Massachusetts Institute of Technology
Instrumentation Laboratory
Cambridge, Massachusetts

LUMINARY Memo #19

To: Distribution

From: A. Klumpp

Date: 16 March 1968

Subject: Comparison of Body Drive and Gimbal Drive FINDCDUW Routines

Two FINDCDUW routines have been written and are both fully operational. The first routine, called "body-drive" runs largely along the lines specified by the lunar landing GSOP. The second routine called "gimbal-drive" has identical interfaces with the users and with the autopilot, but features a completely different concept for determining the required maneuver which at once is simpler, computationally more direct, and completely avoids gimbal lock in all cases where the input commands do not determine a terminal attitude in gimbal lock. The body-drive version, on the other hand, may produce a maneuver which passes through the gimbal lock region even though the terminal attitude is outside. A gimbal lock protection fix has been incorporated in the body-drive version to stop the middle gimbal angle at the boundary (70 deg) but this will have the effect of reducing the maneuver rate and may arrest the maneuver entirely if the gimbal lock cone is approached at a right angle. This situation is not unlikely in an abort during a lunar landing.

In addition to avoiding gimbal lock, the gimbal-drive version is faster by 15 to 25 milliseconds during phases where radar is in operation and execution time is critical, and this version provides basic subroutines which may be used by other programmers to further relieve the present execution time problem.

As I understand NASA's direction concerning gimbal lock avoidance, MIT is not to incorporate gimbal lock avoidance if it entails any considerable cost. Items of cost which must be considered are development time at the expense of schedule, computation time, program length in word count, and degradation of the performance of the guidance and control system from the standpoint of main engine or RCS propellant consumption, degraded thrust pointing, or other. It should not be necessary to prove that the gimbal-drive version is superior in all respects. Considering that it has at least one major advantage, it should only be necessary to show that it has no compensating deficiency. The following table will show this to be the case.

COMPARISON OF GIMBAL DRIVE & BODY DRIVE FINDCDUW

CONSIDERATION	GIMBAL DRIVE	BODY DRIVE
1. Gimbal lock	Never gimbal lock if final attitude not in gimbal lock. PNGCS abort guidance not dependent upon astronaut to maneuver around gimbal lock cone.	Attitude maneuvers can yield gimbal lock even though neither the initial attitude nor terminal attitude are in gimbal lock. PNGCS abort guidance dependent upon astronaut to take over in a gimbal lock producing maneuver.
2. Execution time	Nominal 175 ms, max. 190 ms, (Max can't occur during radar opn) will benefit from QUICTRIG	Nominal 190 ms, max 200 ms, (Max can occur during radar opn) will benefit from QUICTRIG
3. Word count	399 decimal	318 decimal
4. Basic subroutines	1. NB2CDUSP computes the 2's comp SP CDU ∢'s from nav base vectors. DCMTOCDU can be deleted with impunity for a savings of 40 words, and this will solve Kalcmanu's abort on gimbal lock problem* Execution time≈12.5 ms. 2. ARCTRGSP computes a 2's complement unambiguous angle anywhere in a circle, given the sine and cosine. Other uses? Execution time≈1.25 ms. 3. Sparcsin computes an angle in the region ±70 degrees given its sine. Needed by descent guidance. Execution time 450 microseconds.	1. NBGMB transforms incremental rotations in NB coords to gimbal increments. No other uses. Executio[n] time 18.2 ms.
5. Rate limiting	Rate about each axis limited independently. Present values 10°/sec. Vector rate limiting with priority normal to X axis could be incorporated.	Vector body rate limited to 10°/sec. with first priority given to rate norm[al] to X axis.
6. RCS propellant consumption	May use some extra fuel in a large maneuver involving rates about two or more axes due to increased vector rate. For normal mission fuel diff $<$ 1 lb.	May use some extra fuel in a large maneuver involving a large middle gimbal angle due to transient in body rates every two seconds. For normal mission fuel diff $<$ 1 lb.

* Kalcmanu presently accepts inputs determining 90° MGA and may produce ARCSIN abort.

CONSIDERATION	GIMBAL DRIVE	BODY DRIVE
7. Main engine propellant consump.	No diff on normal mission. Will achieve terminal attitude in minimum time on aborts, therefore save propellant.	No diff on normal mission. Aborts may hang up on gimbal lock cone, impair trajectory and use excessive propellant.
8. Thrust pointing steady state	Virtually no inherent error.	Virtually no inherent error.
9. Thrust pointing during transients	Thrust offset not corrected during X axis transient. Trivial deficiency in practice. Dead-beat response to step command (exact terminal attitude commands produced on first iteration)	Response to step command is a convergent series of attitude maneuver commands to autopilot. Imperfect thrust pointing and excessive RCS prc pellant consumption. Trivial deficien in practice.
10. Window pointing	Window pointing vector may lie out of the ZX body plane by approximately the Z component of the thrust offset angle vector multiplied by the sine of the angle between the window vector and the Z body axis. The spacecraft will approach the landing site with the Z axis in the plane of motion.	Window vector will be kept in the ZX body plane. The spacecraft will appro the landing site with the Z body axis displaced from the plane of motion by the Z component of the thrust offset angle vector multiplied by the tangent of the angle between the window vecto and the Z body axis.
11. Gimbal lock alarm	Alarm appears immediately when inputs to FINDCDUW determine a terminal attitude in gimbal lock.	Alarm does not appear until spacecra is maneuvered to within 20 degrees of gimbal lock.
12. Verification	Approx. 40 bench tests have been run, and all environmental simulations since Sundance Rev. 275 (March 7) have used the gimbal drive version. Every branch has been tested with every possible outcome, therefore every path, every instruction has been executed and observed to work as planned. Autopilot inputs have been verified for consistency by direct computation and by production of phase plane plots which demonstrate correct transient and steady state response to the satisfaction of the autopilot engineers, and the author.	Same except environmental simulatior run primarily before March 7.

CONSIDERATION	GIMBAL DRIVE	BODY DRIVE
13. Documentation	GSOP and other documentation must be redone.	Same. Although a fine testing and documentation job has been done by Kriegsman and Gustafson, it is not wholly applicable to either version.
14. Effects on other problems.	Provides basic routines which other programmers can use to further relieve the present execution time problem.	Provides nothing of use to others.

Summary:

The primary difference between the gimbal drive and body drive versions of FINDCDUW is that the gimbal drive version avoids gimbal lock completely on any maneuver in which the terminal attitude is not in gimbal lock. This makes the PNGCS abort guidance not dependent upon manual intervention.

In contrast, the body drive version may produce a maneuver penetrating the gimbal lock cone even though the terminal attitude is not in gimbal lock. This could require manual intervention to maneuver around the gimbal lock cone, and during the process excessive main engine propellant would be consumed and the trajectory would be impaired.

The gimbal drive version is faster and also provides basic subroutines which other programmers can use to further relieve the present execution time problem.

All other differences between the two routines are insignificant. Therefore we should use the gimbal drive routine.