Abstract—the unmanned aircraft systems (UAS) are playing increasingly prominent roles in defense programs and strategies around the world. This paper presents a design of lateral autopilot of a Small Unmanned Aerial Vehicle (SUAV). The designed autopilot is applied to an Ultrastick-25e fixed wing UAV depending on lateral linear model and analytic linear model of a coordinated turn derivation with trimmed values of straight and leveling scenario. The lateral motion controller design is started with the design of most inner loop (roll rate feedback) of the lateral system, then roll tracker design with a Proportional Integral (PI)-controller. The guidance and control system is related with the design of heading direction controller with P-controller. Yaw damper is designed with washout filter to maintain a zero sideslip angle. The performance of two classic controller approaches for the design of autopilot are compared and evaluated for both linear and non-linear models. The results show a good performance in both disturbance rejection and robustness against sensors noise.

Keywords— autopilot, inner loop, outer loop, roll tracker, yaw damper, heading direction controller.

I. INTRODUCTION

UAV Automatic Flight Control System (AFCS) presents a very comprehensive treatment of UAV control and related technologies. The inherently unstable nature of typical open loop UAV configurations necessitates a rigorous approach to the analysis and design of UAV control technologies, as well as a thorough understanding of stability issues.

For any dynamic system, there may be requirements on certain frequency (to ensure the dynamics are “fast”) and damping (to ensure that the oscillations die out quickly) specifications on the pole locations, and minimizing steady tracking error to commanded input. The typical solution to satisfy these requirements is to use linear feedback control to modify the pole locations and loop gains [1].

The complete state of the UAV comprises its position, airspeed ($V_a$), attitudes (roll ($\phi$), pitch ($\theta$), yaw ($\psi$)), angle-of-attack ($\alpha$), sideslip angle ($\beta$), and rotation (roll ($\rho$), pitch ($\theta$), and yaw ($\psi$)) rates. Position, airspeed, and attitudes are also known as the navigation state [2]. The main purpose of this paper is to design a lateral motion controller for SUAVs to completely control lateral states ($v$, $p$, $r$, $\phi$, $\psi$) by the lateral input controls (Ailerons ($\delta_a$), Rudder ($\delta_r$)). In general terms, an autopilot is a system used to guide an aircraft without the assistance of a pilot. For manned aircraft, the autopilot can be as simple as a single axis wing-leveling autopilot: a full complete complicated autopilot as a full flight control system that controls position (altitude, latitude, longitude) and attitude (roll, pitch, yaw) during the various phases of flight (e.g., take-off, ascent, level flight, descent, landing, and loiter).

For SUAVs, the autopilot is in complete control of the aircraft during all phases of flight. From beginning, the design of autopilot is separated into two separate designs: longitudinal and lateral motion controllers [3]. These separate autopilots are designed after modeling of ultrastick-25e fixed wing UAV [4], the longitudinal dynamics (forward speed, pitching, and climbing/descending motions) and the lateral dynamics (rolling, and yawing motions). This simplifies the development of an accurate autopilot simply.

SUAV control and stabilization is more difficult than larger one. This is due to several factors, including the low mass of
the vehicle, lower Reynolds numbers, and light wing loading. These factors make it more difficult to design a flight control system [5].

In order to fly an aircraft, low-level inner loops must stabilize the airframe using available sensors and actuators, higher-level outer loops control will implement path following (guidance), while the inner loop keeps the aircraft flying (stabilization). Detailed design procedures of a flight control system to adequately stabilize and control SUAV are utilized by designing autopilot inner loops, and outer loops.

The two derived linearized models (state space and analytical linearized models) for Ultrastick-25e (thor) aircraft were used in the design of autopilot [4]. The behavior of the aircraft due to the desired scenarios results were compared between (the state space linearized model and the analytical linearized model) and (the nonlinear aircraft dynamics), the results is too matched between all of the three.

The outer-loop was designed to achieve the tracking command requirements in (ground track angle). The inner loops are designed to track roll attitude reference signals required for the outer loop. Several design goals were introduced against the inner loop performance that the closed loop rise time should be less than 1 second, and the overshoot has to be smaller than 5% in some cases. Root locus technique and PI-controller were tuned using the two linearized models of the aircraft [6].

