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# APOLLO SPACECRAFT SOFTWARE CONFIGURATION CONTROL BOARD PROGRAM CHANGE REQUEST

NUMBER (Completed by FSB) 884

## 1.0 COMPLETED BY ORIGINATOR

| | | | | |
|---|---|---|---|---|
| 1.1 ORIGINATOR<br>R. F. Stengel | DATE<br>8-15-69 | 1.2 ORGANIZATION<br>MIT/IL | APPROVAL<br>George W. Cherry | DATE<br>8/18/69 |

1.3 EFFECTIVITY: LUMINARY 2

1.4 TITLE OF CHANGE: Directional Stability and Turn Coordination During Manually-Controlled Lunar Landing

1.5 REASON(S) FOR CHANGE

(a) To improve LM handling qualities during Lunar Landing.

(b) To aid in achieving pinpoint landings.

1.6 DESCRIPTION OF CHANGE (a) Bias yaw attitude error to null lateral translational velocity. (b) Bias yaw rate error by roll angle to follow heading rate-of-change. (c) Bias errors only during forward flight with horizontal velocity greater than a threshold. (d) Implement in ATT HOLD only during P64, P66, and P67.

## 2.0 SOFTWARE CONTROL BOARD OR FLIGHT SOFTWARE BRANCH DECISION FOR VISIBILITY IMPACT ESTIMATE BY MIT

2.1 ☐ APPROVED ☐ DISAPPROVED

2.2 REMARKS:

2.3 SOFTWARE CONTROL BOARD OR FLIGHT SOFTWARE BRANCH SIGN OFF

DATE

## 3.0 MIT VISIBILITY IMPACT EVALUATION:

3.1 SCHEDULE IMPACT

3.2 IMPACT OF PROVIDING DETAILED EVALUATION

3.3 STORAGE IMPACT 50

3.4 REMARKS:

3.5 MIT COORDINATOR George W. Cherry

DATE

## 4.0 SOFTWARE CONTROL BOARD ACTION

4.1 ☐ IMPLEMENT AND PROVIDE DETAILED CHANGE EVAL. ☒ PROVIDE DETAILED CHANGE EVALUATION ☐ DIS-APPROVED

4.2 REMARKS: off line assembly approved.

4.3 SOFTWARE CONTROL BOARD SIGN OFF

DATE 10-9-69

## 5.0 MIT DETAILED PROGRAM CHANGE EVALUATION

5.1 MIT COORDINATOR

DATE

5.2 MIT EVALUATION

## 6.0 SOFTWARE CONTROL BOARD DECISION ON MIT DETAILED PROGRAM CHANGE EVALUATION

6.1 ☐ START OR CONTINUE IMPLEMENTATION ☐ DISAPPROVED OR STOP IMPLEMENTATION

6.2 REMARKS:

6.3 SOFTWARE CONTROL BOARD SIGN OFF

DATE

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1.5 Reasons for change

1.6 Description of Change

By keeping the vehicle Z-axis in the vertical plane which contains the horizontal velocity vector, the pilot is always able to identify his flight path and its ground projection. The visual ambiguity between yaw rotation and lateral translation is removed. Spacecraft response is more nearly like that of an aircraft in forward flight and, with yaw biases "locked out" at low velocity, like that of a helicopter in hover.

Directional stability aligns the yaw axis with the flight path azimuth and is similar to the "weathercock stability" which an aircraft's vertical tail provides. It is obtained by biasing the yaw attitude error. The forward and lateral horizontal velocities, $V_{Y_H}$ and $V_{Z_H}$, which are derived in the LGC from inertial data and are currently displayed to the crew on a cross-needle meter, determine the sideslip angle, the angle between yaw attitude and flight azimuth. Setting the yaw bias to the sine of the sideslip angle provides a correction of the proper sign which is conservative at large angles and which nulls at the desired attitude. For pitch and roll angles near zero, the appropriate yaw bias angle is:

$$\phi_B = V_{Y_H} / \sqrt{V_{Y_H}^2 + V_{Z_H}^2} \tag{1}$$

As RCS thrusters command yaw in response to $\phi_B$, $V_{Y_H}$ diminishes, and $\phi_B$ approaches null. The steady state heading error is zero.

