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**FUZZY LOGIC TRAJECTORY DESIGN AND GUIDANCE FOR TERMINAL AREA
ENERGY MANAGEMENT**

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Introduction

The second generation reusable launch vehicle will leverage many new technologies to make flight to low earth orbit safer and more cost effective. One important capability will be completely autonomous flight during reentry and landing, thus making it unnecessary to man the vehicle for cargo missions with stringent weight constraints. Implementation of sophisticated new guidance and control methods will enable the vehicle to return to earth under less than favorable conditions.

The return to earth consists of three phases--Entry, Terminal Area Energy Management (TAEM), and Approach and Landing. The Space Shuttle is programmed to fly all three phases of flight automatically, and under normal circumstances the astronaut-pilot takes manual control only during the Approach and Landing phase. The automatic control algorithms used in the Shuttle for TAEM and Approach and Landing have been developed over the past 30 years. They are computationally efficient, and based on careful study of the spacecraft's flight dynamics, and heuristic reasoning. The gliding return trajectory is planned prior to the mission, and only minor adjustments are made during flight for perturbations in the vehicle energy state.

With the advent of the X-33 and X-34 technology demonstration vehicles, several authors investigated implementing advanced control methods to provide autonomous real-time design of gliding return trajectories thus enhancing the ability of the vehicle to adjust to unusual energy states. [2-7] The bulk of work published to date deals primarily with the approach and landing phase of flight where changes in heading angle are small, and range to the runway is monotonically decreasing. These benign flight conditions allow for model simplification and fairly straightforward optimization. This project focuses on the TAEM phase of flight where mathematically precise methods have produced limited results. Fuzzy Logic methods are used to make onboard autonomous gliding return trajectory design robust to a wider energy envelope, and the possibility of control surface failures, thus increasing the flexibility of unmanned gliding recovery and landing.

Fuzzy Logic Trajectory Design and Guidance

Human beings perform a wide variety of complex tasks in every day life without precise mathematical calculations. One apt example is driving an automobile. The human operator readily adapts to different vehicles, and moves the controls to precisely navigate the vehicle without calculating steering angles, pedal pressures, etc. Fuzzy Logic methods provide a method to formalize proven human knowledge into an autonomous algorithm making it unnecessary for precise math models or dynamic inversion of a plant. [9] Fuzzy Logic control has been used in a wide array of applications including approach and landing control of a light aircraft [8]

A simplified dynamic model of a gliding aircraft can be found by treating the vehicle as a point mass, and applying the conservation of linear momentum. The resulting equations are lightly coupled and can be divided into three channels. Vehicle ground track is controlled primarily by bank angle ϕ , the altitude is controlled by normal acceleration N_Z , and the dynamic pressure $\bar{q} = 1/2\rho V^2$ is controlled by either changing the flight path angle γ , or changing the coefficient of drag C_D , by extending drag devices.

Next, each channel of the trajectory is constrained to a shape that intentionally limits the number of parameters needed to describe it. For example, we constrain the ground path to a minimum maneuver trajectory consisting of a shortest direction acquisition turn, a straight portion, and a base to final heading alignment turn (HAC). Each turn is designed as a circular arc. Finally, for each channel, important parameters defining the trajectory are determined through a Fuzzy Logic decision. The adjustable parameters in the horizontal channel are the heading alignment turn radius (YHAC), and position from the runway threshold (XHAC). The vertical trajectory is constrained by initial and final conditions. The spacecraft must reach the Auto-Land Interface (ALI) at approximately 10,000 ft above the runway, 20,000 ft from the runway threshold at a flight path angle depressed 30 degrees from horizontal. To maintain continuity through the trajectory, the vertical path is defined as a cubic polynomial which intersects the ALI at the appropriate altitude and slope. The coefficient on the quadratic term (CUBIC3) of this cubic is adjusted to provide a smooth path from the current state to ALI. We designed a two-input three-output fuzzy inference system to determine XHAC, YHAC, and CUBIC3 based on the spacecraft current energy state, and control surface health. The inputs are the quotient of energy over predicted downrange distance to ALI, and an integer denoting the degree of control surface health. This decision is based on twenty rules which essentially enlarge the turn radius for high energy states or poor maneuverability, or shorten the final approach length and lower the vertical path profile for lower energy states.

