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Vernon L. Grose

Vice President, Tustin Institute of Technology, Santa Barbara, California

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DELETERIOUS EFFECT ON ASTRONAUT CAPABILITY OF VESTIBULO-OCULAR
DISTURBANCE DURING SPACECRAFT ROLL ACCELERATION

Vernon L. Grose
Vice President
Tustin Institute of Technology
Santa Barbara, California

This study discusses the physiological limitations of the human and his susceptibility to error when subjected to extended and accelerated spacecraft rolling. The context for discussion is provided by the Gemini VIII spaceflight emergency of uncontrolled and accelerated rolling which caused the premature abort of the mission. Data from this flight imply that astronaut performance was impaired due to vestibulo-ocular disturbance. Five deleterious effects are attributed to spacecraft roll acceleration: disorientation, dizziness, impaired vision, nausea, and panic. Recommendations for astronaut selection and conditioning as well as spacecraft design are proposed to minimize these effects of accelerated rolling.

Introduction

On 16 March 1966, the Gemini VIII (GT-8) spacecraft successfully rendezvoused with an Agena target vehicle. Shortly thereafter, man's first docking of two vehicles in space occurred. Astronaut Neil A. Armstrong, America's first civilian astronaut, was the command pilot of GT-8, and his copilot was USAF Major David R. Scott.

Within a few minutes following the docking, the GT-8 Orbit Attitude and Maneuver System (OAMS) engine No. 8 initiated, without command, a series of sustained firing periods of varying lengths. These energy impulses caused the two joined vehicles to begin a lengthy period of uncontrolled maneuvering, predominantly in the roll mode. The astronauts attempted almost immediately to stop the motion and decouple the two vehicles. However, due to disorientation resulting from vestibulo-ocular disturbance, their efforts to regain stability were seriously impaired. Several less-than-optimum decisions were made, one of which (firing engines in both of the redundant Reentry Control Systems) necessitated an immediate abort of the mission at an unfavorable landing site.

Discussion

In little more than sixty years, man has moved from the terrestrial environment to which for untold centuries he had become acclimated into the rather hostile environment of space flight. In the recent years, remarkable feats have been accomplished in space by man, but the same feats have highlighted some previously unknown limitations of the human.

Vestibulo-ocular Disturbance

The human ear and eye are so coupled, that during skull rotation, the eyes respond to impulses from the inner ear. This linked inter-coupling is described as the "vestibulo-ocular" function. During quiescent periods when the body is at rest, there is no evidence of the vestibulo-ocular sensors. On the other hand, any movement of the head, (1) by the neck rotation proprioceptors, (2) in conjunction with whole body rotation, or (3) due to external environmental forces which influence the inertial state of rest, produces a vestibulo-ocular reaction to the "disturbance" from a state of rest. This elicitation of response from the vestibulo-ocular sensors is defined as "vestibulo-ocular disturbance" and does not imply, per se, a deleterious situation.

The two vertical semicircular canals of the inner ear are so oriented in the skull that, during pitch or roll head movements, both of the vertical pairs of canals are stimulated (see Figure 1). In contradistinction, movement about the vertical axis of the body (yaw) results in stimulation of the horizontal canal only. The significance of this difference between yaw and the other two directions of movement (pitch and roll) is discussed later.

Vestibulo-ocular disturbance can produce several physiological effects including vertigo, nystagmus, and Coriolis effect. Each of these effects is discussed briefly.

Vertigo. In its broadest sense, vertigo is not only a sensation as if the surroundings were revolving, but it also includes a state of unsteadiness and difficulty in orientation. Vertigo may additionally incorporate the more diffuse sensations of mental bewilderment and confusion, although these may be considered to be more psychological than physiological.

Specific types of vertigo include Coriolis acceleration, vestibular stimulation in roll, and alternobaric.¹²

Soviet cosmonauts Feoktistov and Egorov experienced unpleasant dizzy sensations (vertigo) during moderate or sharp movements of the head while in ordinary orbital flight. The character and extent of illusory sensations and dizziness were the same during the period of free flight as during stabilized flight.¹⁸

Nystagmus. When a person seated on a

revolving chair is rotated, the eyes execute peculiar movements. During the rotation, the eyes fixate upon, and keep in view, a certain object. The eyes, therefore, move in the direction opposite to that of the body. When the eyes have turned as far as possible and the object can no longer be seen, the eyes very swiftly move in the direction of the body rotation and fixate on another object. And thus the process is repeated. The slow movement of the eyes in one direction and the swift motion in the opposite direction is known as "nystagmus."¹⁰

In laboratory experiments conducted on ten different subjects, nystagmus has been found to persist without alteration of directional behavior for as long as rotation continued, i. e., five minutes at 60° per second. Furthermore, the velocity of sustained nystagmus increases progressively with the speed of rotation.² This persistence is a greater problem under accelerated motion than under linear velocities. For example, rotation about a horizontal axis at constant angular acceleration has been demonstrated to yield a continuous nystagmus which persists long after the theoretical end of nystagmus.¹⁰ The persistence of post-rotational ocular nystagmus is particularly severe in the roll plane.⁸

While nystagmus frequently occurs in conjunction with vertigo, it is possible to experience one without the other. For example, the Soviet cosmonauts mentioned earlier did experience vertigo which was not accompanied by nystagmus.¹⁸

