Design of the Automatic Flight and Guidance Controller for 50m Unmanned Airship Platform

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Abstract

The Stratospheric Airship Platform (SAP) has a capability of performing the autonomous and guidance flight to satisfy given missions. To be used as the High Altitude Platforms (HAPs), the capabilities of controlling platform's accurate position and keeping the station point are the most important features. Under this circumstances Autonomous Flight Control System (AFCS) is a critical system and plays a key role in achieving the given requirements and succeeding in missions. In this paper, the design and analysis results of the AFCS algorithms and controller are presented. The brief summary of the AFCS hardware structure is also explained. The autopilot controller and guidance logics were designed based on the linear dynamics of the unmanned airship platform and the full nonlinear dynamics was considered to evaluate and verify their performances.

Key Word : Unmanned airship, Autonomous flight control system, Guidance system

Introduction

In the history of world aviation the airship occupied one of the unique milestones of mankind's dream of flying through the sky. It is widely that the airship was the first means of transcontinental air travel and had been successfully operated and culminated in its zenith in the 1920s and 1930s. In recent times, interest in the airship arose again, and therefore an airship is considered as a new means for conducting multi-roles in civil as well as military applications : for heavy cargo transportation and stratospheric platform for communication. Particularly, as the demands of mobile communication are rapidly growing, Stratospheric Airship Platform (SAP) is being considered as one of the most candidate ones and an alternative to stations or satellites in order to increase the capability of communication networks. Definitely the High Altitude Platforms (HAPs) should provide the all autonomous functions to control the platform's dynamics and reliable guidance capabilities for reach the station-keeping point and doing the station-keeping flight. Therefore, it is not too much to say that the flight control system could be the most major system which decides the performance and reliability of the unmanned vehicle.

This paper describes the structure of the Autonomous Flight Control System (AFCS) and the procedure of designing the autopilot and guidance controllers for the unmanned airship. First

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the full nonlinear 6-degree of freedom airship dynamics are considered and each controller design steps are presented in accordance with given specifications. Finally simulation results are shown for evaluating the performance of the controller under specific mission scenario. The target airship model is the *50m*-long unmanned airship which are developed by Korea Aerospace Research Institute (KARI) for the preliminary stage of developing the SAP.

50m Unmanned Airship (VIA-50)

Korea has launched the development program of the stratospheric unmanned airship as 10-year project under sponsorship from Korea Ministry of Commerce, Industry and Energy : the 1st phase is to develop the *50m* unmanned non-rigid airship for the prototype to demonstrate and evaluate the Autonomous Flight Control System. Fig. 1 shows the developed *50*m unmanned airship, which designated as *VIA-50*.

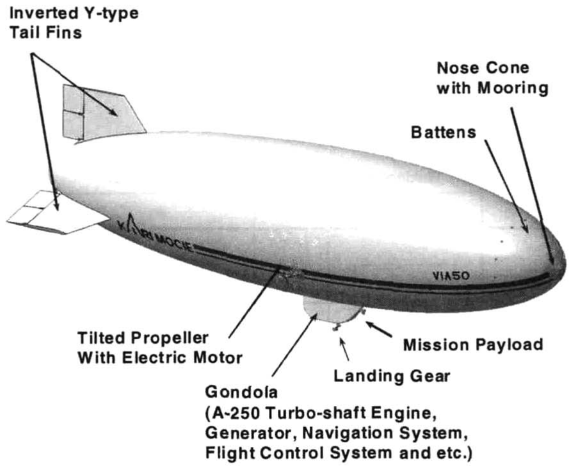

Fig. 1. 50m Unmanned Airship (VIA-50)

VIA-50 is a non-rigid type and the overall length of the hull is *50m*, maximum diameter *12.5m*. The total volume is about $4,090m^3$ and inverted-Y type tail fins are used. The propulsion system consists of a gas turbine engine, generator, and two propellers that are installed at an electric motor with a tilting system. This tilting system can provide a tilting range from $-90°$ to $+120°$. The maximum flight speed is *22m/s* and the pressure height is *5km* with *100kg* payload[1].

Automatic Flight Control System Structure

The AFCS should provide to control the airship dynamics autonomously and manage all states and information of the installed subsystems such as an electric, propulsion, pressurization, communication and mission payload system.

The AFCS hardware block shown in Fig. 2 is composed of several modules: flight control computer (FCC), GPS/INS hybrid navigation system, air data system with, servo actuator for control surface, and switching module for controlling the propulsive system[2].

