Path Tracking and Obstacle Avoidance of UAVs - Fuzzy Logic Approach

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Abstract

This paper addresses the problem of how to make a UAV track a given flight trajectory while at the same time avoid unexpected obstacle(s). If the information about the existence of the obstacle is known in advance, the problem can be readily solved by carefully pre-planning the desired flight path for the vehicle. However, obstacle(s) might appear unexpectedly in practical applications, as such the pre-planned flight path might become "misleading" to the vehicle if no correcting action is taken. Furthermore, obstacles might be of any shape (not necessarily a point mass) and might be either inert or hostile (including seeking a collision). How to avoid unexpected, irregular, even moving obstacles while maintaining close path tracking of UAV is an interesting yet challenging problem.

In this paper, we explore fuzzy logic based approach to path tracking and obstacle avoiding. We consider the case that obstacles are either still or moving and appear along the pre-determined flight path unexpectedly. By using suitable sensors we identify the relative distance between the vehicle and the obstacle and make timely adjustment to the pre-planned flight path. Fuzzy logic control algorithms are developed to achieve close path tracking while avoiding obstacles. Simulation studies on multiple obstacles with various shapes are conducted and the effectiveness of the proposed method is verified.

Keywords: UAV, path planning, obstacle avoidance, control, stability, and fuzzy logic

1. Introduction

Unmanned Aerial Vehicles (UAVs) have attracted increasing attention in the military and civilian applications, such as mapping, patrolling, search and rescue, and reconnaissance. These tasks may be repetitive, dangerous, or both, making UAVs the ideal tools [1]-[4]. In these types of applications, the following issues are fundamental:

1. Path tracking.
2. Obstacle avoidance (including collision avoidance with other aircrafts).

In this paper we consider the following problem:

How to make a UAV track a given flight trajectory while at the same time avoid unexpected obstacle(s)?

If the information about the existence of the obstacle is known in advance, then the problem can be readily solved by carefully pre-planning the desired flight path for the vehicle [3]-[5]

Recently, some methods of UAV navigation for obstacle avoidance have been reported [6]-[8]. Note that the in [6] only a single point mass obstacle is considered. In [7]-[8], no moving obstacle is addressed.

Note that most of the real situation is that more than one obstacle might appear unexpectedly, as such the pre-designed path might become "misleading" to the vehicle if no correcting action is taken. Furthermore, obstacles may be of any shape (not necessarily a point mass) and may be either inert or hostile (including seeking a collision). How to avoid unexpected, irregular, even moving obstacles while maintaining close path tracking of UAV is a challenging problem.

In this paper, we explore a fuzzy logic based approach to path tracking and obstacle avoiding. We consider the case that obstacles are either still or moving and appear along the pre-determined flight path unexpectedly. By using suitable sensors we identify the relative distance between the vehicle and the obstacle and make timely adjustment to the pre-planned flight path. Fuzzy logic control algorithms are developed to achieve close path tracking while avoiding obstacles.

An interesting feature of fuzzy control system is that it is easy to deal with uncertain situations by representing the input and output relation in the "*if-then*" manner and constructing knowledge base. The relation between inputs and outputs in fuzzy rules is shown in Figure 1:

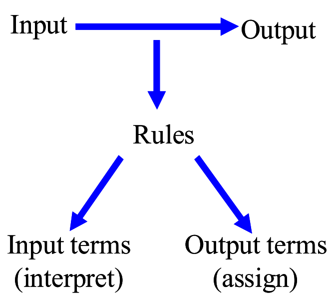

Figure 1. Fuzzy Rules Block

Due to the ability to handle unknown conditions, fuzzy logic system is an ideal tool to address the obstacle avoidance problem. In this paper we combine model-based control with fuzzy logic control for UAV navigation in the presence of stationary, or moving obstacles. This method provides a function for avoiding stationary and moving obstacles by sensing the distance and the angle between the UAV and the obstacles. Once an obstacle has been detected, the previous flight path is corrected to ensure safe flight while minimizing the deviation of UAV from the pre-planned path. Simulation studies on multiple obstacles with various shapes are conducted and the effectiveness of the proposed method is verified.

2. Model-based Control

We consider the problem of UAV trajectory tracking without detail information about the flight environment – only the position of the UAV is available from a GPS (Global Position System) receiver. We assume that the obstacles can be detected by a UAV obstacle sensor. The sensor range is shown in Figure 2.

