieved by using of a micro linear actuator (Firgelli™ L12-P).

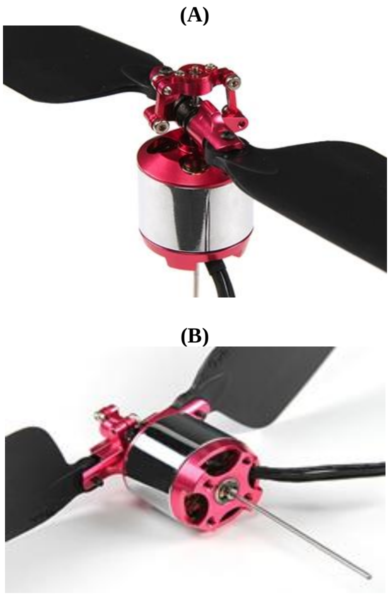

Fig. 3: The Linkages of the Variable Pitch Propellers with Motor Assembly.

The system reads signal from different sensors (airflow and thrust force sensors), performs calculations and controls the linear actuator accordingly. In order for the system to be as responsive as possible, two Arduino Mega microcontrollers were used. One was used to read the data necessary to calculate the efficiency, while the other controls the motor and linear actuator. This allows for the system to be theoretically split into two sub-systems, i.e. data recording and system control. The control system diagram and the feedback loop shown in Fig.4.

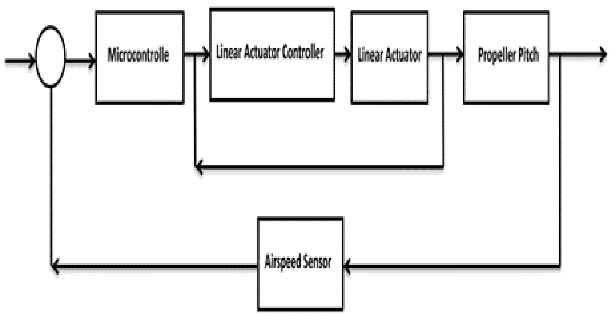

Fig. 4: Control System Diagram Showing the Feedback Loop.

The motor is controlled by the electronic speed controller, which receives a signal from the Arduino mega. By setting the motor so that it rotates with a constant speed, the only variable we have in our control system is the airspeed.

We assumed a constant motor speed from a constant signal due to the fact that as the propeller rotates the loading applied to the propeller is relative to the angle of attack. However, as the relative airspeed increases the microcontroller adjusts the propeller maintaining not only a constant angle of attack, but also a constant loading on the propeller which results in a constant speed.

The linear actuator had a stroke length of 10mm, while the actuating rod on the propeller assembly could only be adjusted by a total length of 6mm whilst maintaining effectiveness. In order to minimize risk to both the variable pitch propeller assembly and the linear actuator, the maximum allowable adjustment was set to 5mm. This was possible due to the fact that the linear actuator position is controlled by the duty cycle of a 1 kHz square wave. Where the percentage of that duty cycle sets the stroke to the same position. That is 100% duty cycle will result in full extension, and 0% duty cycle will result in full retraction. Therefore, by limiting the duty cycle to between 20-70%, the system has a maximum possible adjustment of 5mm.

With the operational limits of the linear actuator set, a relationship between the linear actuators position and the pitch angle could be determined. The pitch angle of the propeller was measured for is position of the linear actuator between its minimum and maximum displacement range with 1mm increment. Fig. 5 shows the relationship between the linear actuator position expressed via the duty cycle and the pitch angle.

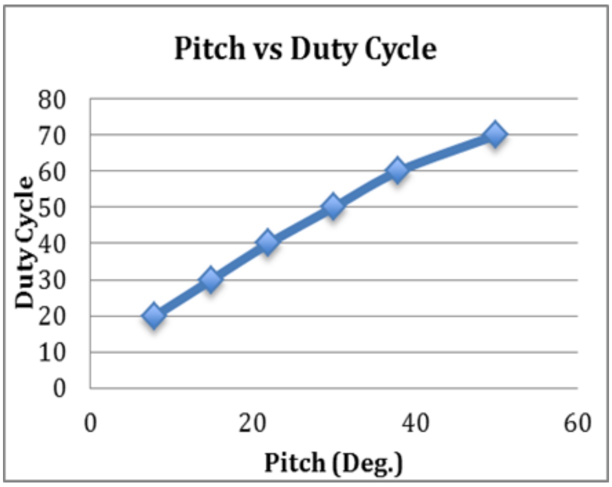

Fig. 5: The Relationship between the Linear Actuator Position and the Pitch Angle.