To perform a function of autonomous flight and mission, autopilot and guidance flight modes are designed and implemented by control laws as shown in Fig. 3. The autopilot inner loops are composed of the pitch hold, altitude hold, airspeed hold, and heading hold mode. Based on these autopilot functions, outer guidance loop can be selected and worked correspondingly by

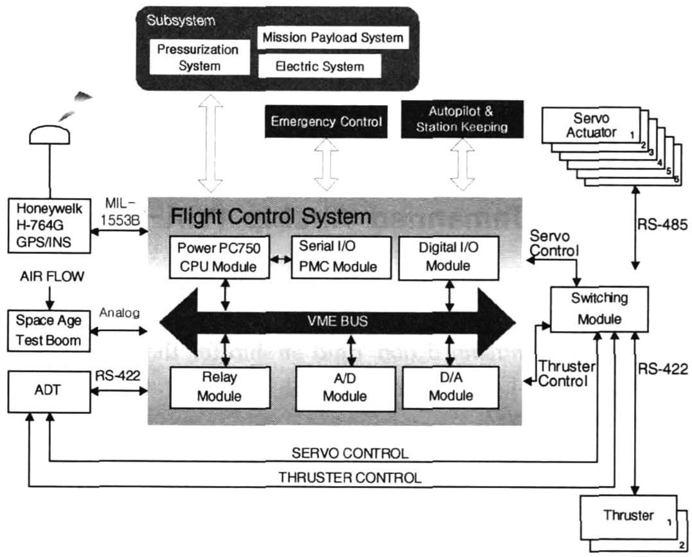

Fig. 2. AFCS Structure

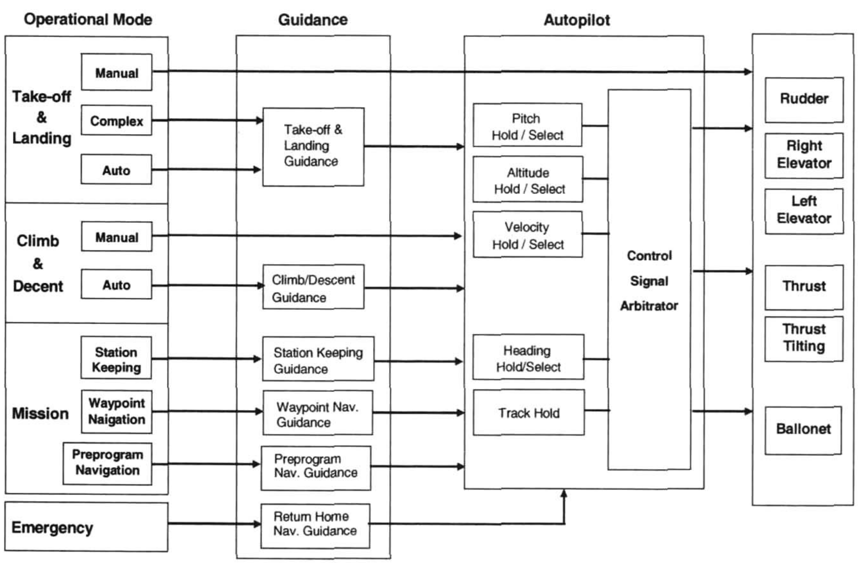

Fig. 3. Autopilot and Guidance Flight Mode

Ground Control Station (GCS) selection command such as station keeping, waypoint navigation, and pre-programmed navigation mode including the emergency mode[2].

Nonlinear Equations of Motion

The airship has many unique and additional features, such as buoyancy, virtual mass, virtual inertia, and so on, which are commonly neglected in aircraft analysis. By these factors to be concerned, the dynamics of an airship includes more nonlinearities in the equations. The important work of Ref. [3] and [4] were used as the basis of the equation of motion of an airship. They derived and summarized the 6-DOF nonlinear mathematical model of airship based on aerodynamic databases by a wind-tunnel test. The coordinate frame is shown in Fig. 4 and the rigid body equations of motion are obtained using Newton's second law. The velocity, $\vec{V}$, is slightly different from that of an aircraft equation because the point of center of gravity (c.g) is not coincide with the origin of body axis and is considered into Eq. (1), (2) and (3).

