

# Trajectory Simulation and Fuzzy Control for a Parafoil Payload Delivery System

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## ABSTRACT:

*This paper describes the investigation of simulation and control of an autonomous parafoil payload delivery system based on the fuzzy concept. Modern airdrop systems face the problem of proper delivery of a payload to a desired location well away from the release point. The guidance and control algorithm must be able to give precision landing while being robust and easy to model and work with. Fuzzy logic and control is helpful in this case. Fuzzy logic will also consider the uncertainties in the system and hence ensures reliability. Initially, a conceptual design of the parafoil is made and an appropriate wind model is also generated. Then the mathematical model of the parafoil equations of motions will be formed and they will be solved to determine the attitude and location. With the help of artificial neuro fuzzy inference system, the model will be trained with the available data obtained through the mathematical model. Result of the training is that, when a new desired trajectory is fed into the system, it will perform all the necessary actions to follow that trajectory based on the learning.*

## KEYWORDS:

*Parafoil; Fuzzy control; Trajectory; Uncertainties; Guidance and control*

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## 1. Introduction

A ram-air parafoil is a modern type parachute whose speed and direction can be controlled by the pilot or a control module. A ram-air parafoil is self-inflated through an opening in its leading edge that gives the necessary airfoil shape. Parafoil based aircraft are capable of delivering a wide range of payloads to desired locations and can also be used for other miscellaneous purposes. These parafoils can be released from a particular altitude and distance from the target and from there it will navigate to the desired location. It can also be launched from the ground if it is assisted with a propulsion system. An inexpensive guidance and control module is used along with the payload for autonomous control. The main advantage of parafoils is that they offer easy navigation because of the wing like shape and control surfaces, which is not possible in the case of round parachutes. Kaminer et al [1], used optimal control analysis for real time trajectory generation using a non-linear tracking algorithm.

Slegers et al [9] showed that a model neglecting relative payload yawing failed to predict the same oscillations. It is shown that persistent oscillations can be eliminated by reduction of feedback gains; however, resulting tracking performance is poor. Brandon et al [10] presented a new on-line trajectory planning algorithm that enables a large, autonomous parafoil to robustly execute collision avoidance and precision landing on mapped terrain, even with significant wind uncertainties. This algorithm is designed to handle arbitrary initial altitudes, approach geometries, terrain

surfaces and is robust to wind disturbances which may be highly dynamic throughout the terminal approach. Balaji et al [5] calculated the effect of leading edge cut on the aerodynamic coefficients which is of great help in this research. Slegers et al [5, 8] have inspected various control and guidance strategies for parafoil payload systems. Even though, there have been control systems based on many different approaches their complexity is still a challenge. This paper describes the investigation of simulation and control of an autonomous parafoil payload delivery system based on the Fuzzy logic and control.

## 2. Conceptual design

A conceptual design of the parafoil is carried out to determine, the basic system performance and other aerodynamic parameters as well as the dynamic terms with the help of calculation procedure by Lingard [4]. The initial geometry of the parafoil was estimated with the help of the desired canopy loading, aspect ratio and other performance parameters. NASA LS (1)-0417 airfoil was selected and the aerodynamic coefficients of the parafoil including the anhedral effect were estimated. Using the calculated aerodynamic coefficients, the stall velocity, glide angle and range for particular drop altitudes are estimated for a steady glide assumption. Then, the mass centre, mass moments of inertia and the apparent mass effects were calculated. To be concise, the calculations are skipped and the parameters are shown in Table 1.

Table 1: NASA LS(1)0417 Parafoil characteristics

Parameter	Value
Total mass	110 kg
Wing loading	5 kg/m <sup>2</sup>
Canopy span area	22 m <sup>2</sup>
Aspect ratio	3
Canopy span	8.124 m
Chord	2.708 m
Line length	6.4992 m
I <sub>xx</sub>	822.8348 kg-m <sup>2</sup>
I <sub>yy</sub>	724.5607 kg-m <sup>2</sup>
I <sub>zz</sub>	121.8768 kg-m <sup>2</sup>
I <sub>xz</sub>	5.0811 kg-m <sup>2</sup>

### 3. Parafoil and payload model

The parafoil and payload system is represented by a 6-DOF system consisting of the three inertial positions of the parafoil-payload mass center and the three Euler orientation angles. The velocities with respect to Earth axis (Earth fixed co-ordinate system with the target fixed as origin) are given as follows,

$$\{\dot{x} \dot{y} \dot{z}\} = T^T \{u v w\} \quad (1)$$

$$\{\dot{\phi} \dot{\theta} \dot{\psi}\} = \begin{bmatrix} 1 & s_\phi t_\theta c_\phi t_\psi & 0 & c_\phi - s_\phi 0 & \frac{s_\phi}{c_\phi} & \frac{c_\phi}{c_\theta} \end{bmatrix} \{p q r\} \quad (2)$$