If the controller causes overshoot and degrades the controller performance when coming out of saturation. In order to prevent this, an anti-windup scheme is implemented which checks if the actuator would saturate on the current time step and does not perform the integration if this case is happened [7]. Roll angle reference is constrained at 45°.

This paper is organized as follows; 1st section is the introduction, 2nd section investigate the design procedures of a lateral motion controller, 3rd section is the design of the inner loops of lateral motion controller, 4th section shows the inner loops design results, 5th section is the design of the heading direction controller, 6th section is the design of the yaw damper, 7th section shows the performance of the whole lateral motion controller in the scenario of rectangular motion command to the aircraft, and 8th is the last section which is the conclusion.

II. LATERAL MOTION CONTROLLER DESIGN PROCEDURES

The lateral motion controller uses the rudder and ailerons to keep the aircraft flying in a coordinated turn and following a commanded turn rate (including a zero turn rate for straight flight), it consists of inner loops and outer loop to manage the navigation of the aircraft in the lateral motion and zero side slip angle control, the dynamics affected the lateral motion begin with the body axis roll rate which is fed back to the ailerons to modify the damping of the roll mode.

Yaw rate feedback is designed to modify the damping of the dutch roll mode, but yaw rate feedback only is not sufficient due to coupling between yaw and roll which results a steady state yaw rate component during turns, a simple solution is use a washout filter on the output of the yaw rate sensor. The high pass filter action of the washout filter is to remove this steady state component. The output of the washout approximates a differentiated yaw rate which is suitable feedback for the dutch roll mode [8].

For large angle of attack another problem can be appeared which is that the roll pole coupled with the spiral pole to form a complex pair, the solution of this is to deal with the system as multi input multi output system due to the coupling between the inputs and the outputs at high angle of attack, or we can assume that the maximum angle of attack is 20 degrees. The last assumption is good and suitable for laminar conditions because great values of angle of attack can cause turbulent so the stolen condition will be happened to fail the flight of the aircraft [9].

After that the controller of roll attitude (bank angle hold controller) will be designed from the inner loop of roll rate by PI-controller.

The last controller is the outer loop and used for UAV guidance; the heading direction of aircraft with P-controller only which satisfies the designed purpose. The whole lateral motion controller block diagram as shown in Fig. 1.

![Fig. 1: Lateral motion controller block diagram.](image)

III. INNER LOOPS OF LATERAL MOTION CONTROLLER (ROLL ATTITUDE TRACKER) DESIGN.

Roll rate feedback is designed to increase the damping of roll rate and is the most inner loop of the roll attitude (bank angle) hold controller. The analytical open loop linearized transfer function of roll rate from aileron is used to design the roll damper then bank angle tracker. After that the main test results.

Roll rate \((p)\) from aileron transfer function can be approximately simplified to a reduced linear transfer function (roll mode) [4, 10] considered as eqn. (1).

\[
p(s) \approx \frac{-156.5}{(s+16.09)} \delta_u(s) \tag{1}
\]

The chosen pole will move from -16.09 to the left to be -24.8 with \(k_{d,p} = -0.055\), the gain value is chosen to smooth the response trajectory of roll tracker.

After that, the next inner loop is the roll angle \((\phi)\) tracker by integrating the roll rate transfer function to extract the roll attitude, and design the controller using PI-controller MATLAB structure as in Fig. 2.

The performance analysis of roll tracker with two controllers in linear and nonlinear models is showed in the next section. The UAV Laboratory Web site provides detailed information on the airframe, avionics, and software architecture [11]. The flight software is available as an open source software package available upon request, this open source package has a classic PID controller for autopilot, and
the proposed autopilot design modifies the performance of the classic one. Again the classic controller parameters for roll tracker \((k_{d_p} = -0.07, k_p \phi = -0.52, \text{ and } k_i \phi = -0.2)\) and the designed controller parameters \((k_{d_p} = -0.055, k_p \phi = -0.89, \text{ and } k_i \phi = -0.45)\).