$$\vec{F} = \frac{d(m\vec{V})}{dt} = \frac{d}{dt}\left[m\left(\vec{\mu} + \frac{d\vec{p}}{dt}\right)\right] = \frac{d}{dt}[m(\vec{\mu} + \vec{\omega}\times\vec{p})] \quad (1)$$

$$\vec{M} = \frac{d\vec{H}}{dt} = \frac{d\vec{H}_b}{dt} + m\vec{p}\times\frac{d\vec{\mu}}{dt} \quad (2)$$

$$\vec{V} = \vec{\mu} = \frac{d\vec{p}}{dt} = \vec{\mu} + \vec{\omega}\times\vec{p} \quad (3)$$

where

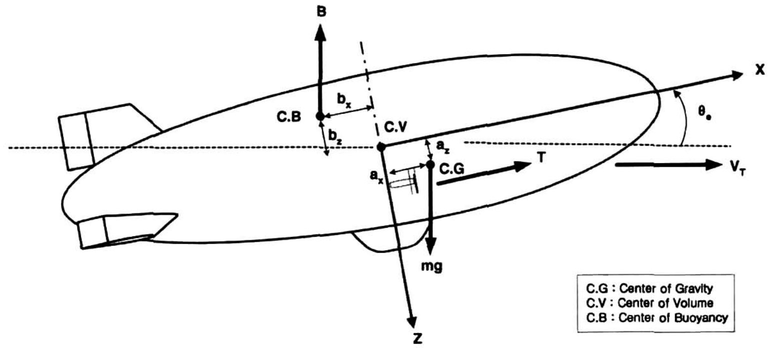

Fig. 4. Coordinates of an Airship

Since the airship is symmetric about the oxz-plane in Fig. 2, $J_{xy}=J_{yz}=0$, $a_y=0$. Then the six degree of freedom equations of motion can be developed as Eqs. (4) and (5).

- axial force : $m_x\dot{U} + m_zQW - m_yRV + (ma_z - X_{\dot{q}})\dot{Q} - ma_x(Q^2+R^2) + ma_zPR = X$
- side force : $m_y\dot{V} - m_zPW + m_xRU - (ma_z + Y_{\dot{p}})\dot{P} + (ma_x - Y_{\dot{r}})\dot{R} + ma_xPQ + ma_zQR = Y$ (4)
- normal force : $m_z\dot{W} + m_yPV - m_xQU - (ma_x + Z_{\dot{q}})\dot{Q} - ma_z(P^2+Q^2) + ma_xPR = Z$

- rolling moment : $J_x\dot{P} - J_{xz}(\dot{R} + PQ) + (J_z - J_y)QR - (ma_z + L_{\dot{v}})\dot{V} - ma_z(RU - PW) = L$
- pitching moment : $J_y\dot{Q} + J_{xz}(P^2 - R^2) + (J_x - J_z)PR - (ma_x + M_{\dot{w}})\dot{W}$ (5)
  $- ma_x(PV - QU) + (ma_z - M_{\dot{u}})\dot{U} + ma_z(QW - RV) = M$
- yawing moment : $J_z\dot{R} - J_{xz}(\dot{P} - QR) + (J_y - J_x)PQ + (ma_x - N_{\dot{v}})\dot{V} + ma_x(RU - PW) = N$

where m is the mass of the airship, (m_x, m_y, m_z), are the virtual mass, and J is the virtual moment of inertia. Terms of the right hand side of the Eqs. (4) and (5), external forces and moments, are composed of four kinds of parts such as aerodynamic force and moment, gravitational force, buoyancy and propulsive force, respectively. Especially, aerodynamic forces and moments can be calculated from the aerodynamic database, which was constructed by the wind-tunnel test by using the *1/25* scaled airship model. Finally the full nonlinear dynamic equations of an airship and can be summarized as form of Eq. (6).

$$\dot{\mathrm{X}} = \mathrm{M}^{-1} \cdot f(\mathrm{x}, \mathrm{u}, t) \quad (6)$$

where we have the state vector; flight airspeed, angle-of-attack, sideslip angle (V_T, α, β), angular rates (P, Q, R), Euler angles (ϕ, θ, ψ) and position (X_E, Y_E, Z_E). The elements of the input vector will comprise, respectively, elevator deflection (δ_e), rudder deflection (δ_r), left thrust (δ_{TL}), right thrust (δ_{TR}) and tilting angle (δ_μ).

Autopilot Design

Pitch Attitude Hold Mode

The Pitch attitude hold controller is one of the main autopilot controllers for a longitudinal dynamics. As shown in Fig. 5, the proportional and integral feedback control scheme is used for controlling the pitch attitude and a pitch stability augmentation controller is included as an inner loop to increase the damping. Though the general fixed wing aircraft used this pitch stability augmentation controller to attain the adequate response of a short-period mode[5], we use it to acquire a sufficient phase and gain margin for stability in case of an airship. In accordance with the given requirements of Table 1, we select the gain as K_q=1.2 and K_θ=-3.0 from a root locus in Fig. 6 and bode plot. Fig. 7 shows the normalized response of the pitch attitude and satisfies the requirement[6].