The accelerations with respect to Earth axis are given as,

$$\{\ddot{u} \ddot{v} \ddot{w}\} = \frac{1}{W} (F_{AE} + F_W) - T S_\omega T^T \{u v w\} \quad (3)$$

$$\{\ddot{p} \ddot{q} \ddot{r}\} = I_T^{-1} (M_{AE} - S_\omega I_T \{p q r\}) \quad (4)$$

The aerodynamic forces and moments are derived using the following,

$$F_{AE} = \frac{1}{2} \rho S V_A (C_{L0} + C_{L\alpha} \alpha + C_{L\delta a} \delta_a) \{w 0 - u\} - \frac{1}{2} \quad (5)$$

$$M_{AE} = \frac{1}{2} \rho S V_A^2 \left\{ C_{l\phi} \bar{b} \phi + \frac{C_{lp} \bar{b}^2 p}{2V_A} + \frac{C_{l\delta a} \bar{b} \delta_a}{d} C_{m0} \bar{c} + C_n \right\} \quad (6)$$

The transformation matrices are given as follows,

$$T = \begin{bmatrix} c_\theta c_\psi & c_\theta s_\psi & -s_\theta & s_\phi s_\theta c_\psi & -c_\phi s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\theta s_\phi \\ c_\theta s_\psi & c_\theta c_\psi & s_\theta & s_\phi s_\theta s_\psi & c_\phi c_\psi & s_\phi s_\theta c_\psi & c_\theta c_\phi \\ -s_\theta & s_\theta & c_\theta & s_\phi c_\theta & -c_\phi & s_\phi s_\theta & c_\phi c_\theta \end{bmatrix} \quad (7)$$

$$S_\omega = [0 \quad -r q r \quad 0 \quad -p \quad -q p \quad 0] \quad (8)$$

Mass moments of inertia matrix and the weight vector are obtained as follows,

$$I_T = \begin{bmatrix} I_{xx} & 0 & I_{xz} & 0 & I_{yy} & 0 & I_{yz} & 0 & I_{zz} \end{bmatrix} \quad (9)$$

$$F_W = W g \{-s_\theta s_\phi c_\theta c_\phi c_\psi\} \quad (10)$$

Forces and moments due to apparent mass effects are,

$$F_A = -A\dot{u} - Cwq + Bvr \quad (11)$$

$$F_B = -B\dot{v} - Aur + Cwp \quad (12)$$

$$F_C = -A\dot{w} - BVp + Auq \quad (13)$$

$$M_A = -I_A \dot{p} - (I_C - I_B)qr - (C - B)wv \quad (14)$$

$$M_B = -I_A \dot{q} - (I_A - I_C)rp - (A - C)uw \quad (15)$$

$$M_C = -I_A \dot{r} - (I_B - I_A)pq - (B - A)uv \quad (16)$$

Parafoil is easily affected by the wind. Hence, knowledge about the wind profile is necessary to achieve proper control. Future wind profile through the atmosphere is predicted with the help of periodic radiosonde data through Auto Regressive Moving Average (ARMA). Here, radiosonde data for the Chennai station for the years 2012, 2013 and 2014 is used for forecasting. Apparent mass is defined as the quantity having the dimensions of mass that is added to a body moving non-uniformly in a fluid medium in order to consider the effect of the medium on the body. For airplanes, it is negligible because of high wing loading, but for parafoil, the canopy loading is less than 5 kg/m<sup>2</sup> and hence, these terms have to be considered. The apparent mass terms are calculated with the help of empirical relations provided by Lissaman and Brown [3] who modeled the Parafoil as a cylindrical body. The calculated parameters are summarised in Table 2.

Table 2: Apparent mass effects

Description	Symbol	Value	Unit
Surge term	A	25.54172	kg
Side slip term	B	3.9316	kg
Plunge term	C	34.86231	kg
Roll term	IA	139.6911	kg-m <sup>2</sup>
Pitch term	IB	9.009351	kg-m <sup>2</sup>
Yaw term	IC	141.631	kg-m <sup>2</sup>

### 4. Fuzzy logic and control

Fuzzy logic is revolutionary in modern control technology. The simplicity of the control module is very promising in the development of control systems for complicated systems whose mathematical governing equations are difficult to solve or the non-linearity of the system is very high. Unlike the classical control theory, fuzzy control takes membership values between 0-1 i.e. instead of verifying whether true or false; it looks for the trueness of a membership. Fuzzy logic controllers are used particularly for non-linear dynamic systems where there are multiple inputs and multiple outputs. Fuzzy logic algorithms contain elements of the human way of thinking and problem solving. The control systems are trained with human experience and the system decides how to control based on this learning experience. The non-linear characteristic of a fuzzy control contributes to higher robustness of the system. A membership function of a set is a function that assigns values or membership degree to every member belonging to the set. Then that set is known as a fuzzy set. Humans are used to linguistic terms for values like near, far, very far, high, low, very low etc. In a similar manner, these linguistic variables can be used in implementing control. These are better

than using numerical values that do not replicate human intelligence.