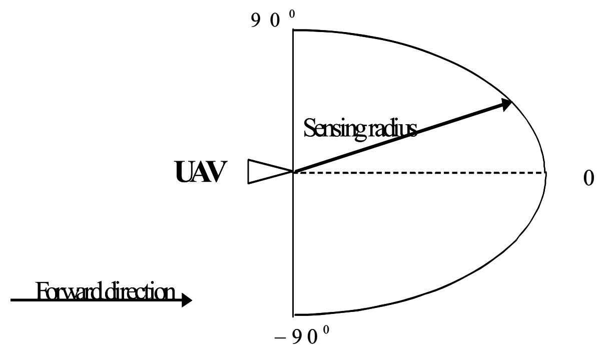

Figure 2. Sensor range of UAV

We are interested in controlling heading speed and heading angle of UAV, as described by [9]:

$$\begin{aligned} \dot{v} &= -\frac{1}{\tau_v} v + \frac{1}{\tau_v} v_c, \\ \ddot{\theta} &= \frac{1}{\tau_\theta} \dot{\theta} + \frac{1}{\tau_\theta} \theta_c, \end{aligned} \tag{1}$$

where v_c and θ_c are the commanded velocity and heading angle to the autopilots. τ_v and τ_θ are the time constants of aircraft autopilot system.

We reconstruct the UAV system equations in two-dimension coordinate shown in Figure 3. From the coordinate, we have

$$\begin{cases} x = l\cos\theta \\ y = l\sin\theta \end{cases}, \quad (2)$$

where $\dot{l} = v$, in which l is the distance between the UAV and the departure point, x and y are the horizontal and vertical distance between UAV and the departure point respectively. Clearly we have

$$\begin{cases} \dot{x} = v\cos\theta - (l\sin\theta)\dot{\theta} \\ \dot{y} = v\sin\theta + (l\cos\theta)\dot{\theta} \end{cases}, \quad (3)$$

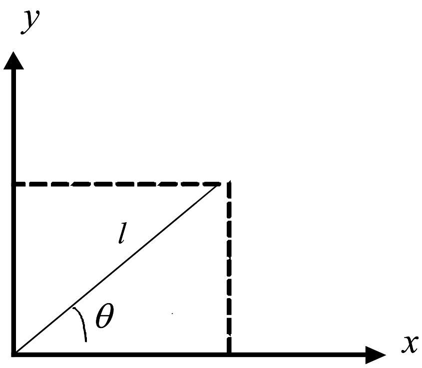

Figure 3. UAV in Inertial Frame

By defining

$$X = \begin{pmatrix} x \\ y \end{pmatrix},$$

and

$$J = \begin{pmatrix} \cos\theta & -l\sin\theta \\ \sin\theta & l\cos\theta \end{pmatrix},$$

we get

$$\dot{X} = J\begin{pmatrix} v \\ \dot{\theta} \end{pmatrix}. \quad (4)$$

and

$$\ddot{X} = \dot{J}\begin{pmatrix} v \\ \dot{\theta} \end{pmatrix} + J\begin{pmatrix} \dot{v} \\ \ddot{\theta} \end{pmatrix}, \quad (5)$$

where

$$\dot{J} = \begin{pmatrix} -\sin\theta\dot{\theta} & -v\sin\theta - l\cos\theta\dot{\theta} \\ \cos\theta\dot{\theta} & v\cos\theta - l\sin\theta\dot{\theta} \end{pmatrix}.$$

Combining (1) and (5) leads to

$$\ddot{X} = F + GU, \quad (6)$$

where

$$F = \left(\dot{J} + \begin{pmatrix} -1/\tau_v & 0 \\ 0 & 1/\tau_\theta \end{pmatrix} \right) \begin{pmatrix} v \\ \dot{\theta} \end{pmatrix},$$

$$G = \begin{pmatrix} 1/\tau_v & 0 \\ 0 & 1/\tau_\theta \end{pmatrix} \text{ and } U = \begin{pmatrix} v_c \\ \theta_c \end{pmatrix}.$$

The control objective is to design the control input U such that the actual flight path tracks the desired trajectory, i.e., $X \to X^*$, where $X^* = \begin{pmatrix} x^* \\ y^* \end{pmatrix}$ while avoiding the unexpected obstacle. For this purpose, we define the tracking error

$$E = X - X^*. \quad (7)$$

The model based control law is designed by

$$U = G^{-1}(-kE - F - X^*). \quad (8)$$

It can be readily shown that the control scheme (8) is able to drive the tracking error E to zero asymptotically.

