Direction Stabilization and Simulation of an Aerial Delivery System with Ram-Air Parachute

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Research Article

Keywords: Aerial Delivery System, PID controller, Direction Stabilization, Flight Dynamics

Posted Date: March 21st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1458039/v1

Direction Stabilization and Simulation of an Aerial Delivery System with Ram-Air Parachute

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Abstract

In this study, a controller system to stabilize the direction of an aerial delivery system with Ram-Air Parachute is developed. First, a simulation platform is prepared in Matlab, Simulink. Simulink 6DOF vehicle model is used for simulations. The aerodynamic forces and moments on the vehicle are mathematically modelled and implemented. Control algorithms for regulation of yaw, yaw rate and descent rate are developed and tested. The roll rate and pitch rate are observed parameters to examine the flight stability.

Keywords: Aerial Delivery System, PID controller, Direction Stabilization, Flight Dynamics

1 Introduction

With the developing technology, the usage areas of smart systems in both industry and daily life are increasing. These areas also include parachute cargo systems.

In traditional landing systems, cargoes are dropped from a certain altitude based on multiple analytic calculations. In these systems that do not have any active controller, unexpected environmental conditions cause huge deviations between predicted and actual destination location. Therefore, steerable parachute systems were needed. These systems, which were first introduced in the 1960s, have been developed to date. Various parachute types have been studied for delivery systems. It is observed that high glide ratio parachutes (parasail, cloverleaf, parawing, sailwing, parafoil etc.) are more controllable than other ones [10]. Ram-air parafoils are the most popular one for aerial delivery systems.

In this study, a simulation platform is designed for an aerial delivery system with ram-air parachute. 6DOF model is used for simulation. Direction stabilization system is developed to control yaw angle, yaw rate and descent rate.

2 Aerodynamic Characteristics of Ram-Air Parachutes

Ram-Air parachutes can be considered low aspect-ratio wings. Thus, conventional theories for wings are acceptable.

To calculate lift curves for wings with high aspect ratio, lifting-line theory can be useful [8].

$$C_{L\alpha} = (\pi C_{L\alpha}^{\alpha} AR)/(\pi AR + C_{L\alpha}^{\alpha}(1+\tau), \tag{1}$$

where $C_{L\alpha}$ lift-curve slope coefficient versus angle of attack, $C_{L\alpha}^{\alpha}$ is airfoil (two-dimensional) lift-curve slope coefficient, AR is aspect ratio and τ is the parameter depending on the aspect ratio.

This theory has been extended for wings with low aspect ratio. Hoerner and Borst have redefined [7].

$$C_{L\alpha}^{\alpha}{}' = C_{L\alpha}^{\alpha} k, \tag{2}$$

$$k = ((2\pi AR)/C_{L\alpha}^{\alpha}) \tanh{(C_{L\alpha}^{\alpha}/(2\pi AR))}, \tag{3}$$

The difference of the lift coefficient for wings with low opening ratio is defined by Hoerner and Borst [7].

$$\Delta C_L = k_1 \sin^2{(\alpha - \alpha_0)} \cos{(\alpha - \alpha_0)}, \tag{4}$$

$$k_1 = \begin{cases} 3.33 - 1.33AR & 1 < AR < 2.5 \\ 0 & AR \geq 2.5 \end{cases}, \tag{5}$$

where α is angle of attack and α_0 is the zero lift angle.

Total lifting for parachute can be written using corrected equations and coefficients.

$$C_L = C_{L\alpha}(\alpha - \alpha_0) + k_1 \sin^2(\alpha - \alpha_0)\cos(\alpha - \alpha_0), \tag{6}$$

where C_L is the lift coefficient. Drag coefficient for a rectangular wing according to lifting-line theory can be calculated as;

$$C_D = C_{D0} + (C_L^2(1+\delta))/(\pi AR), \tag{7}$$

where C_D is the drag coefficient, C_{D0} is the profile drag and δ is a parameter to allow for nonelliptic loading.

For low aspect ratio wings, drag coefficient difference is defined by Hoerner [6].

$$\Delta C_D = k_1 \sin^3(\alpha - \alpha_0), \tag{8}$$

Assembling these equations together, total drag coefficient can be obtained.

$$C_D = C_{D0} + (C_{LC}^2(1+\delta))/(\pi AR), \tag{9}$$
$$C_{LC} = C_{L\alpha}(\alpha - \alpha_0), \tag{10}$$

where C_{LC} is the circulation lift. Lift coefficients are corrected according to the dihedral angle(epsilon) (fig. 1).

