References

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Thrust Vector Orientation in Pilot-Controlled Lunar Landings

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Nomenclature

K = angle between thrust vector and line of sight to a visual reference, deg
h = altitude above lunar surface, ft
$\dot{r}$ = radial velocity, fps
$r\dot{\theta}$ = transverse velocity, fps
R = range of travel over lunar surface, ft
ΔV = characteristic velocity, fps
F = thrust, lb
W = earth weight, lb
V = total velocity, fps

Subscripts

0 = initial condition
t = terminal condition
S = orbiting spacecraft reference

Introduction

THE primary guidance and control systems of current spacecraft are automatic. In manned space missions, however, it has been shown that man can improve the reliability of a system, if he is given the opportunity to act as a backup to the primary system. In order to permit manual control, it is necessary to provide the pilot with a suitable control system and with information pertinent to the task. In the case of the latter requirement, out-of-the-window scenes should be of great value and, in fact, might be the only information available, if the necessity for manual control is caused by a failure that affects the vehicle display panel or situation sensors.

The study to be discussed in this paper is concerned with the use of visual references for performing the lunar landing maneuver. The primary control function in this task is proper orientation of the vehicle thrust vector. The problem to be examined, therefore, is to determine if there are any convenient visual references to aid the pilot in thrust vector orientation and to determine the sensitivity of terminal conditions to errors in use of the reference or in vehicle initial conditions (start of braking maneuver).

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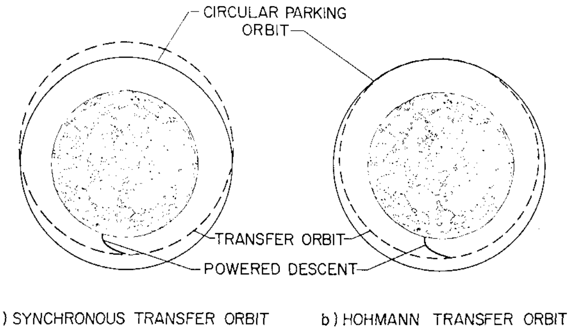

Fig. 1 Transfer orbits used in this investigation.

The procedure used in this study was to compute an efficient reference landing trajectory (gravity turn) and then to determine the orientation of the thrust vector relative to several references. The purpose was to determine if any convenient geometric relationships existed between the thrust vector and the line of sight to the various references. The references examined were the downrange and uprange horizons, the nominal landing site, and an orbiting spacecraft. All of the visual references were assumed to be in the plane of motion.

Analysis

It is assumed that a spacecraft, consisting of a command module, a service module, and a lunar excursion module, establishes a circular parking orbit 80 naut miles above the lunar surface. The lunar excursion module then separates from the spacecraft and establishes an elliptic transfer orbit having a pericynthion altitude of 50,000 ft. Two elliptic transfer orbits are being considered for the lunar mission, namely, an elliptic orbit that has the same orbital period as the circular parking orbit (Fig. 1a) and an elliptic orbit established by a 180° Hohmann transfer (Fig. 1b). At pericynthion of the transfer orbit, an efficient landing is accomplished by thrusting against the velocity vector (gravity turn).

The equations of motion used were for a point mass moving in a central force field and subject to a thrust force in the plane of motion. A constant-thrust landing engine producing an initial thrust-to-earth-weight ratio of 0.485 and having a specific impulse of 305 secs was assumed for the landing. These landing trajectories were then examined to determine the orientation of the lander thrust vector with respect to the various visual references mentioned previously.

Results and Discussion

Two types of transfer orbits were examined, one having the same period as the parking orbit (synchronous transfer) and the second being a Hohmann transfer orbit. The synchronous orbit was studied in more detail than the Hohmann, and most of this paper will be concerned with descent from the synchronous orbit.

Synchronous transfer orbit

Nominal landing trajectory: As stated in the Introduction, a gravity-turn descent was computed from the pericynthion of the synchronous orbit. The orientation of the thrust vector relative to the uprange and downrange horizons, the landing site, and the orbiting spacecraft was then examined, and the results are shown in Fig. 2. The figure shows the variation, during the landing, of the angle between the thrust vector and the line of sight to the various references. As can be seen, the angle between the thrust vector and the line of sight to the orbiting spacecraft remains very nearly constant throughout the landing maneuver. The other references do not appear to be quite as convenient.

Table 1 Comparison of terminal conditions of the reference gravity-turn descent with those generated by thrusting 23° behind the orbiting spacecraft

Condition	Terminal condition for	
	Gravity turn	$K_s = 23°$
$\dot{r}$, fps	0	−15.2
$r\dot{\theta}$, fps	0	0
h, ft	5,466	4,748
R, ft	857,158	858,073
ΔV, fps	5,870	5,850

New landing trajectories were then computed, based on maintaining a constant angle between the thrust vector and the line of sight to the orbiting spacecraft. It was found that, if an angle of about 23° were maintained throughout the braking maneuver, the descent trajectory very closely approximated the gravity-turn descent as shown in Fig. 3. This figure shows the variation of altitude with range and the variation of velocity with altitude for the two trajectories, and the agreement is very good. A comparison of the characteristics of the two trajectories at an altitude of about 5000 ft is shown in Table 1 and again shows very close agreement. It appeared, therefore, that the orbiting spacecraft would be a convenient reference for manual control of the lunar landing or for monitoring the progress of an automatic landing.

