Aircraft Waypoint Navigation Control with Neural Network-Based Altitude-Hold Control

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Abstract

Flight control design for the autonomous waypoint navigation of aircraft is presented in this study. The waypoints are defined in terms of desired longitude and latitude. The control design is conducted in longitudinal and lateral directions, respectively. The lateral control is based upon coordinated turn strategy for which no sideslip is allowed under the turning maneuver. The longitudinal control is mainly focused on altitude hold during navigation. Neural network control approach is applied to the altitude-hold mode control. Simulation of the proposed control strategy has been performed under various conditions. A graphical simulation tool was developed to visually demonstrate the control technique developed in this study.

A method to simulate the gas turbine transient behavior is developed. The basic principles of the method

Key Word : Aircraft waypoint navigation, coordinated turn, altitude-hold, neural network, graphical user interface software

Introduction

The waypoint navigation is a principal function in autonomous flight mode by which the aircraft fly over a prescribed trajectory[1,2]. Majority of modern aircraft are equipped with waypoint navigation capability. The CDU(Command and Display Unit) is primarily used to store pre-defined coordinates for the multiple way points[2]. Each waypoint is uploaded to determine the reference heading information with respect to the current location of the aircraft. Once the aircraft reach a desired waypoint then a new waypoint information replaces the old one. The aircraft then makes a turning maneuver toward the next desired waypoint. The current location information of the aircraft is usually provided by INS((Inertial Navigation System) or GPS(Global Positioning System)[3,4]. The recent trend is to employ INS as principal equipment while GPS is used as additional navigation aids.

As mentioned above, majority of waypoint navigation are executed autonomously. For

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autonomous navigation, the auto-pilot is an essential element. In general, aircraft auto-pilot commands the aircraft to follow desired external reference inputs. The reference command is usually constructed from navigation requirement. The auto-pilot in this study consists of two separate parts: one is longitudinal auto-pilot, the other one is lateral auto-pilot. The lateral auto-pilot is designed for turning maneuver while the longitudinal auto-pilot is intended for altitude-hold mode. Also, some types of stability augmentation can be implemented to provide stability of motion.

In this paper, we propose flight control algorithms for multiple waypoints navigation. The waypoints are defined by longitude and latitude coordinates on the Earths surface. The waypoints coordinates are transformed into equivalent heading commands. The reference heading commands are used to build lateral auto-pilot commands

The navigation technique between two positions is to follow a great circle connecting the two points over the Earths surface. In addition to the lateral auto-pilot, the longitudinal auto-pilot is implemented primarily for altitude-hold purpose. A neural network-based altitude-hold control is also investigated. Computer simulation results are presented to verify the overall algorithms studied in this paper. The results of this study may be applied to the future autonomous navigation mission of Unmanned Aerial Vehicle(UAV) in conjunction with cost-effective positioning systems such as GPS and INS.

Waypoin Navigation

For aircraft navigation, it is necessary to understand the relationship between geometry and associated navigation requirement. First, we try to derive the reference attitude by using given information between two designated points. The geometry of the Earth with a great circle [2] connecting two points is given in Fig. 1.

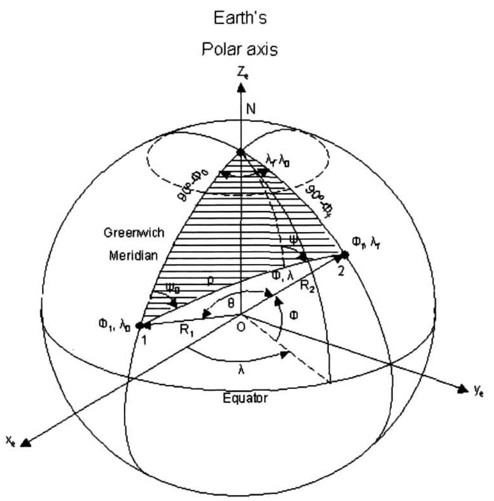


Fig. 1. Spherical triangle for great circle computations

The latitude and longitude of the present and desired points are denoted as ϕ_1, λ_1 and ϕ_2, λ_2, respectively. An attractive technique tracking two designated points on the Earths surface is so-called *Great Circle Steering(GCS)*. The GCS is known to be a minimum-time path, and leads to a unique path formed by the two points and the Earths center[2]. If the two points are connected through the great circle, then a spherical triangle is generated with respect to the north pole and the two points. Most of the derivations here are adopted from [2]. The average radius of the Earth is defined as