The bank guidance commands are generated by dividing the TAEM phase into four sub-phases, then applying rules appropriate to the variables of interest during each phase. The sub-phases are Acquisition, HAC Turn, and Pre-Final. This division is identical to Shuttle TAEM [10]. In acquisition phase, the spacecraft uses maximum available bank to turn in the shortest direction to point directly at the center of the HAC turn. Once the spacecraft is pointing at the center of the HAC turn, a set of 89 rules are used to intercept and fly the HAC. These rules are based on the author's own experience totaling more than 2000 hours of flight in military jet aircraft. For instance, many instrument approach procedures require the pilot to fly a circular arc around a VHF Omnidirectional Range with Distance Measuring Equipment. In order to fly such an arc, the pilot considers his distance from the station, and relative bearing and adjusts bank angle accordingly. [1] In the pre-final phase, bank is determined from a combination of distance from runway centerline and component of horizontal velocity orthogonal to runway centerline.

The normal acceleration guidance uses altitude error and vertical velocity error to generate commands up to $\pm 1/2$ g and restore the vehicle to the desired glidepath. During supersonic flight, the X-33 speed brake remains closed, and the normal acceleration guidance overrides flight path angle corrections as necessary to keep the dynamic pressure from exceeding nominal limits. During all phases of flight, the fuzzy guidance will generate a nose-down command if the dynamic pressure approaches the stall limit. For this work, we use the existing X-33 speed brake guidance

Results

The fuzzy inference systems described above were rapidly prototyped, tuned, and tested using Matlab and the Fuzzy Logic Toolbox. The simplified three degree of freedom dynamics described in the previous section were programmed in Matlab and served as a realistic model of

a reusable launch vehicle in the TAEM phase. After obtaining satisfactory results that demonstrated robustness to varying initial conditions and degrees of control surface health, we integrated our fuzzy systems with a high fidelity six degree of freedom simulation available at Marshall. Limited further tuning was required to replicate the results obtained in Matlab. A low pass filter was added to the bank commands to inhibit control saturation resulting in instability. Normal acceleration commands were multiplied by the reciprocal of the cosine of pitch angle

The ground track and bank angle of four high fidelity simulations are shown in Figure 1. The solid lines represent the trajectory with full flight control health. Dotted lines represent the trajectory when flight controls are degraded such that bank angle is limited to 36 degrees. The axes on the ground track plot do not have equal scaling so that differences are emphasized. Current entry guidance will provide a heading perturbation at TAEM interface of ± 10 degrees. Note that we have varied the initial heading by ± 30 degrees, thereby creating an energy initial state lower than nominal. All four cases reach a successful landing at 1500 to 2500 feet from the runway threshold.

One fascinating discovery is that the filters have complimentary effects although each channel was designed separately. For example, for a case with flight control limitations, and nominal initial energy, the trajectory designer will direct a wide radius HAC. The ground track predictor then computes a longer than normal ground track. Subsequently, the normal acceleration guidance keeps the flight path angle shallow during the acquisition phase of flight.

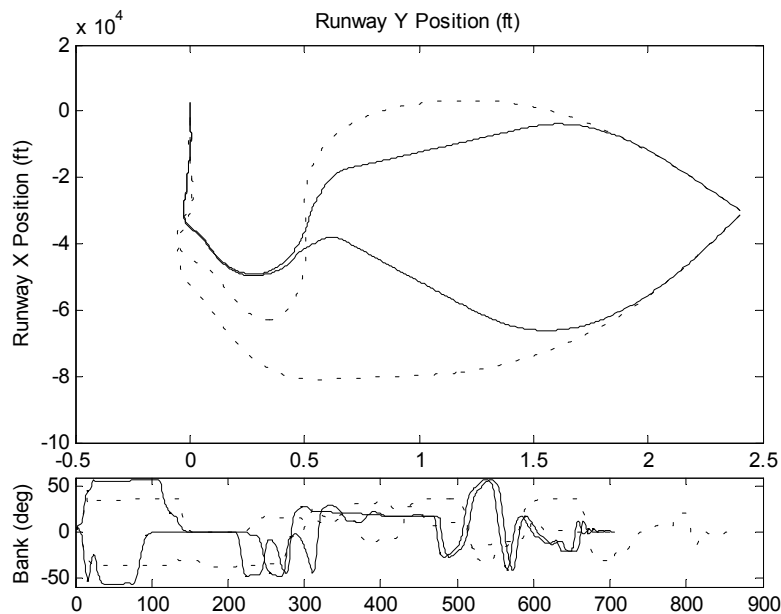


Figure 1: Vehicle Ground Track and Bank Angle Using Fuzzy Trajectory Design

This is then advantageous to the bank guidance since the spacecraft will reach subsonic flight sooner, and will thus be ready to intercept the HAC.

Conclusions

Fuzzy logic control is extremely powerful for control of complex systems without precise models. By applying the knowledge from Shuttle TAEM guidance and the author's own flight experience, we have developed an algorithm to design and fly gliding return trajectories for varying initial energy conditions and degrees of control surface integrity.

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