![Fig. 2 MATLAB structure of bank angle hold controller.](image)

**IV. INNER LOOPS OF LATERAL MOTION CONTROLLER TEST RESULTS.**

The tests executed are the following tests:

- **Time domain analysis.**

  **TABLE I**
  
<table>
<thead>
<tr>
<th>The property</th>
<th>Classic con.</th>
<th>Designed con.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t_r) [sec]</td>
<td>0.4194</td>
<td>0.2568</td>
</tr>
<tr>
<td>(t_s) [sec]</td>
<td>3.1875</td>
<td>3.2009</td>
</tr>
<tr>
<td>Max.o.s%</td>
<td>16.2839</td>
<td>7.2120</td>
</tr>
<tr>
<td>Undershoot%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Peak</td>
<td>1.1628</td>
<td>1.0721</td>
</tr>
<tr>
<td>Peak time [sec]</td>
<td>1.1737</td>
<td>0.7733</td>
</tr>
</tbody>
</table>

  **Doublet signal response.**

  When the input (desired output) in the roll attitude is five degree doublet signal, the output responses with the two controllers are shown in Fig. 3 where the designed controller graph is better than the classic assuring that the time domain characteristics in Table I.

  - **The effects of sensors noise in the response.**

    The effect of the sensors noise with \(\sigma = 1.0*10^{-3}\) rad/sec in the response of the roll attitude as shown in Fig. 4.

  ![Fig. 4 The effect of noise in the roll tracker](image)

  **Doublet response comparison between the classical and designed controller for roll tracker**

  - **The effect of disturbance in the doublet response.**

    The ability of the disturbance rejection between two controllers is shown in Fig. 5 where the designed controller response to disturbance is high in the value, but it attenuated more speed than the classic controller.

  ![Fig. 3 +5 degree doublet signal in roll response.](image)
By the previous tests, the roll tracker of the designed controller assures that it has a good performance and good robustness and disturbance rejection; it’s closely matched with the desired requirements. The next controller is the direction heading controller, it’s considered as an outer loop of the roll tracker and related with the guidance and control navigation system of SUAV.

V. OUTER LOOP LATERAL MOTION CONTROLLER (HEADING HOLD CONTROLLER) DESIGN.

From equation (2) [10], the heading rate $\dot{\psi}$ is related with the pitch rate $q$ and yaw rate $r$ and pitch attitude $\theta$ and roll attitude $\phi$.

$$\dot{\psi} = q \sin \phi \sec \theta + r \cos \phi \sec \theta$$

During a coordinated turn, in the absence of wind or sideslip, we have that $va = vg$, and $\psi = \chi$.

$$\dot{\chi} = \frac{g}{V_a} \tan \phi = \frac{g}{V_a} \tan \phi$$

Equation (3) can be rewritten as:

$$\psi = \frac{g}{V_a} \phi + \frac{g}{V_a} (\tan \phi - \phi)$$

$$= \frac{g}{V_a} \phi + \frac{g}{V_a} d\psi$$

By expressing the equation in Laplace form

$$\psi = \frac{g}{V_a} s (\phi(s) + d\phi(s))$$

Equation (4) is the last expression that we can use it to control the heading from roll attitude; Fig. 7 illustrates the MATLAB structure block diagram of the lateral autopilot.

VI. LATERAL DIRECTION CONTROLLER TESTS RESULTS

After designing the heading controller, the following tests were executed to check its performance as shown in the following figures (8, 9, and 10); the comparison between the classic and designed controllers is matched so much, but the contribution here is the analytical linearized model and a controller with a new Simulink model and compares it with the Minnesota university test platform [11]. The first test is the time domain specs, then linear analysis, and the nonlinear
analysis with a scenario of rectangular motion.

- **Time domain analysis.**

<table>
<thead>
<tr>
<th>The property</th>
<th>Classic con.</th>
<th>Designed con.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_r$ [sec]</td>
<td>0.6308</td>
<td>0.5826</td>
</tr>
<tr>
<td>$t_s$ [sec]</td>
<td>3.2707</td>
<td>0.9220</td>
</tr>
<tr>
<td>Max. O.S. %</td>
<td>14.1546</td>
<td>1.3984</td>
</tr>
<tr>
<td>Undershoot%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Peak</td>
<td>1.1415</td>
<td>1.0140</td>
</tr>
<tr>
<td>Peak time [sec]</td>
<td>1.4129</td>
<td>1.2066</td>
</tr>
</tbody>
</table>

From Table II the designed controller is better than the classic one in the rise time and settling time, and maximum overshoot (this property is obvious in the step response test).