$$a = \frac{R_1 + R_2}{2} \tag{1}$$

Application of the law of cosines for spherical triangles yields

$$\cos(\rho/a) = \cos(\pi/2 - \phi_1)\cos(\pi/2 - \phi_2) + \sin(\pi/2 - \phi_1)\sin(\pi/2 - \phi_2)\cos(\lambda_1 - \lambda_2) \tag{2}$$

or

$$\cos(\rho/a) = \sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos(\lambda_1 - \lambda_2)$$

so that

$$\rho = a\cos^{-1}[\sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos(\lambda_1 - \lambda_2)] \tag{3}$$

The initial heading angle, in conjunction with the above relationships, is given by

$$\cos\psi_0 = \frac{\sin\phi_2 - \sin\phi_1 \cos(\rho/a)}{\cos\phi_1 \sin(\rho/a)} \tag{4}$$

The above equation can be rearranged into

$$\psi_0 = \cos^{-1}\frac{N}{D} \tag{5}$$

where each parameter is given as

$$N = \sin\phi_2 - \sin\phi_1 \sin\phi_2 \sin\phi_1 + \cos\phi_2 \cos\phi_1 \cos(\lambda_2 - \lambda_1)$$
$$D = \cos\phi_1 \sqrt{1 - [\sin\phi_2 \sin\phi_1 + \cos\phi_2 \cos\phi_1 \cos(\lambda_2 - \lambda_1)]^2}$$

The cross-range is defined as the line between two points, which is normal to the great circle. Also, the down-range represents a distance from the current position to the point where the line crosses the cross-range. Figure 2 shows the cross-range and down-range with respect to the two points.

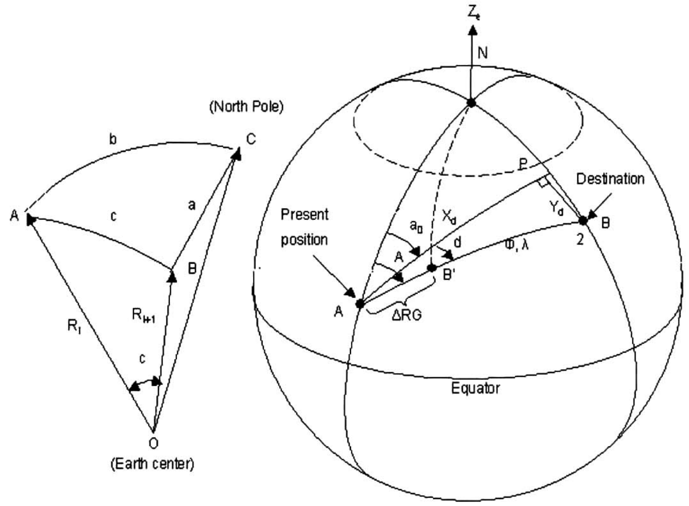


Fig. 2. Geometry for calculating the down-range and cross-range

The cross and down-ranges are used to determine the how accurately the reference trajectory is followed. Mathematically, they are given by[2]

$$X_d = R_{avg}\cos^{-1}\left[\frac{\cos(RG/R_{avg})}{\cos\{\sin^{-1}[\sin(RG/R_{avg})\sin d]\}}\right] \tag{6}$$

$$Y_d = R_{avg}\sin^{-1}[\sin(G/R_{avg})\sin d] \tag{7}$$

where $d = A - a_0$, R_{avg} is the average radius of the Earth, and RG represents the distance between two points.

On the other hand, the time required to travel along a great circle from waypoint 1(or from j) to waypoint 2(or to point $j+1$) is computed as follows[2]

$$\Delta t_j = (a/V_j)\cos^{-1}[\sin\phi_{j+1}\sin\phi_j + \cos\phi_j\cos\phi_{j+1}\cos(\lambda_j - \lambda_{j+1})] \tag{8}$$

where

$$V_j = \sqrt{V_x^2 + V_y^2}$$

and V_x, V_y are velocity components on the great circle for the two points.

