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SPACE SHUTTLE GUIDANCE

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SUMMARY

The guidance requirements for the Shuttle Vehicle and the possible candidate guidance schemes are discussed. The MASCOT Guidance Scheme appears to be ideally suited for the rendezvous guidance phase of the flight, and by modifying the guidance equation to include the lift and drag forces, the MASCOT scheme can be adapted for the ascent guidance phase. The basic parts of the MASCOT guidance scheme, a numerical integration algorithm and an iteration algorithm, can be used to develop a fast-prediction guidance scheme for the reentry phase.

I. INTRODUCTION

In the area of guidance, the Space Shuttle has created many interesting problems. This write-up discusses the guidance problems associated with the Shuttle vehicle and presents the approach being taken by the Aero-Astrodynamics Laboratory in developing a guidance scheme to meet the stringent guidance requirements of the Space Shuttle.

Typical missions for the Space Shuttle include (1) placement and retrieval of satellites, (2) rescue missions, (3) supply of the Space Station, and (4) delivery of propellants to orbiting vehicles. All of these missions consist of three distinct guidance phases: the ascent, the rendezvous, and the deboost and reentry phases. Each phase has its own inherent guidance problems. Our approach has been to examine each phase separately and decide what the guidance requirements are for that particular phase. Once the guidance requirements are established, the next question to be answered is, "What guidance schemes are available or will have to be developed in order to satisfy these requirements?" The following three paragraphs will elaborate on the guidance requirements for the ascent, rendezvous, and deboost and reentry phases.

II. SHUTTLE GUIDANCE REQUIREMENTS

A. Ascent Phase

Compared to present-day space vehicles the Space Shuttle has a relatively high L/D ratio. Preliminary studies indicate that, by flying optimal lifting trajectories, the advantage of the lifting characteristics of the Shuttle can be used to increase the payload delivered to orbit. The ascent guidance will have to be capable of flying optimal lifting trajectories through the atmosphere in order to realize their potential increase in payload.

Because lifting trajectories will be extremely sensitive to inflight perturbations, the ascent guidance scheme will have to be adaptive to these perturbations. This dictates closed-loop guidance during ascent through the atmosphere, a deviation from the current Saturn guidance which is open-loop through the atmosphere.

B. Rendezvous Phase

The first guidance requirement for the rendezvous phase is that the rendezvous maneuver be performed in an optimum manner in order to minimize the on-orbit ΔV requirements. The second requirement for the rendezvous guidance, a very important one, is that of "self-targeting," a term used here to mean the onboard determination of the following:

(1) time to initiate the first burn,

(2) transfer ellipse between the Shuttle's orbit and the target's orbit, and

(3) time to terminate coast and initiate the final burn.

The importance of the self-targeting requirement is reflected in the Shuttle Base Line Document, which states that the Shuttle shall have the capability of being launched with only 2 hours notice. Guidance schemes that are presently being flown require that targeting information for rendezvous be determined before launch and stored onboard as a function of launch time. The Shuttle guidelines will essentially eliminate this mode of targeting.

C. Deboost and Reentry Phase

Because the Space Shuttle will reenter the earth's atmosphere from parking orbits with various altitudes and inclinations, the Shuttle will be confronted with various sets of reentry conditions. Also, guidance and navigation errors during deboost will result in perturbed initial entry conditions; thus, the deboost and reentry guidance will be required to handle a wide range of entry conditions. Once within the atmosphere, the Shuttle will experience severe perturbations in the atmospheric density, as much as 100 percent at high altitudes, and will be even more sensitive to inflight perturbations than the Gemini and Apollo type vehicles because of its high L/D characteristics. Therefore, the ability of the reentry guidance scheme to adapt to inflight perturbations is a must.

The above discussion does not include all guidance requirements associated with the three phases of flight; however, it is felt that the requirements that have been pointed out are the most demanding as far as the development of a guidance scheme is concerned. These requirements for the various phases are condensed in Table 1.

TABLE 1

Guidance Requirements

Ascent Phase	Rendezvous Phase	Deboost & Reentry Phase
• Optimal lifting trajectories	• Optimal maneuvers	• Flexibility with respect to end conditions.
• Adaptive (closed-loop)	• Self-targeting	• Adaptive to inflight perturbations.

Candidate guidance schemes for the three guidance phases are listed in Table 2.

TABLE 2

Candidate Guidance Schemes

	Rendezvous	
• IGM	• IGM	• Linear Perturbation
• Open-loop/MASCOT	• Cross Product Steering	Path Controller Terminal Controller
• MASCOT with Atmosphere	• MASCOT	• Fast-Prediction Guidance

In discussing the candidate guidance schemes it is appropriate to start with the rendezvous phase since the reader is probably less familiar with the MASCOT scheme than the other schemes listed, and it is best described in relation to a rendezvous mission.

A. Rendezvous Phase

The Iterative Guidance Mode (IGM), which has thus far successfully flown the Saturn vehicles, was the first guidance scheme considered for the rendezvous phase. Unfortunately, the IGM does not meet the self-targeting requirement. Also, the IGM equations are not suited for burn arcs greater than about 40 degrees (exceeding the limit results in a loss in payload), and it is possible that some Shuttle rendezvous profiles may require burn arcs that exceed this value. Thus, it was decided that IGM was not suitable for the rendezvous guidance phase.

