Development Flight Path Control for Unmanned Combat Aerial Vehicle (UCAV) Using Total Energy Control System (TECS)

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Abstract. UCAV (Unmanned Combat Aerial Vehicle) is a unmanned flying vehicle designed to carry out combat missions by carrying weapons. In the UCAV mission profile there is usually a cruise mission. In this cruise phase the vehicle must have a good control system and control altitude. In this paper, the UCAV altitude control system is designed to use the TECS (Total Energy Control System). TECS coordinates changes in speed and change in altitude by considering the total energy contained in the flying vehicle. The UCAV dynamic model that is used as the basis of the development is the fixed wing UCAV model which is equivalent to one of the UCAVs that are currently operating. As a comparison, a conventional control system (speed hold system and altitude hold system) was developed. The results showed that the altitude control system with TECS can adjust flight altitude and speed in a more coordinated manner, so that there is no change in the drastic and sudden variable values of flying when maneuvering. change in height begins.

1. Introduction
UCAV (Unmanned Combat Aerial Vehicle) is an unmanned flying vehicle designed to carry out combat missions or can be referred to as combat drones. The development of UCAV vehicles cannot be separated from the control design used to operate the vehicle in the air. One of the systems needed to operate the UCAV vehicle is a fly height control system used in the roaming flight phase. For the purpose of controlling this roaming phase, speed hold system can be used and the altitude hold system is operated together to maintain flight height and speed. This control design based on SISO (single input single output) still has some disadvantages in it, one of which is that there is no coordination between one system and another. Altitude hold system is used to adjust the height of the aircraft by giving the elevator deflection command, while the speed hold system is used to adjust the thrust needed by the aircraft to adjust the flight speed.

Both systems work without coordinating with each other, so that the response of the resulting plane to regulate elevators and thrust becomes out of sync. When one variable is controlled, the other variable will move away from the balance condition. For example, when a speed hold system is adjusting the speed with a fixed deflection of the elevator, crossing the vehicle will be affected. Likewise on the contrary, when the hold system's altitude is regulating the flight path with fixed thrust, there will be speed deviation.
One of the problem-solving strategies that has been used and tested is the Total Energy Control System (TECS). TECS is a control technique that uses the total mechanical energy of an aircraft to regulate flight altitude through the detection of total energy error and distribution energy errors. In the implementation of the regulation of flight height, changes in velocity are detected as changes in kinetic energy while changes in altitude (crossing flight) are detected as changes in the potential energy of the aircraft, as on Fig. 1. There is a coordination between changes in speed with changes in altitude that occur on the plane [1,2].

![Figure 1. UCAV flight profile](image)

Furthermore, a study and design of the Total Energy Control System will be conducted for the UCAV vehicle which has a mission profile as in Figure 1. The TECS model and analysis will be implemented to adjust the flight height on the cruise phase. The flight dynamics model as the basis of the control system design was built based on the motion equation of the vehicle in the roaming phase, where the aerodynamic parameters used were obtained using Digital DATCOM software [3]. Based on the flight dynamics model that has been built, further development of the fly height control system with TECS is developed. The resulting control system is then simulated and analyzed with MATLAB / Simulink software [4]. Analysis of the results obtained is complemented by a comparison between the TECS system and the fly height control system that uses a conventional approach, namely by using a combination of speed hold system and altitude hold system [5-7].

2. TECS
The concept of the Total Energy Control System (TECS) is built from the total formulation of the mechanical energy of an air vehicle by looking at the state of the vehicle represented in altitude, airspeed and flight path. If there is a change in the state of the vehicle, it will cause a total energy error and an energy distribution error. In this approach, to control the total energy error throttle is used while to control the energy distribution error between the flight path and airspeed an elevator is used.

The derivative of the TECS equation refers to reference [2,8], where the total energy of an air vehicle can be determined by adding up the potential energy and kinetic energy of the vehicle.

\[ E = E_{KE} + E_{PE} = E = \frac{1}{2}mV^2 + mg \]

With \(E_{KE}\) is kinetic energy and \(E_{PE}\) is potential energy. The equation has a constant variable in the form of mass, so that the equation can be simplified to:

\[ E = mg \left( \frac{1}{2} \frac{V^2}{g} + h \right) \]  

By using small-disturbance theory, relative to trim conditions, aircraft energy at steady flight conditions, can be expressed as:

\[ E_0 + \Delta E = mg \left( \frac{1}{2} \frac{(V_0 + \Delta V)^2}{g} + (h_0 + \Delta h) \right) \]
Assuming $\Delta V$ is small $\Delta V^2 \approx 0$, so that:

$$\frac{d}{dt}(E_0 + \Delta E) = m g \frac{d}{dt} \left( \frac{1}{2} \left( \frac{V_0^2}{g} + \frac{2V_0 \Delta V}{g} \right) + (h_0 + \Delta h) \right)$$

So that is obtained,

$$\Delta \dot{E} = m g \left( \frac{V_0 \Delta \dot{V}}{g} + \Delta \dot{h} \right)$$

By dividing the above equation with the trim speed $(V_0)$ obtained:

$$\frac{\Delta \dot{E}}{V_0} = m g \left( \frac{\Delta \dot{V}}{g} + \Delta \gamma \right)$$

With $\Delta \gamma \approx \frac{\Delta h}{V_0}$, is the flight path angle.