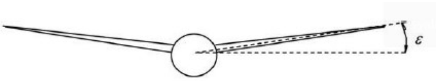

Fig. 1 Wing dihedral angle

$$C_L = C_{L;\,\epsilon=0}\cos^2\epsilon, \tag{11}$$

This equation can be written for parachutes with anhedral angle [7] (fig. 2).

$$\epsilon = b/4R, \tag{12}$$

Lift coefficient can be defined with the anhedral effect.

$$C_L = C_{L\alpha}(\alpha - \alpha_0)\cos^2\epsilon + k_1 \sin^2(\alpha - \alpha_0)\cos(\alpha - \alpha_0), \tag{13}$$

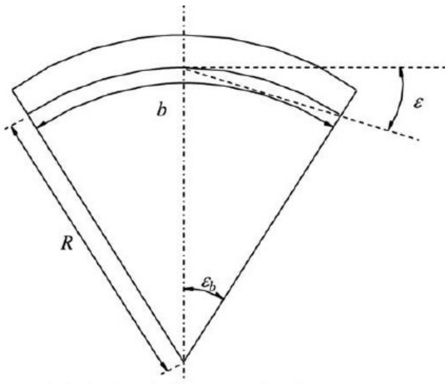

Fig. 2 Parachute anhedral angle

3 Equations of Motion

Parachute needs to be modeled mathematically in order to simulate and control the parachute landing systems. Many studies have been carried out on this subject in the literature. The studies are gathered under two main scopes. In one of them, parachute and cargo are considered as a single rigid body and the system is modeled in this way. 3,4 and 6 DOF models are developed [5][4]. This study is based on 6 degrees of freedom model.

For the 6 DOF model, first of all, it is necessary to write the equations of motion. The dynamic equations can be written by adding the sum of the forces and moments on the center of mass to the angular and linear momentum equations.

$$mI_{3x3}\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = F - mS(\omega)\begin{bmatrix}u\\ v\\ w\end{bmatrix}, \tag{14}$$

$$I\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} = M - S(\omega)I\begin{bmatrix}p\\ q\\ r\end{bmatrix}, \tag{15}$$

where m is mass, I is inertia matrix, [u v w] are linear velocities, [p q r] are angular velocities in body frame, $S(\omega)$ is a skew-symmetric matrix consisting of linear velocity vectors, F is force and M is moment.

Due to the x-z symmetry plane of the parachute landing systems, inertial matrices consist of 4 unique components.

$$S(\omega) = \begin{bmatrix}0 & -r & q\\ r & 0 & -p\\ -q & p & 0\end{bmatrix}, \tag{16}$$

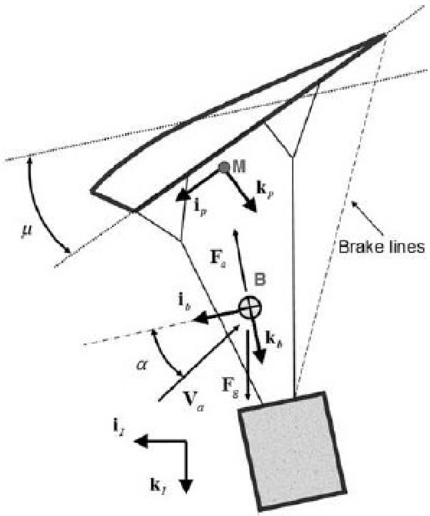

Fig. 3 Free body diagram of the aerial delivery system [3]

$$I = \begin{bmatrix} I_{xx} & 0 & I_{xz} \\ 0 & I_{yy} & 0 \\ I_{xz} & 0 & I_{zz} \end{bmatrix} \tag{17}$$

The forces and moments affecting the parachute are caused by gravity and aerodynamic forces. Gravitational force can be written according to the body (b) axis shown in fig. 3.

$$F_g = mg \begin{bmatrix} -\sin(\theta) \\ \cos(\theta)\sin(\Phi) \\ \cos(\theta)\cos(\Phi) \end{bmatrix}, \tag{18}$$

The aerodynamic forces acting on the system are written using the relevant aerodynamic coefficients $(C_{D0}, C_{D\alpha^2}, C_{D\delta_S}, C_{Y\beta}, C_{L0}, C_{L\alpha}, C_{L\delta_S})$ according to the body axis.