3. Fuzzy Logic Controller

The Fuzzy Logic Controller is activated when the obstacle sensor detects any obstacle. The FLC will generate UAV velocity and heading angle change corresponding to different situations.

The fuzzy control rules are given in the following form:

Rule i: if d is F_d^i and α is F_α^i, then u is ρ_i, where ρ_i, $i = 1, 2, \cdots, n$ are the singleton control actions and F_d^i and F_α^i are the labels of the fuzzy sets.

The defuzzification of the controller outputs is accomplished by the method of center of gravity:

$$U_{flc}[d,\alpha,\rho_i]=\frac{\sum_{i=1}^{n}\phi_i\times\rho_i}{\sum_{i=1}^{n}\phi_i} \qquad (9)$$

where ϕ_i is the firing weights of the ith rule. d is the distance from obstacle and α is the angle with expect to the obstacle. The fuzzy rules can be constructed by two parameters-their distance d from obstacles and their angle α from obstacle. The distance d is in feet from the center of UAV. A distance of approximately 150 feet indicates that UAV is safe. The angle α of approximately $\pm\pi/4$ is safe angle for UAV avoiding obstacles without large overshoot.

With the model-based controller and fuzzy logic controller, the UAV system block diagram is shown in Figure 4.

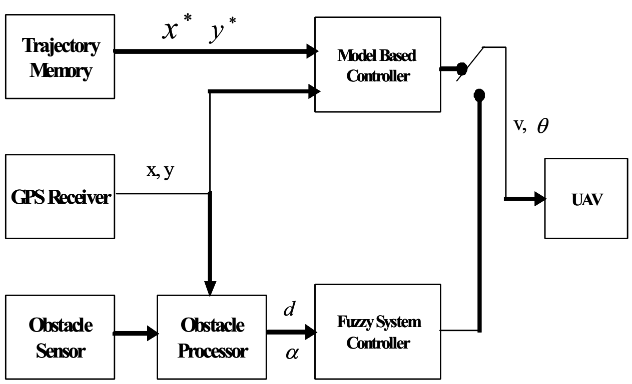

Figure 4. Block Diagram of UAV Control System

The rule base is constructed based on human experience. Here in this case triangular membership functions have been chosen. Changing the membership function would change the performance of the system.

The inputs variables "d" in this system can be divided into a range of "states", such as: "Danger", "Alert", "Medium" and "Safe", "α" divided into "Negative Leaving", "Negative Fit", "Negative Heading", "Positive Heading", 'Positive Fit" and "Positive Leaving". The outputs velocity change can be divided into "Very Slow", "Slow", "Medium", and "High" and the change of the heading angle can be divided into "Negative Large", "Negative Medium", "Negative Small", "No Change", "Positive Small", "Positive Medium" and "Positive Large". We define the inputs and outputs states using "membership functions" shown as Figures (5), (6), (7) and (8):