- **Doublet signal from standalone Simulink model.**

![Fig. 8 Doublet signal response of the heading hold controller.](image)

Fig. 8 Doublet signal response of the heading hold controller.

Fig. 8 illustrates the matching between two controllers if the input is a doublet response.

- **The effect of sensor noises.**

The noise test is executed under the noise at $\sigma = 1\times10^{-3}$ rad/s

![Fig. 9 The effect of noise in the heading hold controller.](image)

Fig. 9 The effect of noise in the heading hold controller.

- **The effect of disturbance (the ability to disturbance rejection).**

The disturbance signal is a signal with amplitude 5 degree and pulse width of 0.2 sec applied after steady state of the response at a time from 8 to 10 Seconds. From Fig. 10, the two controllers are good in the rejection of disturbance.

In the test platform linear simulation; the executed scenario is the rectangular motion, the command and response is shown in Fig. 11.

- **VII. YAW DAMPER DESIGN**

Yaw rate is fed back to the rudder to modify the dutch roll mode. The purpose of the stability augmentation of the yaw rate feedback is to use the rudder to generate a yawing moment that opposes any yaw rate that builds up from the dutch roll mode. The resulting feedback is a type 0 yaw rate with zero command input [13].

We will use a washout filter on the output of the yaw rate sensor to remove the steady state components of the yaw rate during turns.

Washout filter time constant is a compromise; too large value is undesirable since the yaw damper will then interfere with the entry into turns [1]. Too small value will reduce the achievable dutch roll damping. Time constant ($\tau$) was chosen to be 0.5 s.

The transfer function of yaw rate loop can be found by using a root locus technique [4] to get the gain value which damp the rate and make it suitable for maintaining yaw rate from rudder to be zero. Yaw damper is designed with washout filter as mentioned above. From the lateral state space linearized model [4], the linearized transfer function of yaw rate to rudder was called to be used.
The lateral model has two pair complex poles (-1.84 ± 5.28i) with a lightly damping ratio (0.329) and natural frequency (5.59 rad/sec). The purpose of the damper is to increase this damping ratio.

The controlled system was designed by assigning the gain \( k_d = 0.065 \) and the washout filter with transfer function:

\[
H(s) = \frac{r_s}{r_s + 1}
\]

Time constant \( \tau = 0.5 \) s

VIII. CHECK THE PERFORMANCE OF THE LATERAL MOTION CONTROLLER FOR SUAV.

The following test; the rectangular motion response in Software In Loop (SIL) which is applied in the non-linear model of aircraft, Fig.12 illustrates the response of heading angle due to rectangular motion command, Fig. 13 shows the relation between the latitude and longitude, and Fig.14 show the roll change (inner loop command) which make the rectangular motion.

![Fig. 12 Heading command rectangular motion response.](image)

![Fig. 13 The shape of the aircraft trajectory due to rectangular motion commands in the heading angle.](image)

![Fig. 14 The change in the bank angle due to rectangular motion in the aircraft.](image)

IX. CONCLUSION

In this paper, the design of autopilot is overviewed with the detailed design of lateral motion controller. Most inner loop was designed with feedback gain, and then roll attitude hold controller was designed with PI-controller far away from complexity with good performance in the time domain characteristics. The design procedures began with roll rate feedback, the roll attitude controller, Linearization of the nonlinear equation of motion of heading rate is derived to get a linear relation between heading angle and roll attitude. The outer loop controller is a simple P-controller. Yaw damper was designed with washout filter. At last a rectangular motion command is applied in the non-linear model to check the behavior of the aircraft. The environment disturbances and sensors noise are modeled and the performance of the system is checked in the existence of them. Longitudinal motion controller is in the development stage to design the whole autonomous SUAV with a robust autopilot.

X. REFERENCES