$$F_a = QS({}_w^bR) \begin{bmatrix} C_{D0} + C_{D\alpha^2}\alpha^2 + C_{D\delta_S}\bar{\delta}_S \\ C_{Y\beta}\beta \\ C_{L0} + C_{L\alpha}\alpha + C_{L\delta_S}\bar{\delta}_S \end{bmatrix}, \tag{19}$$

In this equation, S represents the parachute surface area, $\bar{\delta}_S$, symmetric trailing edge deflection and $({}_w^bR)$, the rotation matrix from the aerodynamic coordinate system to the body axis.

$$R_\alpha = \begin{bmatrix} \cos(\alpha) & 0 & -\sin(\alpha) \\ 0 & 1 & 0 \\ \sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix}, \tag{20}$$

$$R_\beta = \begin{bmatrix} \cos(\beta) & \sin(\beta) & 0 \\ -\sin(\beta) & \cos(\beta) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{21}$$

$$({}^b_w R) = R_\alpha R_\beta, \tag{22}$$

Angle of attack and slip angle are obtained from the velocity vector in the body axis.

$$\alpha = \tan^{-1}(v_z/v_x), \tag{23}$$

$$\beta = \tan^{-1}(v_y/(\sqrt{(v_x^2 + v_z^2)}), \tag{24}$$

The velocity vector in the body axis consists of global velocity and wind effect.

$$V_a = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} u \\ v \\ w \end{bmatrix} - ({}^b_n R) \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix}, \tag{25}$$

R is the rotation matrix from the coordinate system on the North-East-Down axis which has the origin in center of mass of the parachute, to the body axis. Euler angles (roll, pitch, yaw) are used in this notation.

$$R_\Phi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\Phi) & \sin(\Phi) \\ 0 & -\sin(\Phi) & \cos(\Phi) \end{bmatrix}, \tag{26}$$

$$R_\theta = \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix}, \tag{27}$$

$$R_\psi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\psi) & \sin(\psi) \\ 0 & -\sin(\psi) & \cos(\psi) \end{bmatrix}, \tag{28}$$

$$({}^b_n R) = R_\Phi R_\theta R_\psi, \tag{29}$$

Aerodynamic moments affecting the parachute can also be written using the relevant coefficients $(C_{l\beta}, C_{lp}, C_{lr}, C_{l\delta_a}, C_{m0}, C_{m\alpha}, C_{mq}, C_{n\beta}, C_{np}, C_{nr}, C_{n\delta_a})$. These are roll, pitch and yaw moments, respectively. [2].

$$K_1 = b(C_{l\beta}\beta + 0.5(b/V_a)C_{lp}p + 0.5(b/V_a)C_{lr}r + C_{l\delta_a}\bar{\delta}_a), \quad (30)$$

$$K_2 = \bar{c}(C_{m0} + C_{m\alpha}\alpha + 0.5(c/V_a)C_{mq}q), \quad (31)$$

$$K_3 = b(C_{n\beta}\beta + 0.5(b/V_a)C_{np}p + 0.5(b/V_a)C_{nr}r + C_{n\delta_a}\bar{\delta}_a), \quad (32)$$

$$M_a = 0.5\rho V_a^2 S \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix}, \quad (33)$$

where ρ is air density, $\bar{c}$ represents mean aerodynamic chord, $\bar{\delta}_a = \delta_a/\delta_{a_{max}}$, is asymmetric trail edge deflection and S is canopy reference area.

4 Simulation

Matlab Simulink program was used in simulation studies.(Fig. 4) As for the model, 6 degrees of freedom were chosen. The parameters required for simulation were used considering the autonomous landing system with a parachute named Snowflakes (Table 1) [3].

The forces and moments acting on the system are given in equation 19 and equation 33. After the sub-blocks consists of forces and moments were created, the simulink block containing 6 degrees of dynamics was added to the force and moment blocks. Altitude is determined as the simulation stop condition. The simulation is terminated automatically when the landing is accomplished.

5 Results and Discussion

The parachute was dropped from an altitude of 100m in windless environment. Then 5 m/s wind is added in -x direction. Path of both flights are plotted in Fig. 5 and Fig. 6.