It is a third order polynomial with an R2 value of 0.999 and can be deemed an accurate representation of the data.

By using the MATLAB abilities, we can find the resulting equation of this relationship that became the governing equation of the system and can give us an idea about the system operation, Eq. (4).

$$duty = -(0.0002 \times pitch^3) + (0.008 \times pitch^2) + (1.3155 \times pitch) + 9.1059 \tag{4}$$

By testing the system experimentally in a variable airflow, it is possible to evaluate the performance of the system.

4. Results and discussion

The system was tested with a variable airflow by using wind tunnel. Fig. 6 shows the relationship between the advance ratio and the efficiency of the propeller with different airflow speeds.

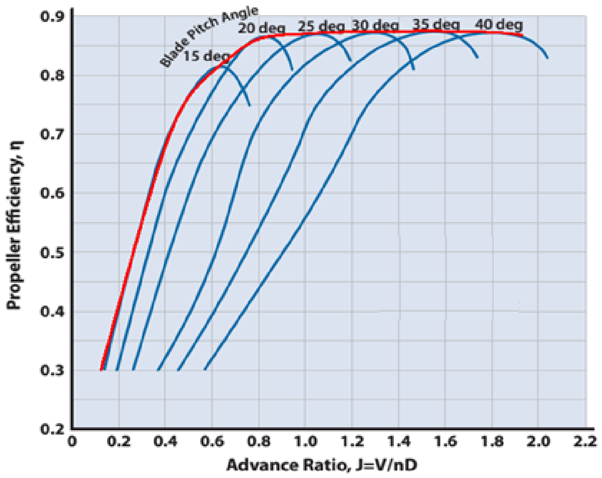

Fig. 6: The Relationship between the Advance Ratio and the Efficiency of the Propeller with Different Pitch Angle.

From comparing the graphs with typical efficiency of multiple fixed-pitch propellers as shown in Fig. 7, the efficiency of propeller with a fixed-pitch angle will increase as its forward velocity increases, that is until it reaches its maximum efficiency, after which it begins decreasing while in the suggested system the pitch is constantly adjusted, and it is possible to maintain maximum efficiency for a range of different forward velocities.

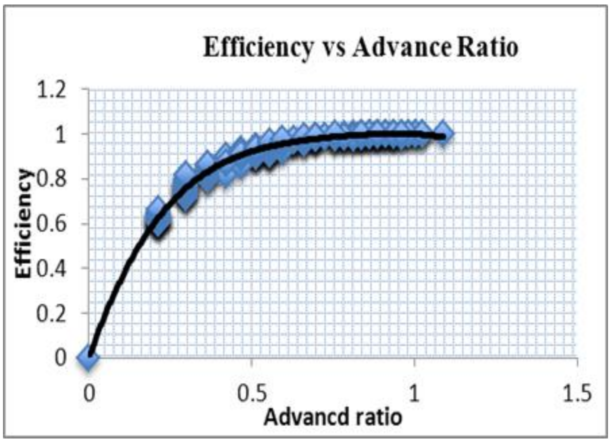

Fig. 7: Graphs of the Variable Pitch Propeller Efficiency from the Present Paper Results.

5. Conclusion

Although variable pitch propeller systems have been around since as early as the 1920's, a relatively small amount of researched has been done on implementing these systems into small-scale UAV's for maximising efficiency. The purpose of this system is to increase the maximum efficiency range of a propeller by continuously adjusting the pitch of the propeller with regards to the relative airspeed.

From the suggested system results, we can see that the system was adjusting the pitch of the propeller with regards to the relative airspeed. It is clear that the suggested system was able to maintain the optimal angle of attack, resulting in maximising the operational efficiency of the propeller. If this system were to be implemented into a UAV it is expected, from the results, that the flight time and therefore range, of the UAV would be increased.

However according to these graphs, the system achieved the maximum efficiency but there would be losses due to the drag from the propellers and kinetic and rotation kinetic energy imparted to the air, along with frictional forces from bearings within the motor assembly. The equation used to determine the efficiency is very idealistic and does not take into account any of these loses.

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