Thus, it can be seen that for a certain speed the change in energy from an air vehicle depends on changes in speed and changes in the angle of flight.

If the change in the total energy of the air vehicle depends on the engine thrust given, then using the cruise flight equation is obtained:

$$m \Delta \dot{V} = \Delta T - \Delta D - m g \sin \Delta \gamma$$

Assuming that $\Delta \gamma$ is small so $\sin \Delta \gamma \approx \Delta \gamma$, modifying equation 7 will obtain the following relationship:

$$\Delta T = m g \left( \frac{\Delta \dot{V}}{g} + \Delta \gamma \right) + \Delta D = \frac{\Delta \dot{E}}{V_0} + \Delta D = \frac{\Delta E_s}{V_0} \Delta D$$

Assuming that in the steady flight conditions change the drag is small, the relationship is obtained:

$$\Delta T \propto \left( \Delta \gamma + \frac{\Delta \dot{V}}{g} \right)$$

Then the relationship between the total specific energy rate $(\Delta E_s)$ is controlled by the throttle and the conditions of the flight vehicle are as follows:

$$\Delta T \propto \Delta \gamma + \frac{\Delta a_{long}}{g} = \Delta E_s$$

And for the specific energy rate distribution error $(\Delta \dot{L}_s)$ referring to reference [8,9], it is a potential energy minus kinetic energy. Where the elevator can be used as a transformation of potential energy into kinetic energy and vice versa. So that $\Delta \dot{L}_s$ is stated as:

$$\Delta \dot{L}_s = -\Delta \gamma + \frac{\Delta a_{long}}{g}$$

Where $\Delta a_{long}$ is acceleration in the plane of symmetry of the vehicle or in the longitudinal dimension.
3. Aircraft Model

UCAV used has a fixed-wing configuration with Y-tail. And it is equipped with great power compared to similar aircraft, making it possible to carry more payloads and be able to cruise at higher speeds. The following UCAV specifications are used, based on references [10,11], refer to Table 1.

| Specification     | value | unit |
|-------------------|-------|------|
| Mass              | 4760  | kg   |
| Wing span         | 20    | m    |
| Wing area         | 17.7  | m²   |
| HTP area          | 6.05  | m²   |
| VTP area          | 1.45  | m²   |
| Engine max power  | 115   | hp   |
| Propeller diameter| 2.8   | m    |

4. TECS Model

TECS is used to control the vehicle in the longitudinal dimension, more precisely to control the altitude of the vehicle. In accordance with the equation stated in section II, the parameters used are the specific energy distribution rate ($\dot{L}_s$) and the total energy specific rate ($\dot{E}_s$). The following is the TECS block diagram used, as shown in Fig. 2.

The inner loop is an energy distribution error ($\dot{L}_s$) which is controlled using an elevator. Whereas the outer loop is the total energy error ($\dot{E}_s$) which is controlled by thrust, $\dot{L}_s$ and $\dot{E}_s$ are directed to zero. Seen in Figure 2, the TECS block design uses PI gain (manual tuning) for the energy distribution error circled in red. For total energy error, the Kh gain (yellow circle) is used to get the corresponding $\dot{h}$ and PI gain (blue circle).

5. Results and Discussions

5.1. Effect of H gain

In designing TECS it takes several gains to help the system achieve the expected conditions. One of these gains is the gain of Kh, following the effect of the Kh gain on the vehicle response, as shown in Table 2 and Fig. 3.
Table 2. Kh gain variation

| Gain  | Gain Variation |
|-------|----------------|
| Kh1   | 0.015          |
| Kh2   | 0.018          |
| Kh3   | 0.021          |
| Kh4   | 0.024          |

This gain greatly affects the rate of climb of the vehicle, it can be seen in Figure 3(a) that the greater the gain value of Kh, the speed of the vehicle to reach the intended height is faster. Kh1 has the smallest rate of climb while Kh4 has the largest rate of climb. But if the gain used is too large, overshoot will occur. The fast and slow vehicle response can be verified by the total energy error ($\dot{E}_s$) and energy distribution error ($\dot{L}_s$) responses that occur in each gain, see Figures 3(b) and 3(c).