Table 1 Parameters of Snowflake

Parameter	Value
Mass (m)	1.9kg
Canopy Reference Area (S)	$1m^2$
Inertia Matrix (I)	$\begin{bmatrix} 0.042 & 0 & -0.0068 \\ 0 & 0.027 & 0 \\ -0.0068 & 0 & 0.054 \end{bmatrix}$
Maximum brake deflection	0.25m
Aerodynamic coefficients	$\begin{bmatrix} C_{D0} = 0.15 & C_{D\alpha^2} = 0.90 \\ C_{Y\beta} = -0.05 & C_{L0} = 0.25 \\ C_{L\alpha} = 0.68 & C_{m0} = 0.0 \\ C_{m\alpha} = 0 & C_{mq} = -0.265 \\ C_{l\beta} = -0.036 & C_{lp} = -0.355 \\ C_{lr} = 0 & C_{l\delta_a} = 0.15 \\ C_{n\beta} = -0.036 & C_{np} = 0 \\ C_{nr} = -0.09 & C_{n\delta_a} = 0.003 \end{bmatrix}$

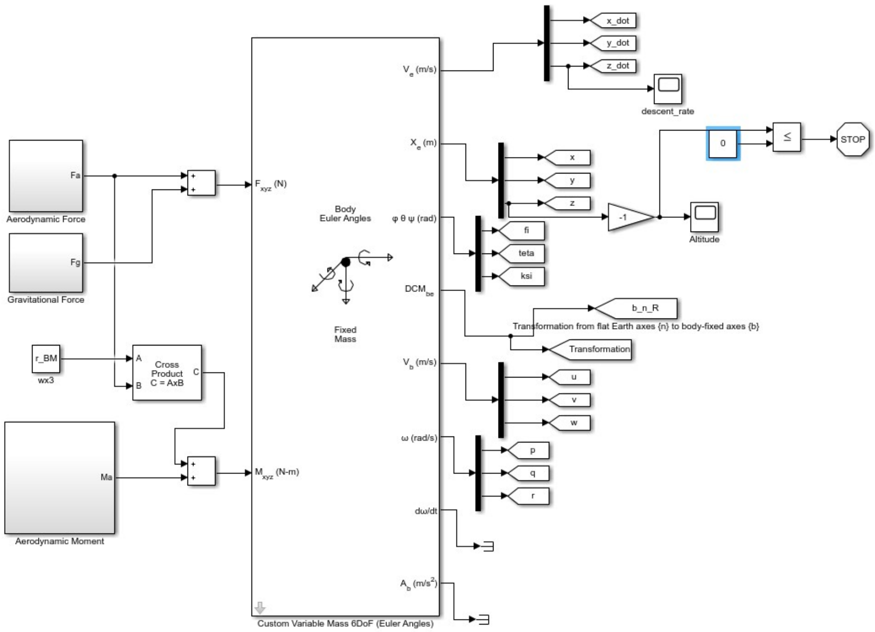

Fig. 4 Parachute Landing System Simulink Model

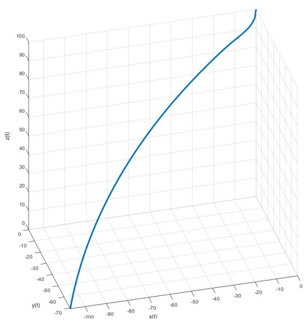

Fig. 5 100m Free fall parachute path (windless)

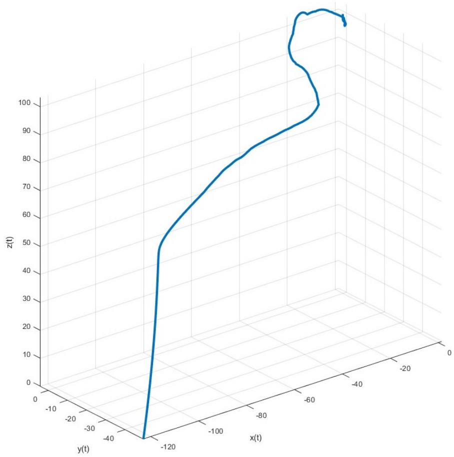

Fig. 6 100m Free fall parachute path (windy)

The control of the landing system to the desired destination must be carried out according to the determined path. One of the controls required to ensure movement in this path is the yaw angle control. PID controller has been developed for yaw angle in simulation environment and system has been tested with and without wind effect.(Fig.7, Fig. 8) Errors are plotted in Fig. 9 and Fig. 10.