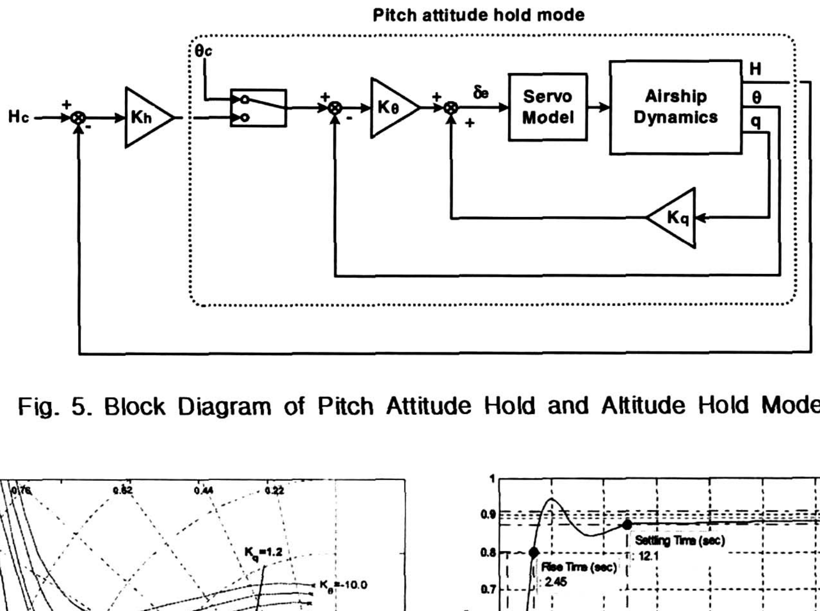

Fig. 5. Block Diagram of Pitch Attitude Hold and Altitude Hold Mode

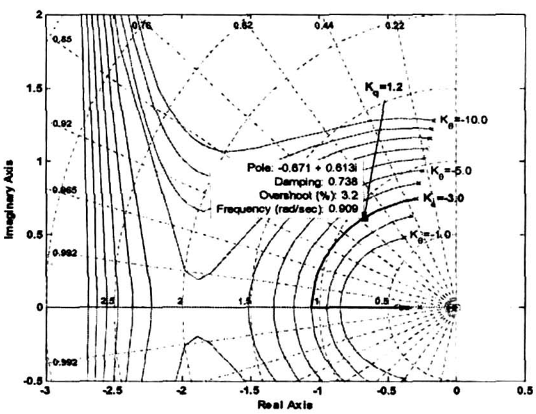

Fig. 6. Root Locus for Pitch Attitude Hold Mode (K_q vs K_θ)

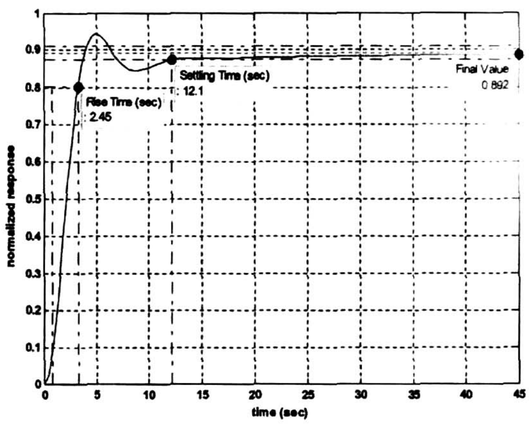

Fig. 7. Normalized Step Response of Pitch Attitude Hold Mode

Table 1. Requirement for Pitch Attitude Hold Mode

Static Error	Percent Overshoot	Damping Ratio	Settling Time	Rise Time	Gain/Phase Margin
< ±2.0 deg	< 10 %	> 0.707	< 15 sec	< 5 sec	> 8 dB > 60 deg

Altitude Hold Mode

The altitude hold controller uses an elevator input to follow the reference command in Fig. 5. Contrast to the fixed wing aircraft, the airship should hold the internal pressure of the envelope This means that the climb rate is restricted by the capacity of the pressurization system. Hence we use the limiter of the pitch attitude from *-30°* to *+30°* to do this purpose. Table 2 summarizes the requirement of the altitude hold mode and we select the gain as $K_h=0.6$ from a root locus of Fig. 8 [6]. The normalized step response is shown in Fig. 9.