The heading angle defined by Eq. (5) is a reference heading for the aircraft to follow in order to arrive at the desired position. For the great circle navigation, the reference angle changes at every instant with the position change. Thus for a given location, the reference heading needs to be updated continuously. The updated reference heading angle is usually provided by a navigation computer. The navigation computer accepts position information from INS and/or GPS, and calculates the new reference heading based-upon the present location information. For navigation simulation, therefore, the reference heading will be updated since both numerator and denominator in Eq. (5) change as the aircraft continues its flight.

Autopilot Design

For the great circle navigation, the aircraft heading should be controlled in response to the commanded heading angle. One of the principal functions of lateral auto-pilot is to maintain the aircraft heading at a constant value. There are two approaches in changing the aircraft heading angle. The first one is to directly change the heading angle using rudder so that the heading is varied without roll angle changed. This involves directional control system based upon aircraft yaw information. The other one is to create bank angle change in such a way that there is no sideslip during the turn. Turning maneuver using bank angle without sideslip is usually called coordinated-turn, which is frequently employed in majority of aircraft heading change. In this study, we elect to choose the coordinated-turn strategy for heading change in response to the reference command. A linearized system is adopted for base line analysis.

First, the linearized lateral-directional dynamics of the aircraft are given by

$$\dot{\boldsymbol{x}} = A\,\boldsymbol{x} + Bu \tag{9}$$

where

$$A = \begin{bmatrix} Y_v & 0 & -1 & \frac{g}{U_0}\cos\gamma_0 & \\ L'_\beta & L'_p & L'_r & 0 & \\ & N'_\beta & N'_p & N'_r & 0 \\ 0 & 1 & \tan\gamma_0 & 0 & \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ L'_{\delta_A} \\ N'_{\delta_A} \\ 0 \end{bmatrix}, \quad \boldsymbol{x} = \begin{bmatrix} \beta \\ p \\ r \\ \phi \end{bmatrix}$$

where U_0 is the nominal speed of aircraft, β is the sideslip angle, p is body roll rate, r is yaw rate, and ϕ is bank angle. In addition, each stability parameter in the system dynamics is defined in Ref. [1]. Note that the control input(u) is aileron(δ_A) only, which will be used to produce the offset bank angle to change the heading angle.

The turning maneuver employed in this study is a coordinated-turn, for which side acceleration is set to zero during the turn. The kinematic relation during coordinated-turn is given by[1]

$$r = (g/U_0)\phi = \dot{\psi} \tag{10}$$

Equation (10) represents a constraint equation which should be satisfied for the coordinated-turn. Thus we make use of the feedback control strategy to asymptotically satisfy the constraint equation. Figure 3 shows the block diagram for lateral control including the constraint dynamics.

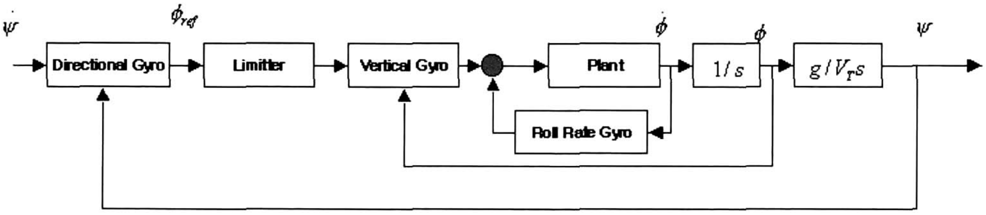


Fig. 3. Aircraft heading control system

It should be noted that the constraint dynamic is incorporated into the block diagram directly.

Now the auto-pilot design is focused on the longitudinal axis. One of the representative auto-pilot functions about the longitudinal axis is altitude-hold. The primary objective of the altitude-hold system is to maintain the aircraft altitude in the presence of unexpected external disturbances. The altitude-hold control loop usually consists of inner and outer loops. The inner loop contributes to augmenting damping of the pitching motion. The outer loop is intended to feedback the error signal between reference and actual altitudes. Some types of limiter could be added to prevent abrupt change of system response. Figure 4 shows the block diagram for a general altitude-hold system including inner damping loop.