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Continued

Turn coordination is provided by making yaw rate equal the rate of change of flight azimuth. Lateral acceleration is provided by tilting the thrust axis about the body-roll axis (in near-vertical pitch attitude), suggesting that the yaw rate bias for turn coordination be:

$$\dot{\phi}_B = \frac{a_{x_{Body}} \sin \psi_{Body}}{V_{Z_H}} \qquad (2)$$

$\theta_{IMU}$ and $\psi_{IMU}$ must be rotated by the yaw angle to obtain $\psi_{Body}$ in this approximation. If this approximation is insufficient at the limits of non-verticality, the exact bias equation, in terms of IMU angles, is

$$\begin{aligned} \dot{\phi}_B = {} & [\, \dot{\phi} \cos \psi + (\dot{\theta} \cos \phi + \dot{\psi} \sin \phi) \sin \psi] \cos \theta \\ & - [\, \dot{\theta} \sin \phi + \dot{\psi} \cos \phi] \sin \theta \end{aligned} \qquad (3)$$

where $\dot{\phi}$, $\psi$, and $\dot{\theta}$ are functions of $A_{Y_{IMU}}$, $A_{Z_{IMU}}$, and $V_{Z_H}$.

REMARKS

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Continued

The effects of this program change, as well as the reasons for suggesting it, are discussed extensively in the references. The mode can be accepted or rejected by means of extended verbs.

References

1. Stengel, R. F., "Manual Attitude Control of the Lunar Module," MIT/IL Report E-2394, Cambridge, June, 1969.
2. Stengel, R. F., "Improved Manual Control of the Lunar Landing," MIT/IL Spacecraft Autopilot Development Memo #24-69, Cambridge, July 29, 1969.

DP#21812

Massachusetts Institute of Technology
Charles Stark Draper Laboratory
Cambridge, Massachusetts

MEMO

TO: Russ Larson
FROM: George R. Kalan
DATE: 15 June 1970
SUBJECT: Results of Off-Line Assembly Study of PCR #884

PCR 884 (Directional Stability and Turn Coordination During Manually-Controlled Lunar Landing) was intended to aid in manual lunar landings by modifying the manual control system so that the LM could be flown like an airplane. The modifications suggested to accomplish this included:

1. Biasing the yaw attitude error with the Y axis translational velocity to provide directional stability by keeping the z axis aligned with the velocity vector.
2. Biasing the yaw rate error with the roll angle to provide turn coordination.
3. Biasing these errors only during P64 or P66 with the Mode Control Switch in the ATT. HOLD position and a positive z axis translational velocity greater than some threshold.

The attitude and rate biases are given in Eq. 1 and Eq. 2.

$$\phi_B = V_y / \sqrt{V_y^2 + V_z^2} \qquad (1)$$

$$\dot{\phi}_B = a_x \sin \psi / V_z \qquad (2)$$

where:

$\phi_B$ = yaw attitude error bias

$\dot{\phi}_B$ = yaw rate error bias

$V_y$ = Y axis translational velocity

$V_z$ = Z axis translational velocity

$a_x$ = X axis acceleration

$\psi$ = body roll angle

The determination of the attitude errors, **E**, and rate errors, $\dot{E}$, for use in the RCS control law varies with the DAP mode. Eq. 3 and Eq. 4 show the form of E and $\dot{E}$ for the P-axis, including the bias terms, in the attitude hold mode.

$$E = \theta_P - \theta_{PD} + \phi_B \tag{3}$$

$$\dot{E} = \text{OMEGAP} + \dot{\phi}_B \tag{4}$$

where:

$\theta_P$ = P axis attitude

$\theta_{PD}$ = desired P axis attitude

OMEGAP = DAP P axis rate estimate

Eq. 5, Eq. 6, and Eq. 7 show the form of E and $\dot{E}$ for the P axis, including the bias terms, when Q or R axis maneuvers are commanded in the manual rate command mode.

$$\text{DXERROR} = \text{DXERROR} + \theta_P - \theta_{P_{n-1}} \tag{5}$$

$$E = \text{DXERROR} + \phi_B \tag{6}$$

$$\dot{E} = \text{OMEGAP} + \dot{\phi}_B \tag{7}$$

where:

DXERROR = manual mode P axis error

$\theta_{P_{n-1}}$ = P axis attitude at previous DAP pass

The biases are also added during P axis manual rate command mode maneuvers in the pseudo-auto control phase. To allow manual override, the rate bias is not included in the calculation of rate error during P axis manual rate command mode maneuvers in the direct rate control phase.

Testing of an off-line LUMINARY assembly which included the proposed modifications revealed two major problems. The first was due to computational lags and granularity in the quantities used to compute $\phi_B$ and $\dot{\phi}_B$ which prevent $\phi_B$ from approximating the integral of $\dot{\phi}_B$. As a result of the granularity and lags, trajectories in the E, $\dot{E}$ phase plane computed using Eq. 6 and Eq. 7 did not follow the RCS control law phase plane parabolas. Consequently, the dynamic response of the yaw attitude during roll maneuvers was erratic and bore little resemblance to the desired motion.

The second major problem caused the failure of the steady state directional stability feature. The primary purpose of the attitude error bias $\phi_B$ was to provide integral compensation for trimming out residual yaw errors in the attitude hold mode after manual maneuvers when the roll angle and $\dot{\phi}_B$ were both zero. Due to the structure of Eq. 3 and the nature of $\phi_B$ as given in Eq. 1, however, the steady state yaw errors were not nulled. If, for example, $\phi_B$ were 1° when the attitude hold mode were entered after completion of a manual maneuver to zero roll angle, then Eq. 3 would be:

$$E = \theta_P - \theta_{PD} + 1^\circ \tag{8}$$

To simplify the discussion, assume that $\theta_P$ and $\theta_{PD}$ were both zero at the end of the manual maneuver. Thus, Eq. 8 becomes:

$$E = 0 - 0 + 1^\circ \tag{9}$$

This error would cause -P RCS jet firings which would reduce the error. However, the yaw rotation would reduce $V_y$ and consequently, cause a reduction in $\phi_B$. The error would be reduced to 0 as illustrated in Eq. 10

before the change in $V_y$ would be detected and reflected in $\phi_B$.

$$E = -1^\circ - 0^\circ + 1^\circ = 0 \tag{10}$$

At this point, the required yaw attitude would be attained and $V_y$ would be zero. However, the zero $V_y$ would soon cause $\phi_B$ to be reduced to zero, causing a error of $-1^\circ$ as illustrated in Eq. 11.

$$E = -1^\circ - 0^\circ + 0^\circ \tag{11}$$

This would cause +P RCS jet firings which would move the LM back toward the original yaw attitude. When the residual yaw errors at the completion of a manual roll maneuver are larger, as they were in the off-line assembly tests, this effect is more serious.

Since the practical considerations mentioned prevent the use of the design suggested in the PCR, an alternate approach was implemented and tested. In this approach, $\phi_B$ was the time integral of $\dot{\phi}_B$ and did not depend upon $V_y$. This improved dynamic response and partially eliminated the first problem. However, the steady state yaw errors were intolerable due to the lack of lateral velocity feedback.

Although other, more elaborate designs could be developed and tested, the benefits of coordinated turns and directional stability, now that P66 AUTO is available to aid in manual landings, would probably not warrant the additional logical complexity, the words required, and the man hours and computer time necessary for verification testing and flight qualification.