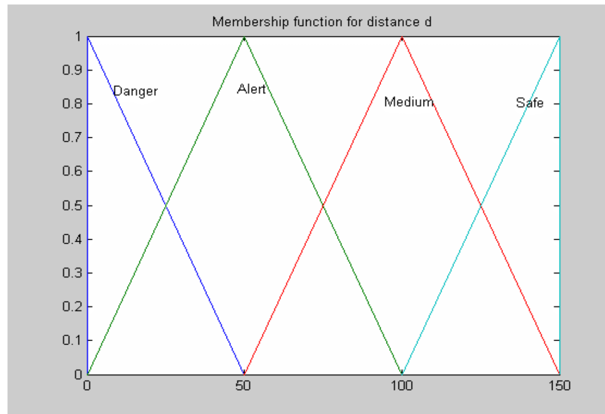

Figure 5. Input Variable Distance d

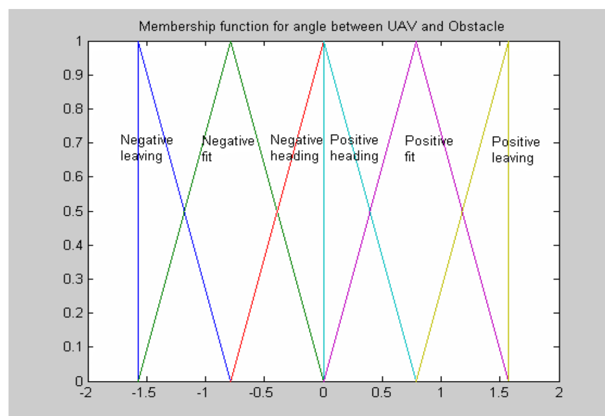

Figure 6. Input Variable Angle α

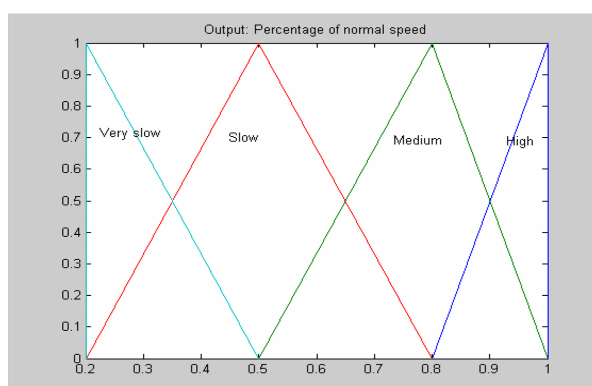

Figure 7. Output Variable Velocity v_c

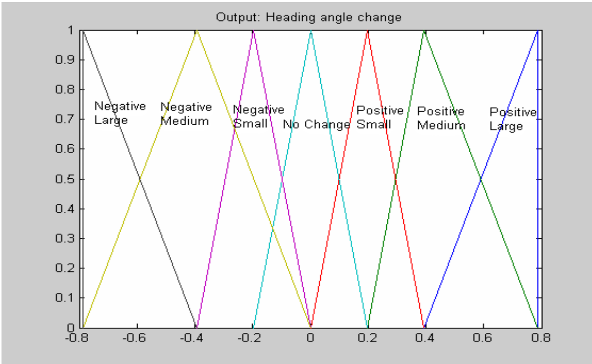

Figure 8. Output Variable Heading Angle θ_c

Using the knowledge base we develop the " *if …and…then* " fuzzy control rules as described in Table 1 (velocity change) and Table 2 (heading angle change) for the fuzzy outputs.

Table 1. Output Velocity Change

In 2 / In 1	PL	PF	PH	NH	NF	NL
S	H	H	M	M	H	H
M	M	M	S	S	M	M
A	S	V	V	V	V	S
D	V	V	V	V	V	V

Table 2. Output Heading Angle Change

In 2 / In 1	PL	PF	PH	NH	NF	NL
S	PS	O	NS	PS	O	NS
M	PS	O	NM	PM	O	NS
A	O	NS	NL	PL	PS	O
D	NS	NM	NL	PL	PM	PS

4. Simulation Results

To test the effectiveness of the developed strategy, we conduct simulation on the path tracking in the presence of obstacles with various shapes. The path tracking process is shown in Figures 9(a), (b), (c) and (d). As can be seen, the control strategy works fairly well for single obstacle and multi-obstacles appearing unexpectedly.

