Effect of Torque Reactuation

If the above analysis is repeated but pointing torques are "reactuated" into a gimbal reaction wheel rather than the host spacecraft (Ref. 1), then the coupling with the host spacecraft occurs only through the translational admittance H_{vv}. The pole-zero spacing, expression (10), then reduces to

$$\frac{(P-Z)_p}{\omega_p} \cong \frac{1}{2}\frac{RA}{1+R} \tag{15}$$

This pole-zero spacing may be greater, or less, than for the unreactuated case [Eq. (10)] depending upon the sign of the parameter B in Eq. (10). This is contrary to what is implied by the argument presented in Ref. 1, which was based upon a single simple example. What is clear from Eqs. (15) and (10) is that torque reactuation helps in achieving pole-zero cancellation of flexible host spacecraft dynamics only if B is positive; i.e., the spacecraft modal deflection (parallel to the direction v in Fig. 1) and the modal slope about the gimbal axis are of the same sign. There is no reason to expect this to be generally the case.

Extension to Three-Dimensional Case

Consider now the three-dimensional case, in which a general inertia distribution as well as a general offset of the CG are allowed for the articulated rigid-body. The articulation at the hinge is in this case defined by two angles. The displacement components are u, v, w. The inertia matrix J is a 3×3 matrix with nonzero off-diagonal elements, and the offset from a reference point on the gimbal axes to the payload mass center has three components. As before, one can define the parameters $A(i, j, k) = (m/\bar{m}_j)\Phi_i\Phi_k$, the parameters $B(i, j, k, l) = (md_l/\bar{c}_j)\Phi_i'\Phi_k'$, and the parameters $R(l, m, n) = md_l^2/J_{mn}$, where $(i, j) = u, v, w$ and $(l, m, n) = 1, 2, 3$. The set $\{A, B, C, D, R\}$, in this case, is of higher dimension. With such a large parameter set, it may be best to work directly with the three-dimensional equivalent of Eq. (4). This equation yields the 2×2 matrix of pointing transfer functions from a modal analysis of the host spacecraft not loaded with the payload. As in the two-dimensional case, one can examine the features of the dynamic coupling in the frequency domain in terms of the effect upon the pointing dynamics. The full analysis for the Space Shuttle's MACE is reported in Ref. 3.

Conclusions

This Note has discussed the transfer function from gimbal torque to inertial pointing angle of a dynamic system composed of a rigid articulated body mounted through a frictionless gimbal on a flexible spacecraft. This transfer function is shown to be slightly modified by spacecraft flexibility. The results of the analysis are useful in the design process. The idea of introducing a reactionless gimbal actuator, as proposed in Ref. 1, has also been revisited. A class of dimensionless parameters has been identified that defines the problem.

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Performance Evaluation of Two Fuzzy-Logic-Based Homing Guidance Schemes

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Introduction

In this Note, homing guidance schemes based on fuzzy logic have been developed for a planar engagement model, with randomly jinking target maneuver and line-of-sight (LOS) rate measurement corrupted with glint noise. Two versions of fuzzy guidance schemes have been proposed, the first one using information required for proportional navigation (PN) and the second one using the information required for augmented PN(APN). The performance of the two fuzzy guidance schemes, in terms of commanded acceleration profiles and the values of the terminal miss distance, have been compared with PN and APN, respectively. It is observed that the fuzzy guidance schemes are able to match closely the performance of PN and APN guidance laws, and in cases where the measurements are noisy and the estimates are inaccurate, the fuzzy guidance schemes are shown to perform better than PN and APN.

Fuzzy-Logic-Based Homing Guidance Schemes

The guidance schemes based on fuzzy logic presented here differ in terms of the input variables required for their implementation.

Scheme 1: Proportional Navigation Based

The PN guidance law requires closing velocity V_c and LOS rate $\dot{\lambda}$ information. Using these two measurements, the first fuzzy guidance scheme (FGS-1) has been developed.

The input and output variables of a fuzzy system are called linguistic variables, as they take linguistic values (e.g., large, small, very large, small positive, large negative, etc.). The input linguistic variables of FGS-1 are P $(= V_c\dot{\lambda})$ and PC $(= \textit{change in } P = P_{\text{present}} - P_{\text{previous}})$ and the output variable is a_C (commanded acceleration). The normalized universe of discourse for all of the above three linguistic variables is $[-1, +1]$.