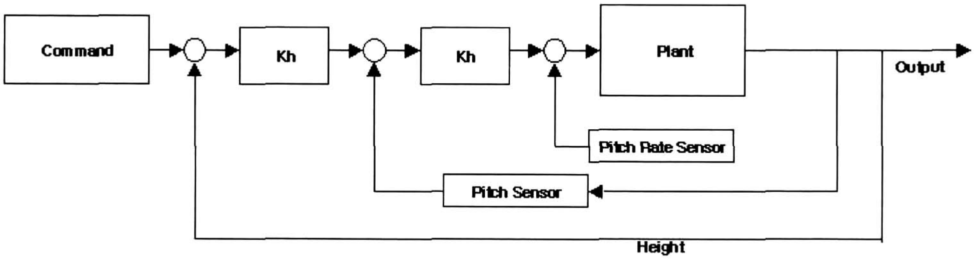


Fig. 4. Altitude-hold system block diagram

In this paper, we take a neural network to design the altitude-hold system. Neural network is known to be robust with respect to unmodelled dynamics. The altitude-hold control block diagram is provided in Fig. 5 by using a neural network.

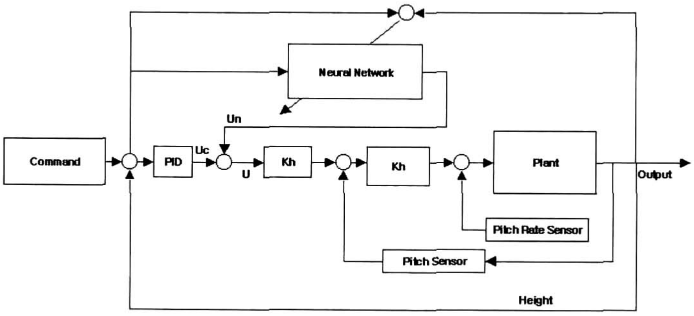


Fig. 5. Altitude-hold system using a neural network

The neural network to be used in this study consists of one hidden layer. The following cost function is introduced in order to update the weighting factors in the neural network.

$$E=\frac{1}{2}u_c^2 \tag{11}$$

Then it follows that

$$\frac{\partial E}{\partial w_{jk}}=\frac{\partial E}{\partial S_{jk}}\cdot\frac{\partial S_{jk}}{\partial w_{jk}}=\frac{\partial E}{\partial S_k}O_j \tag{12}$$

where O_j represents the output of hidden layer and δ_k is defined as

$$\delta_k=-\frac{\partial E}{\partial S_k}$$

In order to obtain δ_k, the following step is taken

$$\delta_k=-\frac{\partial E}{\partial S_k}=-\frac{\partial E}{\partial u_c}\frac{\partial u_c}{\partial S_k} \tag{13}$$

Now since

$$\frac{\partial E}{\partial u_c}=u_c,\quad u_c=u-u_N \tag{14}$$

it should follow

$$\frac{\partial u_c}{\partial S_k}=\frac{\partial(u-u_N)}{\partial S_k} \tag{15}$$

where u_N is the output from the output layer of the neural network. Next rearranging Eq. (13) in terms of O_k yields

$$\delta_k=-u_c\frac{\partial(u-u_N)}{\partial O_k}\frac{\partial O_k}{\partial S_k} \tag{16}$$

Let us assume the function of the neurons corresponding to the output layers in the form of a sigmoid function as

$$O_k=f(S_k)=\frac{1}{1+e^{-S_k}} \tag{17}$$

Therefore, finally we arrive at

$$\delta_k=u_c O_k(1-O_k) \tag{18}$$

The back propagation method in neural network now is applied to update the weighting parameters in such a way that

$$\begin{aligned} w_{jk} &=-\frac{\partial E}{\partial w_{jk}}+\alpha\Delta w_{jk} \\ &=\eta u_c f'(S_k)O_j+\alpha\Delta w_{jk} \end{aligned} \tag{19}$$

where η represents a weighting parameter.

Simulation

The auto-pilot algorithms discussed so far now are tested through simulation study. The moment of inertia of the model aircraft are given as

$$\begin{bmatrix} I_{xx} & 0 & I_{xz} \\ 0 & I_{yy} & 0 \\ I_{xz} & 0 & I_{zz} \end{bmatrix} = \begin{bmatrix} 2.6 & 0 & 0.34 \\ 0 & 4.25 & 0 \\ 0.34 & 0 & 6.37 \end{bmatrix} \times 10^7 (kg - m^2)$$

The stability derivatives of the aircraft model used in this study are available in Ref. [1] : a large four-engined, cargo jet aircraft.