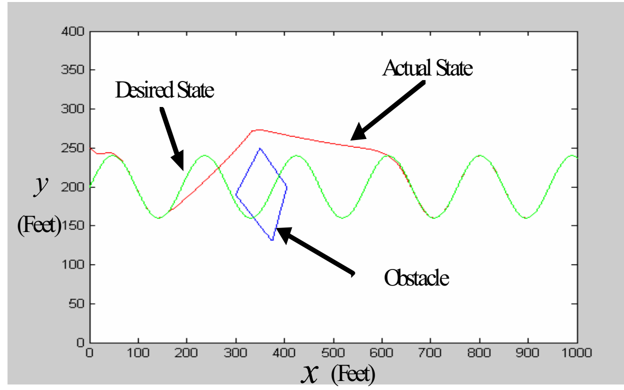

Figure 9 (a). Tracking with One Obstacle – Shape 1

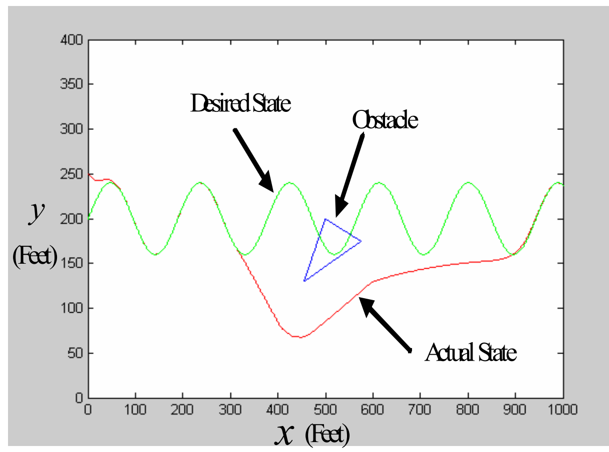

Figure 9 (b). Tracking with One Obstacle- Shape 2

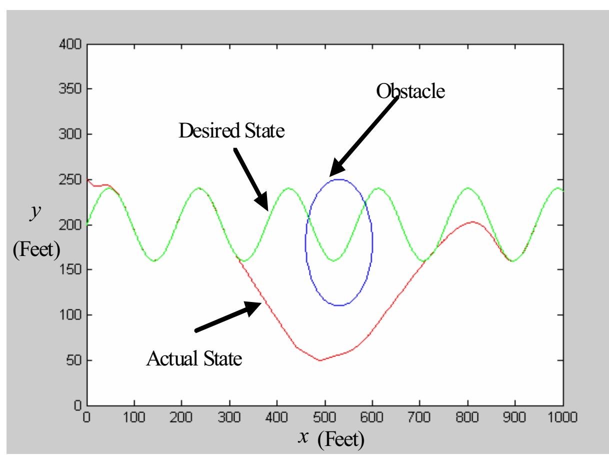

Figure 9 (c). Tracking with One Obstacle- Shape 3

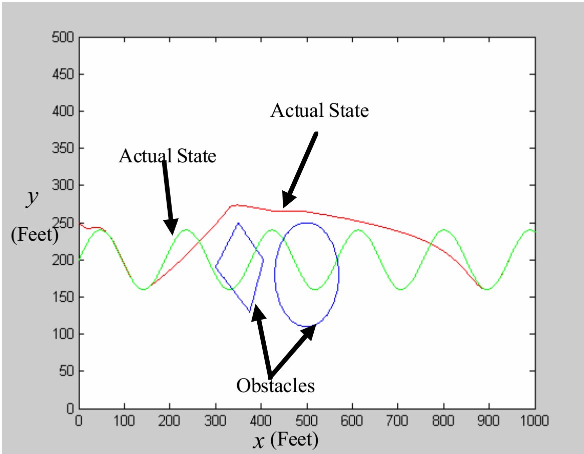

Figure 9 (d). Tracking with Two Obstacles Appearing along a the Same Line

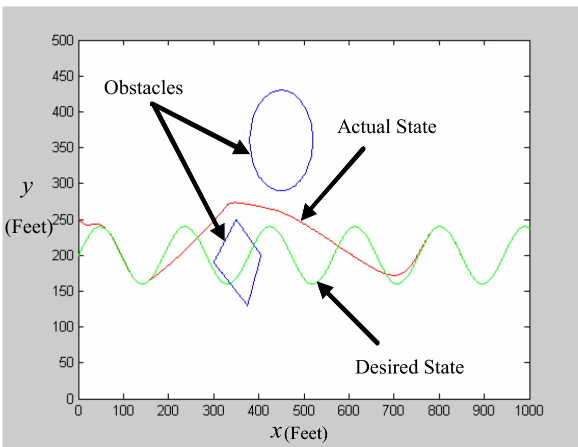

Figure 9 (e). Tracking with Two Obstacles Appearing along both Sides of the Flight Path

5. Conclusion

This paper presented a fuzzy logic approach to path tracking and multi-obstacle avoidance. A two-layered FLC was used to make the UAV track its path while avoiding the fixed, but unexpected obstacles. The sensor inputs were fed in as random values and the desired output values were obtained. Simulation indicates the effectiveness of the proposed method.

Acknowledgement

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