The faster the vehicle goes to the height that is ordered, ($\dot{L}_s$) and ($\dot{E}_s$) are also getting bigger. Because rides require greater energy and also greater energy distribution.

5.2. Effect of P Gain

The following will discuss the effect of changes in P (proportional) gain on the energy distribution error with P gain variation used in Table 3 and Fig. 4.
Table 3. P (Proportional) gain variation

| Gain | Proportional | Integral |
|------|--------------|----------|
| kL1  | -0.005       | 0.0036   |
| kL2  | 0            | 0.0036   |
| kL3  | 0.01         | 0.0036   |
| kL4  | 0.02         | 0.0036   |
| kL5  | 0.03         | 0.0036   |

Figure 4. The effect of P gain variation: (a) elevator input, (b) energy distribution error, (c) altitude response, (d) energy rate response, and (e) thrust response.
Figure 4(a), the P (proportional) gain directly affects the elevator input. At 10-30 seconds it appears that kL1 has a smaller elevator deflection command compared to kL5. So that kL1 has a lower rate of climb compared to kL5 as seen in Figure 4(c). Changes in the negative elevator deflection indicate the plane is moving pitch up, the negative the elevator is the faster the altitude changes. In Figure 4(b) it can be seen that the greater the gain P, the smoother the energy distribution of the system with the change in the deflection of the elevator which tends to be sloping and constant. This results in a smaller change in the energy error of the system so that smaller delta thrust is also needed, see in Figures 4(d) and 4(e).

5.3. Effect of I Gain
The following will discuss the effect of changes in gain I (integral) in the energy distribution error, as presented in Table 4 and Fig. 5.

Table 4. Integral (I) gain variation

| Gain | Proportional | Integral |
|------|--------------|----------|
| kL1  | 0.01         | 0.002    |
| kL2  | 0.01         | 0.003    |
| kL3  | 0.01         | 0.0036   |
| kL4  | 0.01         | 0.004    |
| kL5  | 0.01         | 0.005    |

In Figure 5(c) it can be seen that the greater the gain I, the system response will be smoother and the system will be faster to the equilibrium point. Changes in gain I almost have the same effect as the gain P. However, on gain I the changes that occur will affect vehicle trim conditions. Seen in Figure 5(c), the smaller the gain value I (kL1) in this state there is an increase in altitude which is quite dipping and there is a small increase in elevator deflection from the trim condition, see Figure 5(d). So, the response gain kL1 experiences a high climb rate and experiencing an overshoot which increases the total energy rate so that the thrust needed is also greater. Broadly speaking, the gain used to control the elevator through the energy distribution error (\(L_z\)) affects the total energy conversion given by thrust. The more negative the deflection of the elevator will increase the height and the speed will decrease, and vice versa.

5.4. TECS vs Conventional
To compare the TECS system with conventional systems, several conventional combinations of gain are performed to get a response similar to the TECS response [8]. A combination of gain k1, k2, k3, k4 and k5 is used. Then, a combination of k1 gain is chosen because when viewed from the response, the k1 gain has a rate of climb similar to TECS as seen in Figure 6. However, when the system is given an altitude command, there is a delay in the TECS while in the conventional system the command is immediately executed, Fig. 6(a). Based on the input thrust required in Figure 6(b) it is seen that conventional systems require additional thrust to be slightly lower when compared to TECS. However, the conventional system of thrust changes that occur immediately increases shortly after being given an order to change altitude, while in TECS this does not occur. In Figure 6(c), the change in elevator deflection in a conventional system is larger and immediately returns to the original trim condition, while in TECS the deflection of the elevator is smaller and will be constant in the new trim condition.

Figure 6(d), at the speed change, the TECS will increase and arrive at the new trim condition whereas in the conventional system there is a decrease in speed, but after the height is reached the speed hold system returns the speed to the trim condition.
Figure 5. The effect of I gain variation: (a) elevator input, (b) energy distribution error, (c) altitude response, (d) energy rate response, and (e) thrust response.
Figure 6. Comparison of conventional system vs TECS: (a) altitude hold, (b) delta thrust response, (c) elevator deflection, and (d) velocity response.
6. Conclusion
The development and analysis of height control with TECS can be obtained the TECS simulations on non-linear systems and linear systems have values that are not much different from the same gain range. TECS and conventional systems have advantages and disadvantages, in general the TECS system will have a new system trim condition. While the conventional system will go to a trim value. On the TECS form the response of the system to the height that is ordered depends on the gain of Kh. In the TECS the system energy distribution can be set using PI gain on the \( \dot{h} \) control. TECS provides a more gradual / smooth control variable response and flight variables, there is no large variable value spike at the beginning of the maneuver.

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