The linguistic values taken by these variables are expressed by linguistic sets. Each of the above-mentioned three linguistic variables is assumed to take seven linguistic values as defined:

LN = large negative
LP = large positive
MN = medium negative
MP = medium positive
SN = small negative
SP = small positive
ZE = zero

The linguistic sets are described by their membership functions. For simplicity, triangular membership functions as described in Ref. 1 have been used. Apart from the above linguistic sets, one more linguistic set, ANY, has been assumed for all the three variables. ANY has a membership function of 1.0 at every element.[1]

In fuzzy logic control, system behavior is characterized by a set of linguistic rules. These rules usually take the form IF (antecedent) THEN (consequent) and can be derived from different sources.[2] A great deal of experimentation and trial and error are needed to firm up on the final set of rules. After some experimentation, a set of 15

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rules has been finalized for FGS-1. For illustration, a sample rule is given below:

If P is MN and PC is SP then a_C is SN.

Although the outputs of the linguistic rules are fuzzy, the control input to the plant must be crisp. Therefore, the output of the linguistic rules must be defuzzified before feeding into the plant. The crisp control action is calculated using the center of area defuzzification procedure.[2]

Scheme 2: Augmented Proportional Navigation Based

The second fuzzy guidance scheme (FGS-2) follows the APN guidance law, which requires the target acceleration information in addition to the closing velocity and LOS rate information.

For FGS-2, the input linguistic variables are P ($= V_c\dot{\lambda}$) and a_T (target acceleration) and the output variable is a_C (commanded acceleration). Like FGS-1, the normalized universe of discourse for each of the above three linguistic variables is $[-1, +1]$. For all of these variables, five linguistic sets (LN, SN, ZE, SP, LP) have been considered and triangular membership functions have been assumed. A set of 25 linguistic rules has been finalized for FGS-2. For illustration, a sample rule is given below:

If P is LP and a_T is SN then a_C is SP.

To calculate the crisp control action from the fuzzy output of the linguistic rules, the same center of area defuzzification procedure has been used.

Simulation Results

Engagement Model

The fuzzy guidance schemes have been simulated for a planar engagement model.[3] It is assumed that the target and the missile are point masses and have constant speeds. Target maneuver has been modeled as a random jinking maneuver, in which the target acceleration is assumed to attain a maximum value β (target jinking level) instantaneously, with the direction alternating randomly with time. The average number of sign changes per unit time is given by the jinking rate parameter ν. This type of target maneuver is realized in simulation by passing the white noise of spectral density β^2/ν through a first-order linear system with time constant $1/2\nu$.

The seeker, the noise filter, and the flight control system have each been modeled as a first-order linear system. The parasitic effects of unwanted feedback paths created by the missile radome and the turning rate time constant and measurement noises such as glint noise have been included in the model. Nonlinearity in terms of missile commanded acceleration saturation has been included. Errors in the measurement of LOS rate and estimation of target instantaneous acceleration have also been taken into account.

Performance Evaluation

The commanded acceleration profile and the terminal miss distance have been used as the principal criteria for performance evaluation. Since the first guidance scheme uses the same information required for PN, the performance of FGS-1 has been compared with that of PN. For similar reasons, the performance of FGS-2 has been compared with APN.[4]

The commanded acceleration profiles of PN and FGS-1 for the following two situations have been plotted in Fig. 1: 1) $a_T = 0$ m/s^2, heading error $HE = -10°$, and 2) $a_T = 30$ m/s^2, $HE = 0°$.

It is observed that the acceleration profiles of PN and FGS-1 are almost identical, since the rules of FGS-1 have been tuned to match the acceleration profiles.

Figure 2 shows the acceleration profiles of APN and FGS-2 for the above two cases. For the heading error case, the commanded acceleration profiles match. Although the acceleration profiles of FGS-2 for the target maneuver case does not match that of APN, the error is within acceptable limits.

To evaluate the miss distance performance of the fuzzy guidance schemes, miss distance measures have been studied by varying the various parameters like radome slope, target jinking level, etc. The miss distance performance has been investigated with errors in measurement of LOS rate and estimation of target acceleration to test

Table 1 Miss distance with measurement error in LOS rate (FGS-1 and PN), $\beta = 40$ m/s^2, $\nu = 0.1$ Hz

	Miss distance, m			
	FGS-1		PN	
Percentage error	Mean	1σ	Mean	1σ
−20	3.148	3.321	4.683	18.284
−10	2.547	1.544	4.185	13.017
−5	2.814	1.499	3.605	10.576
0	2.460	2.671	3.690	8.330
5	2.562	2.316	3.683	3.366
10	1.852	1.325	3.191	4.653
20	2.227	1.436	2.495	1.927