Table 2. Requirement for Altitude Hold Mode

Static Error	Percent Overshoot	Damping Ratio	Settling Time	Rise Time	Gain/Phase Margin
< ±25 m	< 20 %	-	< 50 sec	< 20 sec	> 8 dB > 60 deg

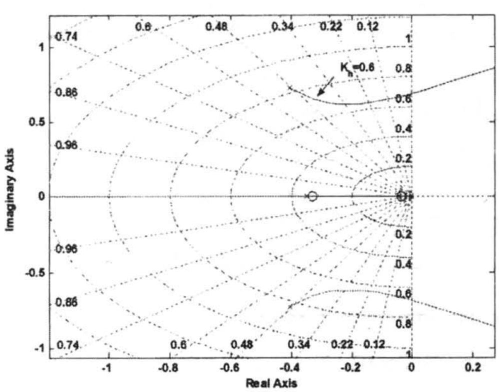

Fig. 8. Root Locus for Altitude Hold Mode

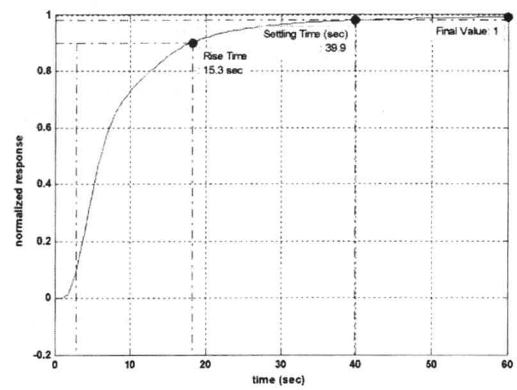

Fig. 9. Normalized Step Response of Altitude Hold Mode

Airspeed Hold Mode

The last controller for longitudinal dynamics is the airspeed hold controller and it adopts the integral gain added to the proportional gain as shown in Fig. 10. Usually thrust force of a propeller is being used as a control input to adjust the airspeed. A time delay of the engine are considered

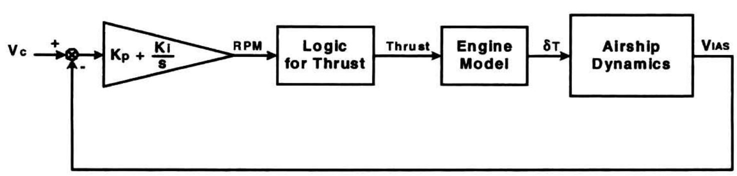

Fig. 10. Block Diagram of Airspeed Hold Mode

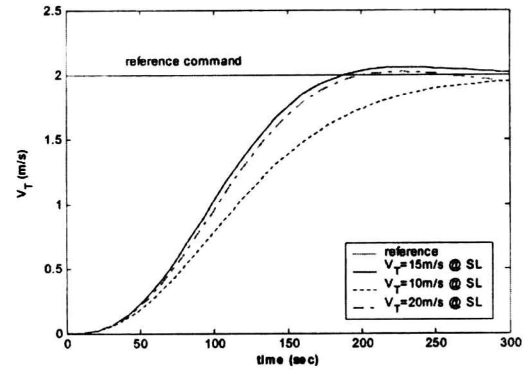

Fig. 11. Time Response of Airspeed Hold Mode

by the engine model and the steady-state error should be less than *±1.0m/s*. Applying similar design procedures, two gains are defined by $K_p=6.0$ and $K_i=0.6$ and the time response are shown in Fig. 11.

Heading Hold Mode

The heading hold mode is the only one for the lateral dynamics of the airship and the algorithm is similar to the pitch attitude controller as shown in Fig. 12. The requirement is also same as that excluding the settling time and rise time because the rudder is just one used compared to the elevator. $K_r=10$ and $K_\psi=-1.5$ are chose by the root locus of Fig. 13 and the normalized step time response and the bode plot prove to meet all requirements as shown in Fig. 14 and 15 respectively.