For simulation, we assumed external side gust disturbance and noise in the sensor signal. The gust response as presented in Fig. 6 shows the behavior of a signal as filtered random noise. Furthermore, the sensor noise is plotted in Fig. 7, which is randomly distributed within the magnitude of 0.1 radians.

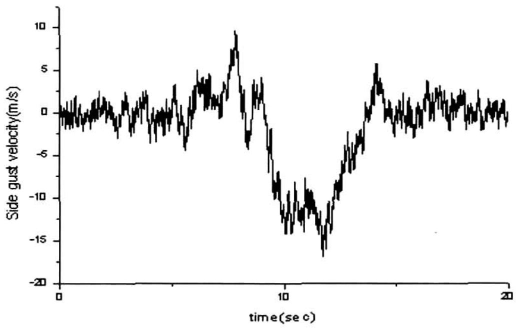


Fig. 6. External side gust response

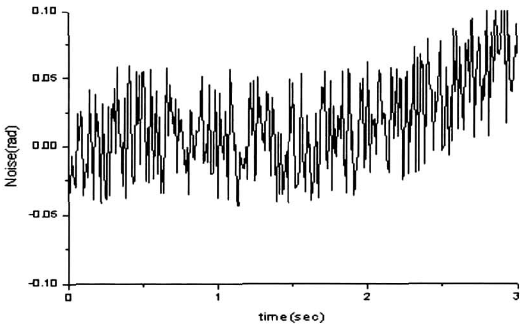
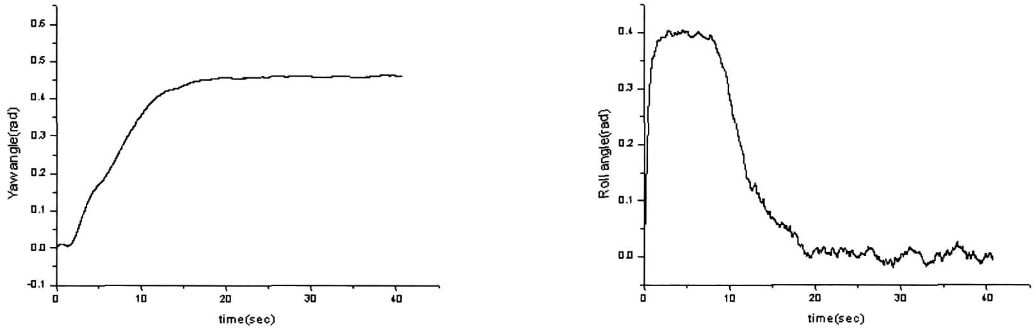


Fig. 7. Sensor noise effect

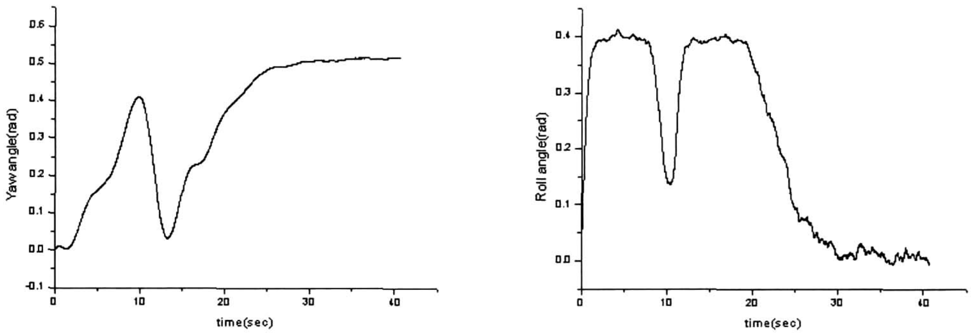
Figure 8 shows the results of heading control without including external gust. Despite the sensor noise, the aircraft heading angle shows satisfactory tracking performance. The heading angle reaches a constant steady value. The roll angle goes back to the initial state after the heading angle change. This validates the kinematic constraint in Eq. (10).