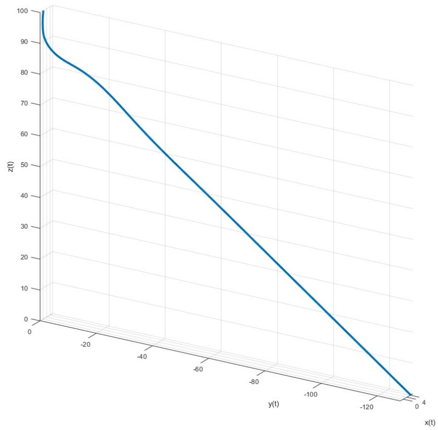

Fig. 7 Yaw controlled flight (90 degrees - windless))

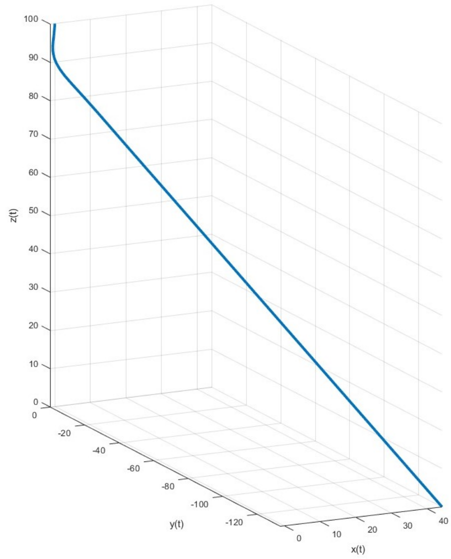

Fig. 8 Yaw controlled flight (90 degrees - windy)

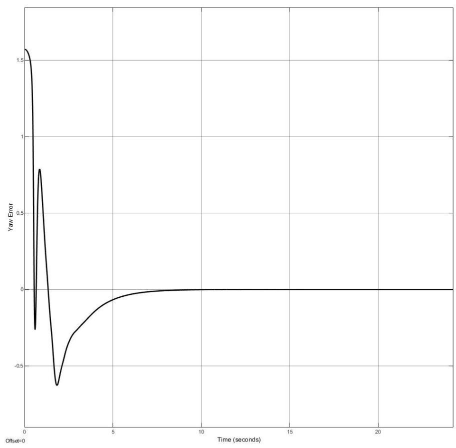

Fig. 9 Yaw error (windless)

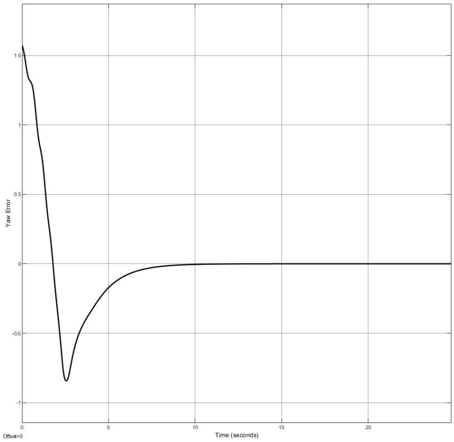

Fig. 10 Yaw error (windy)

In order to investigate stability, roll rate and pitch rate are observed during whole flight.(Fig. 11 - 12)

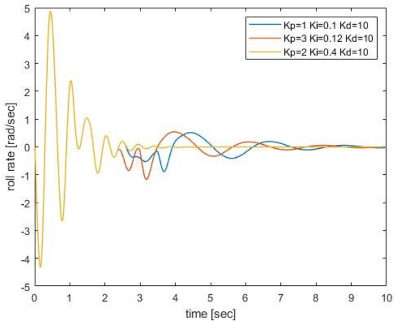

Fig. 11 Pitch and roll rate during yaw controlled flight (windless)

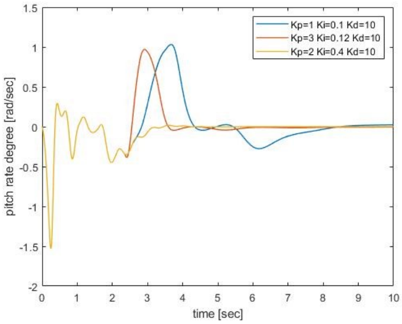

Fig. 12 Pitch and roll rate during yaw controlled flight (windy)