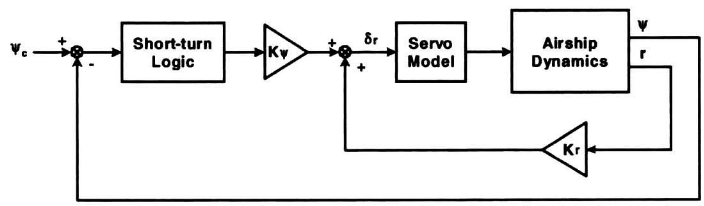

Fig. 12. Block Diagram of Heading Hold Mode

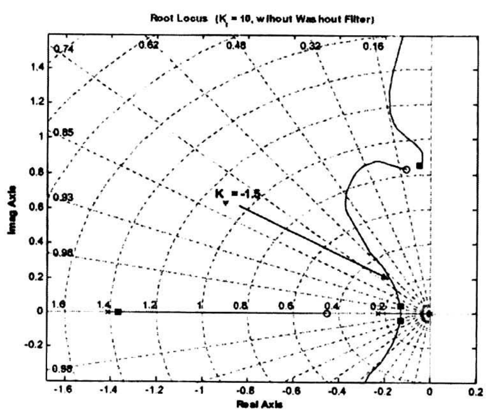

Fig. 13. Root Locus for Airspeed Hold Mode

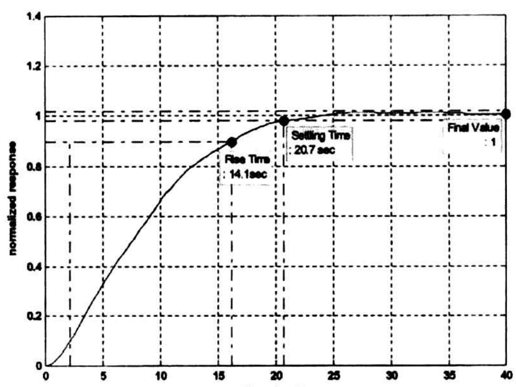

Fig. 14. Normalized Step Response of Airspeed Hold Mode

Table 3. Requirement for Heading Hold Mode

Static Error	Percent Overshoot	Damping Ratio	Settling Time	Rise Time	Gain/Phase Margin
< ±2.0 deg	< 10 %	> 0.707	< 30 sec	< 20 sec	> 8 dB > 60 deg

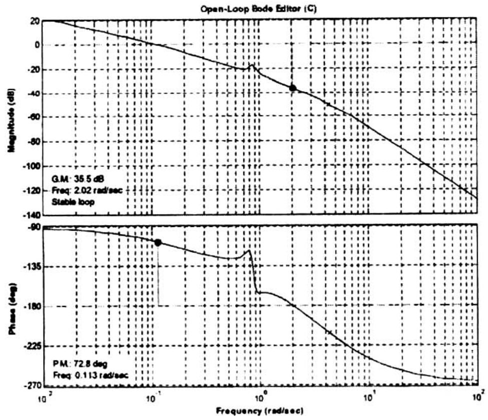

Fig. 15. Bode Plot of Airspeed Hold Mode

Guidance Logic

As explained in the previous section, all autopilot controllers, inner loop of the guidance logic, were designed to satisfy the requirement. Even though the design was made based on the linearized model, it is sure that the performance is adequate after evaluating on the nonlinear model depicted in previous section. Having made this point that the inner loop of the guidance logic is suitable, we may go on to the next design steps. Guidance logics for the mission flight mainly consist of two kinds : level and turning flight. Therefore, other mission flight modes such as station-keeping, point navigation and return home flight can be done by combination these logics.

Guidance for Level Flight

For the guidance logic for the level flight, first we define the position and cross track error (*XTRK*) in horizontal plane of NED (North-East-Down) coordinate in Fig. 16. Here the initial waypoint is P_i, final target waypoint is P_f and the current position is P_c. The objective of the level flight guidance is to align the flight path of the airship to the Leg which is a straight line between P_i and P_f. In other words, the cross track error should be reached zero by decreasing the heading angle error between ψ_{leg} and ψ_{vtw}. Therefore, the *XTRK* can be expressed as Eq. (7) and guidance logic controller is obtained by Eq. (8). Whole structure of the level flight guidance is presented in Fig. 17 and input information is the terminal position of a waypoint, terminal altitude and airspeed during the transient flight.

$$XTRK = \sqrt{(x_f - x_c)^2 + (y_f - y_c)^2}\, sin(\psi_{leg} - \psi_{vtw}) \tag{7}$$

$$\psi_c = \psi_{vtw} - K_{XTRK} \cdot XTRK \tag{8}$$

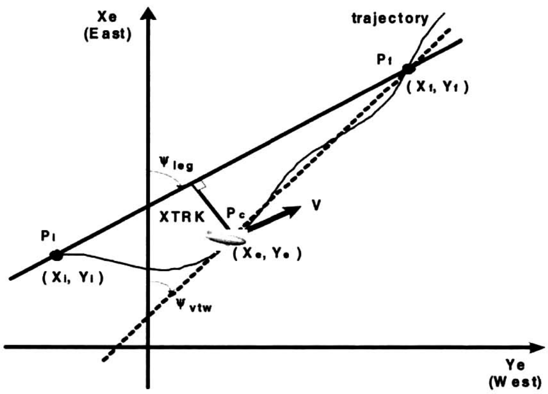

Fig. 16. Definition of Cross Track Error (XTRK)