(a) Heading angle response **(b) Roll angle response**

Fig. 8. Heading angle and roll angle responses

Next, simulation results with external gust included are presented in Fig. 9. As it can be shown, the yaw angle response shows considerable fluctuation due to the gust, but eventually converges to the desired final state. Similar behavior is observed in roll angle response as expected. It is again verified, in a rigorous manner, that Eq. (10) is satisfied by the lateral auto-pilot. The aileron response corresponding to the attitude changes is shown in Fig. 10. Due to the sensor noise, the aileron response is also subject to high frequency oscillation. A low-pass filter may be useful in minimizing high frequency oscillation at the reasonable sacrifice of stability margin.



(a) Heading angle response **(b) Roll angle response**

Fig. 9. Response for heading angle and roll angle in the presence of gust

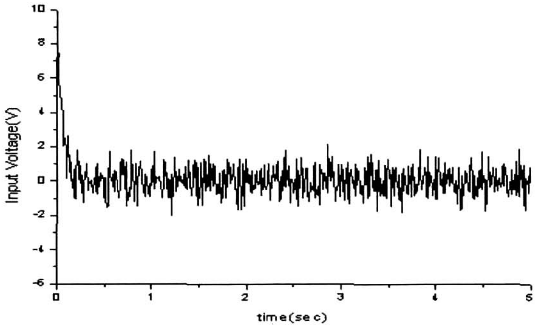
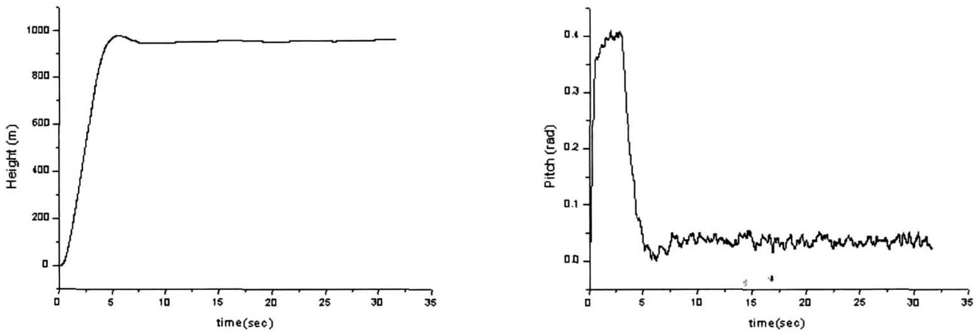


Fig. 10. Response of aileron actuator

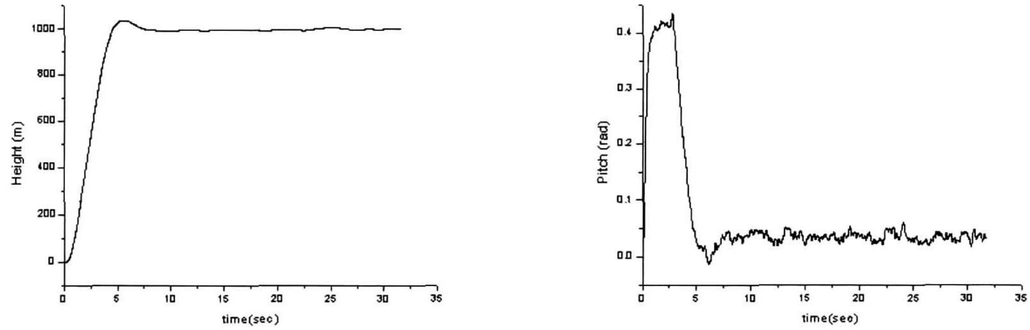
Figure 11 shows the altitude-hold mode simulation result without including the neural network block. The simulation result indicates satisfactory time response is achieved in terms of overshoot. But the exists offset about 100m at the steady state. This may be caused by the nature of altitude response dynamics with respect to the elevator. Altitude dynamics about elevator input are sometimes non-minimum phase systems.