Planning the path for the landing system was considered in two sections as descent and final maneuver. In the descent section, the goal is to follow a spiral route until it reaches the specified altitude. For this, yaw rate control has been studied.(Fig. 13 - 14 - 15 - 16)

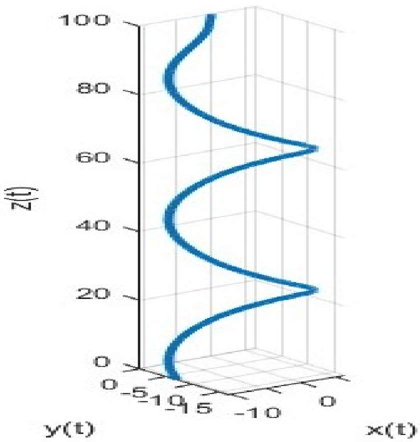

Fig. 13 Yaw rate controlled flight (windless)

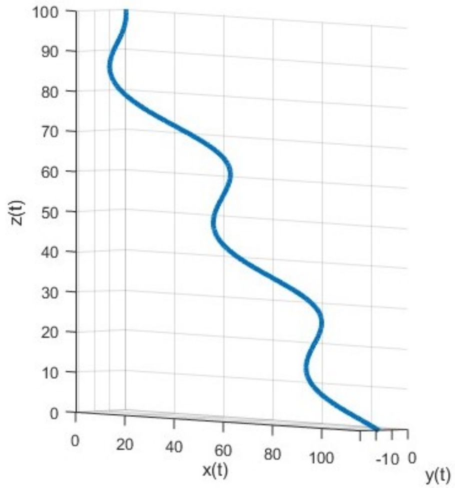

Fig. 14 Yaw rate controlled flight (windy)

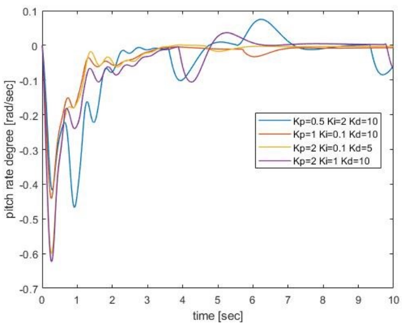

Fig. 15 Pitch and roll rate during yaw rate controlled flight (windless)

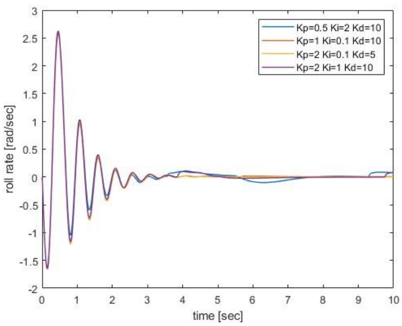

Fig. 16 Pitch and roll rate during yaw rate controlled flight (windy)

Finally, the descent rate control in the landing system is very important in route tracking. In line with the parameters used in the simulation, the system provides landing at descent rates of 4-6 m/s. Therefore, the controller with the reference of 5 m/s was developed and applied to the system.(Fig. 17)

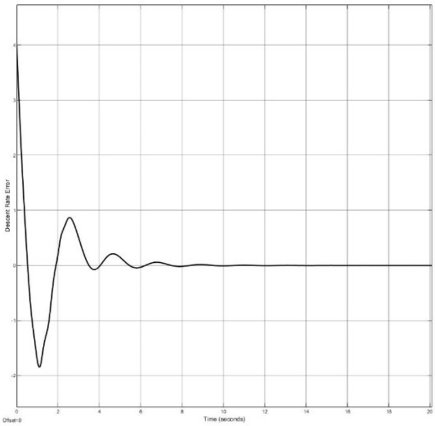

Fig. 17 Descent rate error ($K_p = 1, K_d = 10, K_i = 1$)

6 Conclusion

In this study, yaw, yaw rate and descent rate controllers for parachute landing system are developed and tested in Matlab Simulink environment.

To analyze flight stability, roll and pitch rate are observed during whole flight. According to results, stable flight is provided with all controllers. In the future work, controllers will be implemented for full autonomous flight reaching given target location. The path generation, non-linear controller methods, model predictive controllers and altitude controller for the targets given above the ground plane will be studied. Also, experimental studies will be performed to validate and update the simulation model.

Declarations

Availability of data and materials

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Competing interests

The authors declare that they have no competing interests.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Authors' contributions

K. Güven and A. Şamiloğlu contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

Acknowledgements

Not applicable

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