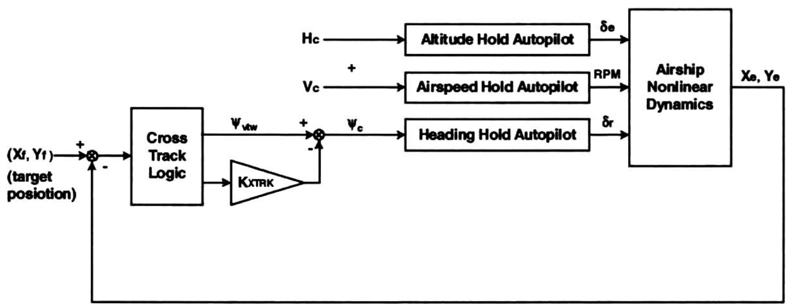

Fig. 17. Block Diagram for Guidance for Level Flight

Guidance for Turning Flight

To design the guidance controller for the turning flight, the heading angle of an airship should be perpendicular to the tangent line of the circle of the turning and be hold the distance from a center of turning and a current position as shown in Fig. 18. Therefore, the final turning guidance controller can be obtained as Eq.(9) and Fig. 19 shows a block diagram. Input information is the center and radius of turning with a altitude and airspeed during the turning flight.

$$\delta_r \psi_c = K_\psi \left(\psi - \psi_c\right) + K_{Radius}\left(d - R\right) \tag{8}$$

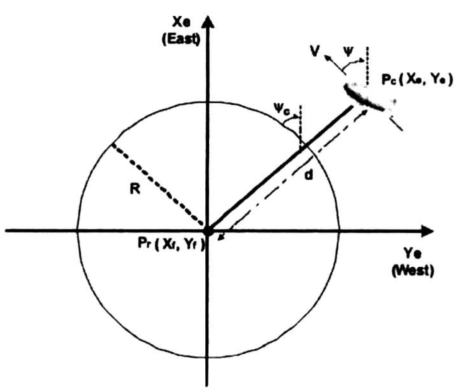

Fig. 18. Guidance Logic for Turning Flight

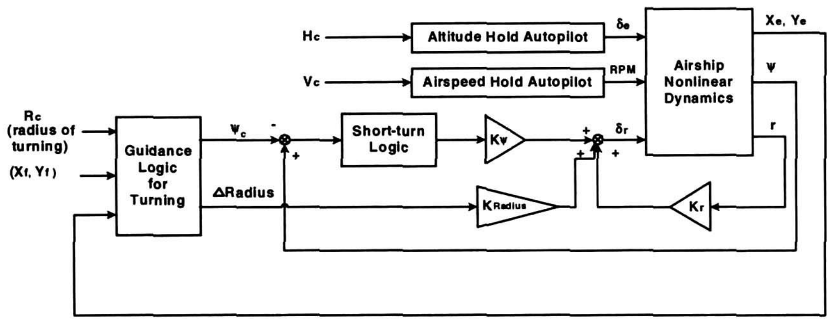

Fig. 19. Block Diagram for Guidance for Turning Flight

Guidance for Station-Keeping Flight

VIA-50 adopts the station-keeping guidance logic as a continuous turning flight with respect to the specific keeping point. Therefore, previous level and turning guidance are combined to be applied together. This method can provide the stable performance in spite of the low flight speed. In low speed flight regime the control surface can not supply the sufficient aerodynamic control force and moment, so the tilting mechanism of the propeller should be applied simultaneously. But this approach causes very complicated coupling phenomenon in such that controlling the airspeed, altitude and attitude at a time.

Mission Simulation

To verify the performance of the designed autopilot and guidance, we use the nonlinear simulation in specific mission scenario. The initial starting position is $(X_n, X_e, H) = (0m, 0m, 0m)$ and airspeed is $V_T=15m/s$ with heading angle is $\psi=0°$. The given mission scenario is presented in Table 4. The full nonlinear simulation can be applied and the three dimensional trajectory results are shown in Fig. 20 and altitude and heading angle results are presented in Fig. 21. All flight results of autopilot and guidance have been successfully operated and given a good performance based on the results. Especially for the station keeping flight (Mission 5) of Fig. 22 presented the boundary of station keeping is *600m* and keeps the track of circle.