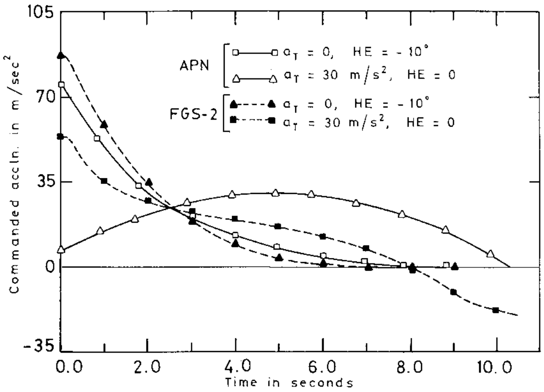

Fig. 1 Acceleration profiles of PN and FGS-1.

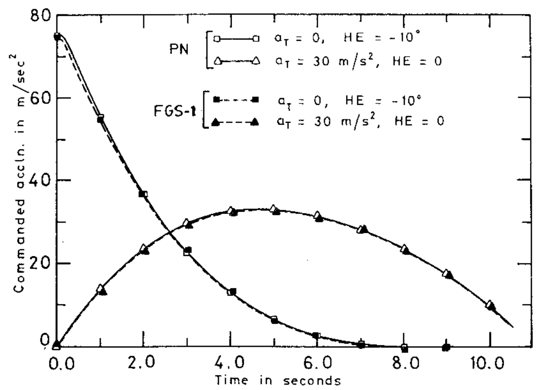

Fig. 2 Acceleration profiles of APN and FGS-2.

the robustness of these schemes. The miss distance values have been averaged out over 50 simulation runs, and the standard deviations (1σ values) have also been calculated.

With the radome refraction and glint noise, the fuzzy guidance schemes give similar performances as PN and APN, respectively. With random target maneuver, for lower values of target jinking level β, the mean and 1σ values of the miss distance for PN and FGS-1 are comparable; but for higher values of β, the mean and 1σ values of the miss distance for PN increase more rapidly compared to FGS-1. The second guidance scheme (FGS-2) result in lower mean and 1σ values of the miss distance compared to APN for all values of β.

With measurement error in the LOS rate, FGS-1 and FGS-2 both give lower miss distance values compared to PN and APN, respectively. With error in the estimation of target acceleration, FGS-2 results in lower mean as well as 1σ values of miss distances compared to APN. As a typical example, Table 1 shows the miss distance performance of PN and FGS-1, with measurement error in the LOS rate.

Equivalent N'

The PN and APN guidance laws both use a dimensionless gain parameter N', called the effective navigation ratio, to calculate the commanded acceleration. The fuzzy guidance schemes do not explicitly use any such gain term. Rather, they compute the commanded acceleration from the linguistic rules. However, an equivalent N' can be defined for fuzzy guidance schemes in the following way:

$$N'_{\text{eq}}|_{\text{FGS}-1} = a_C/(V_c\dot{\lambda})$$

$$N'_{\text{eq}}|_{\text{FGS}-2} = a_C/(V_c\dot{\lambda} + 0.5a_T)$$

Throughout the flight of the missile, the mean and standard deviation of equivalent N' have been calculated for 50 simulations at each time instant. The mean and mean $\pm\sigma$ of N'_{eq} have been plotted vs time and analyzed. The mean equivalent N' has been found to be highly time varying. It starts from a very low value at the beginning of the flight and rises quickly to a value in the range of 4–6, at which range it remains for most of the time, and then toward the end of flight rapidly decreases to a very low value.

On the other hand, the effective navigation ratio in the case of PN and APN remains constant throughout the flight of the missile. In the case of fuzzy guidance schemes, the equivalent N' is time varying in nature, and this can be regarded as a specific advantage of the fuzzy guidance scheme. The superior performance of FGS-1 and FGS-2 over PN and APN, respectively, can be attributed to this time-varying equivalent N'.

Conclusion

It is observed that the two fuzzy guidance schemes proposed handle the inaccurate and imprecise information effectively. The fuzzy guidance schemes are not only able to match the performance of PN and APN, but in cases where measurements are inaccurate and high noise levels are involved, they have shown better miss distance performance. The fuzzy guidance schemes have the inherent ability to generate a time-varying effective navigation ratio, which has a direct impact on the improved performance.

The study reported in this Note demonstrates that fuzzy-logic-based guidance schemes afford possibilities for improved performance.

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