Knowing the forward kinematics of a system, the inverse kinematics of the system can be deduced with the help of a fuzzy inference system constructed using fuzzy logic. Though it is difficult to obtain expressions for inverse kinematics of the mathematical equations of motion due to coupling effects; it is however easier to obtain the forward kinematics data through mere calculations. This data will give out the position and orientation with respect to the flap deflection angle, angle of attack, wind speed and direction, sideslip etc. This data is used for ANFIS (adaptive neuro-fuzzy inference system) network. The learning abilities of neural networks are brought into fuzzy logic using ANFIS. It trains the membership functions with the help of input-output data.

## 5. Results and discussion

The simulation was carried out for two cases, case (i) glide and loiter, case (ii) loiter and glide. The co-ordinates of the trajectory are given and the trained ANFIS determines the control surface deflections to follow the desired trajectory taking the effect of wind into account. Case (i): glide and loiter; release point (8000m, 4000m, 3800m), target point (500m, 500m, 0m) from an arbitrary reference point. From Fig. 1, we can see that the parafoil follows the desired path with very less deviations. However, the deviations are larger in case of with wind simulation, whereas in the case of without wind simulation (neglecting wind effects) the deviations are much less. Case (ii): loiter and glide; release point (2000m, 2000m, 3800m), target point (500m, 500m, 0m) from an arbitrary reference point. From Fig. 2 also we can see that there are not large deviations from the desired path. Hence, irrespective of the type of trajectory, this type of control would give out good results. Fig. 3 shows the error between the coordinates of desired and actual trajectories and it is clear that the errors are small compared to the domain and the maximum deviation is about 50m.

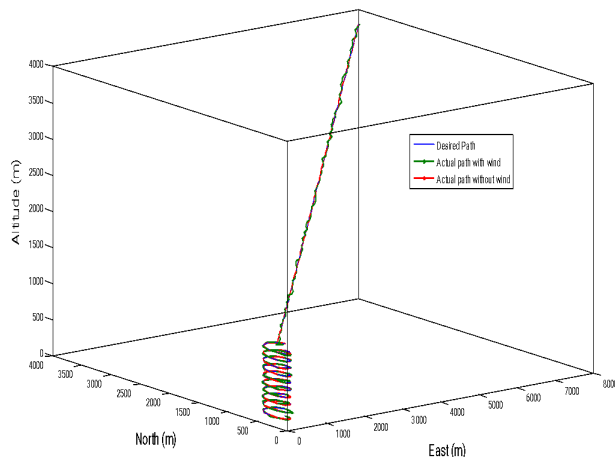


Fig. 1: Simulation for case (i): glide and loiter

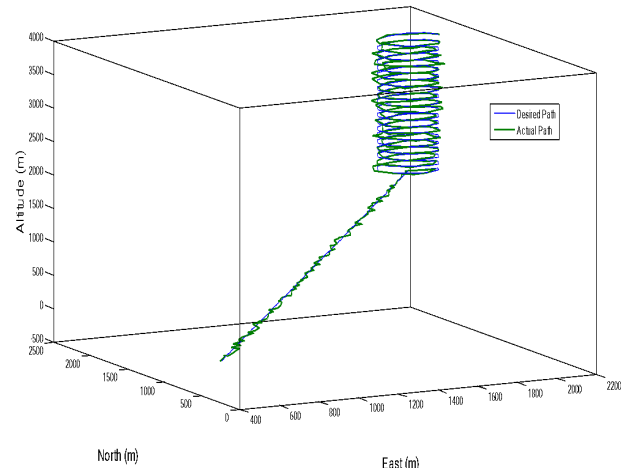


Fig. 2: Simulation for case(ii): loiter and glide

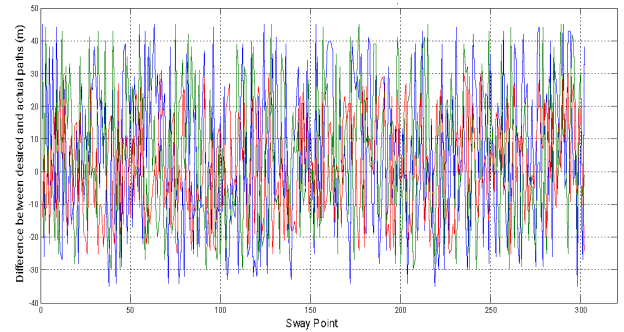


Fig. 3: Error between desired (Red) and actual (Blue) paths

## 6. Conclusion

After conceptual design of the airfoil for the aerodynamic coefficients and mathematical modelling of the parafoil payload system followed by wind estimation, the system is subjected to ANFIS training and the results of the simulation are obtained. From the results, we can see that the parafoil system follows the trajectory very well. After analysing the different cases, we can see that the parafoil performs well without much deviation from the selected course. Even though there is an error of 10 ~ 50m between the desired and the actual path followed based on the estimated control sequence, it is less compared to the actual domain of operation. Most of the landing spots are well within a 100m radius, however offsets of a few trials are very large and that has to be overcome by proper training. The deviations between the desired path and the parafoil path are very less and hence fuzzy logic is useful in the control of the parafoil-payload delivery system. Moreover, it is easy to update or modify the control algorithm or place more levels of operation over the existing model.

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