Error study: Since a completely visual landing will be essentially an open-loop landing, it was of interest to examine the effects of various possible operational errors on terminal conditions. In this respect, terminal conditions are those conditions which exist when one velocity component $\dot{r}$ or $r\dot{\theta}$ reaches zero. The next step, therefore, was to determine the effects on terminal conditions of errors in thrust vector orientation, thrust level, and various initial conditions. The variations of some of the terminal conditions with various types of errors were

$$\partial h_t/\partial K_S = 11{,}000 \text{ ft/deg} \qquad \partial h_t/\partial h_0 = 0.437$$

$$\partial (r\dot{\theta})_t/\partial K_S = 212 \text{ fps/deg} \qquad \partial h_t/\partial \dot{r}_0 = 113 \text{ ft/fps}$$

$$\partial h_t/\partial (F/W_0) = 800 \text{ ft/\%} \qquad \partial R_t/\partial (r\dot{\theta})_0 = 266 \text{ ft/fps}$$

$$\partial R_t/\partial (F/W_0) = 10{,}000 \text{ ft/\%}$$

In general, the terminal conditions are relatively insensitive to the errors, with the exception of the effect of thrust vector orientation on terminal altitude and transverse velocity and of thrust level on range.

The large sensitivity of terminal altitude with sighting angle $\partial h_t/\partial K_S$ can be rather critical, if no in-flight corrections are made. However, it may be possible to use a semiclosed-loop system in which the altitude is monitored at certain intervals after the start of thrusting and changes in thrust angle made based on these measurements. Flight simulations will determine how well a pilot can sense errors in the system and how well he can compensate for these errors.

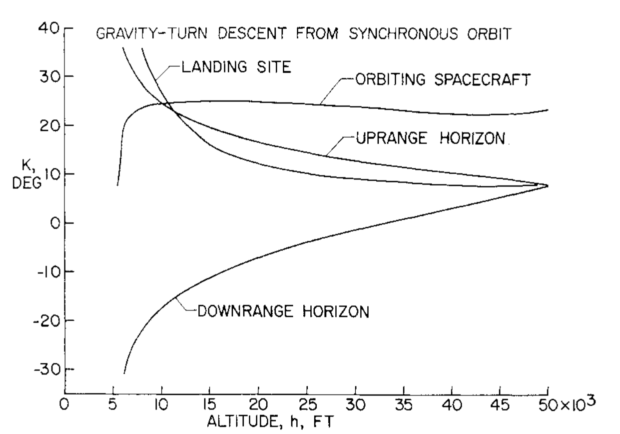

Fig. 2 Variation of the angle between the thrust vector and line of sight to various visual references for descent from pericynthion of the synchronous transfer orbit.

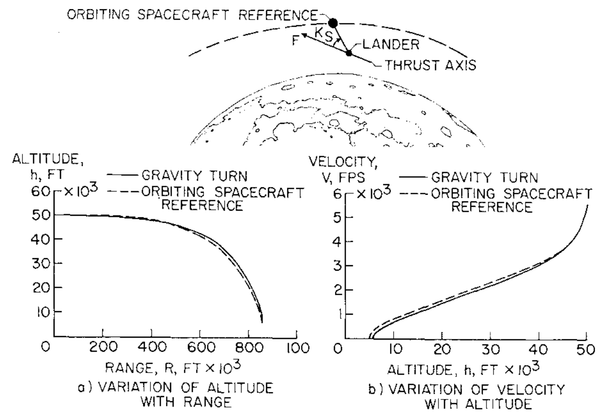

Fig. 3 Comparison of characteristics of the reference gravity-turn descent with those generated by thrusting 23° behind the orbiting spacecraft.

Hohmann transfer orbit

Since the orbiting spacecraft appeared to be such a convenient thrust vector orientation reference for the synchronous descent, it was decided to make a similar study for the Hohmann transfer descent. The results were quite similar, except that the nominal angle between the thrust vector and line of sight to the spacecraft was about 18° for the Hohmann transfer as compared to 23° for the synchronous transfer.

The use of the orbiting spacecraft for thrust vector orientation appears to allow the pilot to perform an efficient maneuver while reducing the vehicle velocity and altitude to relatively low values. The pilot will probably only rely on this technique down to an altitude of about 10,000 ft and then complete the landing by using the lunar surface features for guidance much as is done in visual flight with aircraft. Note that the nominal terminal conditions selected for use in this study are somewhat arbitrary. It appears unlikely that the lunar excursion module will make a vertical descent from an altitude as high as 5000 ft. It is more likely that the last few thousand feet of flight will be tailored to have a shallow flight-path angle. The important point to note is that the procedure examined in this paper permits the pilot to reduce most of the vehicle velocity and altitude in an efficient manner.

A few words concerning the possible application of this technique to the Apollo mission are in order. With the current lunar excursion module (LEM), the command service module is visible through the overhead LEM window and to the rendezvous radar, and hence the technique studied herein appears attractive for monitoring an automatic landing or for manual control of the landing.

Concluding Remarks

An analytical study has been made to determine the possibility of using visual references as an aid in thrust vector orientation for pilot-controlled lunar landings. It was found that during gravity-turn landings, the angle between the lander thrust vector and the line of sight to an orbiting spacecraft remained essentially constant until the landing was almost completed. Nominal trajectories were then computed where the angle between the lander thrust axis and the orbiting vehicle was maintained constant. The results showed that efficient landings could be made in this manner, and it appears as if the technique offers a means of satisfactory manual control during the lunar landing.