(a) Altitude response by altitude-hold **(b) Pitch angle response by altitude-hold**

Fig. 11. Response for altitude and pitch angle by altitude-hold control mode

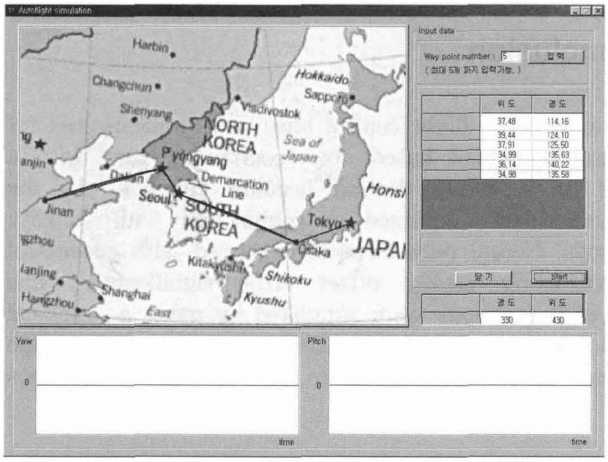
Qualitatively, a similar behavior is observed in the elevator response in comparison with the aileron response in the previous part. In order to eliminate the off-set error in altitude, the idea of control using neural network is applied in the next. The simulation results are shown in Fig. 12.



(a) Altitude response with neural network **(b) Pitch angle response with neural network**

Fig. 12. Altitude and pitch angle response using neural network controller

A noticeable result, different from the previous one, is much smaller off-set error in altitude. This could be attributed to the principal advantages of neural network: being less dependent on system dynamics in performance. Therefore, the neural network could be a potential candidate synthesizing control commands for the altitude-hold scenario for generic aircraft. The non-minimum phase characteristic of the system has been partially overcome by application of the neural network into the control loop.



Way point number : 5

(최대 5개 까지 입력가능.)

	위도	경도
	37.48	114.16
	39.44	124.10
	37.91	125.50
	34.99	135.63
	36.14	140.22
	34.98	135.58

	경도	위도
	330	430

Fig. 13. Main graphic screen for flight path visualization with autonomous navigation

Fig. 14. Aircraft flight under navigation and auto-pilot command

Another simulation conducted is navigation simulation. The navigation part with reference heading angle and the auto-pilot part are combined together to simulate realistic navigation scenarios for autonomous waypoint navigation. For this purpose, a special software tool was developed. The software is implemented on a PC in object-oriented modules using C++ programming language. The software consists of two primary modules: once for navigation simulation and the other one for auto-pilot control. The software is equipped with graphical user interface and three-dimensional visualization function. Figure 13 shows the main graphic screen of the software developed.

Desired waypoints can be selected from a pre-programmed database. The size of the database is variable upon users requirement. Different number of waypoints can be selected depending upon flight planning. Once waypoints are selected, the auto-pilot flight mode becomes operational while navigation equations defining current aircraft location are solved on-line. The aircraft location, updated from a so-called navigation computer module, is used to recalculate the reference heading angle. The reference heading angle is, therefore, updated continuously as it is forwarded to the lateral auto-pilot module. In case the aircraft makes its pproach to a waypoint within a certain boundary, then a new waypoint replaces the old one. The aircraft makes relative large angle turn upon receiving the new waypoint information. The altitude-hold mode is set to operation during navigation. The attitude changes during real-time simulation are displayed in separate graphs.

The software also shows the overall flight path history graphically taken during the navigation. The flight history is represented in the form of sequential connections among the waypoints. Thus the software could be used for the complete ground navigation simulation study. Figure 14 shows the flying aircraft model under navigation and associated auto-pilot commands. Various command switch settings are available in the auto-pilot command module. Graphical environment was created by using a commercial PC-based software tool. Through many simulation runs, it turned out that the control algorithms achieve the original objectives of autonomous navigation. The performance of the developed software was investigated with successful results.

Conclusion

In this study, lateral and longitudinal auto-pilot flight control laws were implemented for autonomous waypoint navigation. The lateral auto-pilot based upon coordinated-turn with a kinematic constraint turned was effective in achieving desired heading changes. As the longitudinal auto-pilot, an altitude-hold system was designed in conjunction with stability augmentation as well as error correction loops. Neural network was employed with successful results for the altitude-hold system eliminating steady offset error significantly. The autonomous navigation and associated auto-pilot functions were simulated by using a graphical software simulation tool. The simulation software designed with C++ programming language and object-oriented architecture will experience further applications in various mission scenarios of navigation and control of aircraft.

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