Table 4. Mission Scenario

Mission No. and Time (sec)	Flight Mode	Autopilot Command			Guidance Command				
		V_T (m/s)	H (m)	ψ (deg)	Target position (X_n, X_e)	Turn H (m)	Turn V_T (m/s)	Level H (m)	Level V_T (m/s)
1: 0sec	AH	15	500	0					
2: 160sec	AH&HH&VH	20	1000	10					
3: 200sec	GPN				(6000,5000)	1000	15	1000	15
4: 1150sec	GPN				(6000,4000)	3500	15		
5: 2000sec	GSK				(8000,9000)	3000	15	3000	15
6: 2800sec	AH&HH	15	500	270					
7: 3400sec	AH&HH&VH	12	500	180					

AH : Altitude Hold Mode, HH : Heading Hold Mode, VH : Velocity Hold Mode,
GPN : Point Navigation Mode, GSK : Station-Keeping Mode

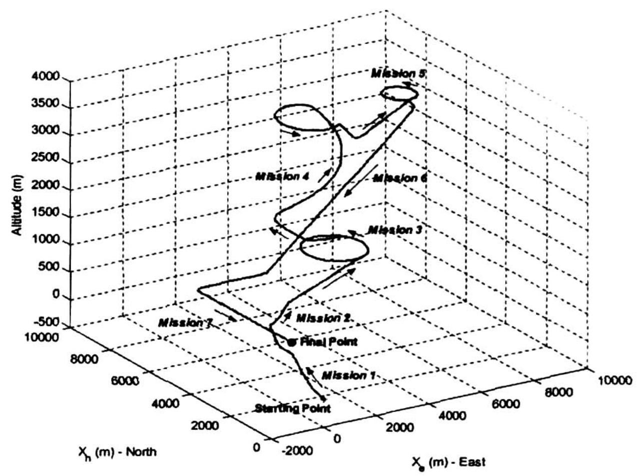

Fig. 20. 3D Position of Mission Flight

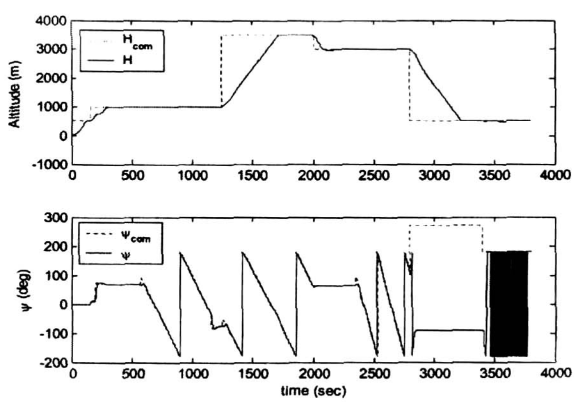

Fig. 21. Simulation Results for Altitude and Heading Angle

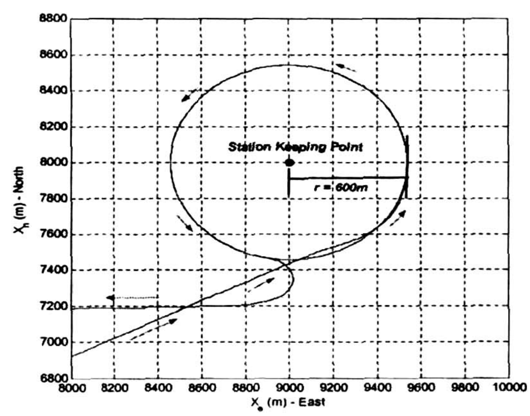

Fig. 22. Simulation Results for Station-Keeping Flight

Conclusions and Remarks

The overall design architecture of the Autonomous Flight Control System for *VIA-50* is introduced briefly including its structure of the controller algorithm. Its main design requirements are briefly presented and various flight autopilot and guidance algorithm has been developed according to fulfil the mission requirements. For autopilot and guidance algorithm verification, the nonlinear 6-DOF simulation program for *VIA-50* has been developed and used for dynamic simulation and HILS (Hardware-In-The-Loop) test has been conducted with the 3-axis motion table.

KARI completed system design, preliminary design and critical design of the AFCS and finished final system assembly through the Ground Integration Test. Flight test has been going on at the Flight Research Center in Go-Heung, located southern part of Korea.

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