The cross product steering used on the Apollo spacecraft has successfully flown rendezvous missions and could possibly be used for the rendezvous phase. However, it has a limited amount of self-targeting capability (some assumptions have to be made concerning transfer angles and where phase change maneuvers should be made), and like IGM, it is not suited for long burn arcs. The cross product steering also contains mission-dependent constants which make it undesirable for the Shuttle.

The MASCOT guidance scheme was developed especially for multiple burn rendezvous missions and is ideally suited for the rendezvous guidance phase. Because MASCOT is a real-time solution to the trajectory optimization problem, it is completely optimum, and because the equations of motion are numerically integrated, no approximations or mission-dependent parameters are necessary. Also, the guidance command is obtained by an iteration technique which is both fast and reliable. Since MASCOT also has self-targeting capability, it is felt that the MASCOT guidance meets all the requirements for the rendezvous phase of the Shuttle flight and could be flown with only minor modifications. A detailed description of the MASCOT guidance scheme can be found in the reference.

B. Ascent Phase

For the ascent guidance phase, we once again considered IGM, but the IGM equations to not allow for lift and drag forces. It appears unreasonable to try to modify the IGM guidance scheme since this would result in a complete reformulation of the guidance equations.

We next considered using a pre-calculated steering program for flight through the atmosphere that would be designed for an optimum lifting trajectory. This profile (steering angle versus time) could be flown open-loop through the atmosphere, and the MASCOT guidance could be used once the Shuttle was out of the atmosphere. Such a scheme could be easily developed, but would not be adaptive to inflight perturbations during the atmospheric portion of the flight. The MASCOT guidance would have to correct for the perturbations that occur during boost, and since these perturbations will be quite large, it is felt that this is not a reasonable approach.

The next approach to the ascent guidance phase was to modify the MASCOT guidance scheme to include the aerodynamic forces. Although this is a major modification to the MASCOT program, it allows the MASCOT guidance to be flown from the launch pad all the way to orbit. Several assumptions, such as constant lift and drag coefficients with respect to Mach number, exponential atmosphere, and constant thrust levels, have been made in order to simplify the computations within the atmosphere. These simplifying assumptions, which will be removed in the future, make it easier to demonstrate the feasibility of the concept.

Even though including the lift and drag forces in the guidance equations has resulted in longer guidance cycle times, it is felt that these can be reduced to acceptable values. Also, the onboard computer requirements have increased, but they still appear reasonable. Use of the MASCOT guidance scheme with the aerodynamic forces included will provide a guidance scheme for the ascent phase that meets the adaptive requirement and has the capability of flying optimum lifting trajectories. Also, the guidance equations for the ascent phase and the rendezvous phase will be essentially the same since the aerodynamic force terms will drop out of the guidance equations when atmospheric density goes to zero.

C. Deboost and Reentry Phase

In the past, linear perturbation guidance has received a great deal of attention for reentry guidance. Since this type of guidance is tied to a nominal trajectory (path controller) or restricts the trajectory to a small region near nominal trajectory (terminal controller), it is felt that perturbation guidance does not offer the flexibility needed for the deboost and reentry guidance phase of the Shuttle vehicle.

The deboost and reentry guidance for the Shuttle must have the capability to assess the present state (position, velocity, etc.) of the Shuttle and project the Shuttle ahead by numerical integration or approximate closed-form solutions to the equations of motion in order to determine the guidance commands needed to deliver the vehicle safely to the desired end conditions. This type of guidance is referred to as "fast-prediction" guidance. Two of the main requirements for fast-prediction guidance are a numerical integration scheme and an iteration scheme. Since both the numerical integration and the iteration schemes are integral parts of the MASCOT guidance scheme, the main algorithms needed for a fast-prediction reentry guidance scheme are already available.

IV. SUMMARY

The MASCOT Guidance with atmospheric force terms added can provide a uniform autonomous set of guidance equations for the Shuttle that can be used for the ascent and rendezvous phases. The main algorithms of MASCOT can be used to develop a fast-prediction guidance scheme for reentry.

It is felt that MASCOT with atmosphere is a sound approach to the Shuttle guidance problems. There are many areas associated with the development of the MASCOT guidance where improvements can be made. Such improvements will result mainly in shorter guidance cycle times and less onboard computer storage requirements. These areas are listed in Table 3.

TABLE 3

Problem Areas

• Problem Formulation
• Development of Better Iteration Techniques
• Development of Better Numerical Integration Schemes
• Efficient Way of Handling Aerodynamic Coefficients
• Efficient Way of Handling Atmospheric Density
• Heating Criteria for Reentry

REFERENCE

Baker, Clyde D., Wilton E. Causey and Hugo L. Ingram, "Mathematical Concepts and Historical Development of the MASCOT Guidance Technique for Space Vehicles," NASA TM X-64502, March 11, 1970. To be published.

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