Coriolis Effect. The Coriolis effect is consequential only where the body being acted upon is in a frictionless environment. Therefore, although it does not affect automobile travel, it is of considerable consequence in spacecraft. Even in deep space where earth gravitational attraction is insignificant, the Coriolis effect cannot be ignored as a source of coordinate error because the solar system itself, together with its near neighbors, is slowly rotating around the hub of our galaxy 30,000 light-years away!¹³

A physiological peculiarity of Coriolis effects is that, during motion about the roll axis for example, the direction and magnitude of such effects vary depending on the geometric relationship between the roll axis and the velocity vector of the astronaut relative to the spacecraft. In other words, either rotation or cocking of the head in the direction of roll would result in additive Coriolis force, making the head feel heavier than normal. Likewise, rotation or cocking of the head opposite to the direction of roll would make the astronaut's head feel lighter than normal.¹¹

Another Coriolis effect is the highly undesirable cross-coupling of the three semicircular canals in the inner ear due to rotating the skull in more than one plane simultaneously (such as occurs in spacecraft rolling) or in a single plane while still experiencing post-rotational effects in the other two planes.⁸

The Coriolis vestibular reaction can be produced readily under laboratory conditions by tilting the head during simple whole-body rotation. In fact, this technique is utilized occasionally to detect those who are likely to have strong tendency to airsickness.¹ Adaptation to a rotating system by making the necessary compensations (learned responses) to overcome Coriolis effects has been successfully demonstrated.¹⁵ However, the feasibility of such adaptation is of questionable practical value.

Effect of Weightlessness

There is no a priori reason to assume that vestibulo-ocular disturbance would result from a state of weightlessness alone. Since the semicircular canals are devices that sense "change," it could be assumed that weightlessness simply represents a revised threshold from which to read change. In recent experiments, this assumption appears valid because no significant differences in nystagmic response could be detected at zero g than at one g (at least in the vertical axis where only the horizontal canals are in the plane of rotation).⁵ However, these tests were performed in a C-131 aircraft which can sustain only 10 seconds of continuous weightlessness during a parabolic maneuver. Herein lies some question as to whether the assumption can be considered valid. Terrestrial simulation of zero g is expensive, brief, and preceded and followed by high gravitational forces. Laboratory test results concerning weightlessness, therefore, must be cautiously trusted.

American astronauts have not apparently experienced vestibulo-ocular disturbance directly attributable to weightlessness. Soviet space experts, on the other hand, interpret the fact that cosmonauts Feoktistov and Egorov experienced vertigo in free flight as well as stabilized flight as indicating that illusory effects and/or vertigo are probably caused not by Coriolis forces alone but also by the direct effect of weightlessness.¹⁸

In another laboratory experiment wherein the vestibular apparatus failed to demonstrate an expected accommodation with changes in the linear acceleration vector, it was postulated that the behavior of the semicircular canal receptors, or the central integration of these signals, is significantly modified in the weightless environment.²

Resolution of whether weightlessness produces vestibulo-ocular disturbance awaits further testing. Data to date are conflicting or inconclusive. Since weightlessness is a foreign environment for the human, the likelihood of its detection by (and thereby disturbance of) the vestibulo-ocular system should not be eliminated as a possibility.

Roll Versus Yaw or Pitch

If either the Superior Vertical or Posterior Vertical semicircular canals in the inner ear were in the pitch plane for the human (i. e., that plane established by spinning head over heels about the waist as an axis), then the remaining canal would have to be in the roll plane, providing the three canals remained orthogonal. Figure 1 clearly shows, however, that when the human pitches forward, both of the mentioned canals are stimulated. Likewise, both canals are again stimulated or disturbed in the roll plane, i. e., that plane established by rotating the body about an axis that passes through the torso from chest to back.

As mentioned earlier, only when the human is rotated about an axis running from his head down through his feet (the yaw axis) does he stimulate a single semicircular canal, the horizontal. For this reason, man is best equipped for yaw motion here on earth. Laboratory studies have further shown that, under various angular velocities as high as 60° per second, the roll and pitch motions produce a considerably greater rate of development of error in response to rotational stimuli than are exhibited by rotating in yaw motion.⁹

Even though two pairs of semicircular canals are stimulated in both roll and pitch (thereby making these two maneuvers more severe than yawing), pitch motion is not considered to be as deleterious to human behavior as rolling. The greatest physiological penalty is attached to rotational movement of the skull in its roll plane.⁸

As further proof that roll maneuvers are more severe than either yaw or pitch motion, optokinetic "following," i. e., tracking and focusing of the eye while the skull is in motion, has been shown to be very much less effective in the roll plane than in yaw or pitch. Roll movements on earth are relatively rare and short, but in flight where they may be sustained, the vestibular drive is quickly lost. Because of the virtual absence of visual tracking in this plane, substantial image slip then ensues.⁶

The problem of "image slip" is compounded when the vestibular signal is incorrect, e. g., during recovery from a roll maneuver (at which time the vestibulo-ocular response is reversed), because eye movement in the roll plane follows

the misleading vestibular signal.⁶

The time constant for the exponential cupular damping of the eye is generally agreed to be 16 seconds in the yaw plane. In the pitch and roll planes, the time constant drops to a third of that for yaw.⁶ This unequal relationship yields a vectorial error in orientation.

Roll Acceleration Versus Roll Velocity

The term, vestibulo-ocular, involves two of the external sensors in the body--the inner ear and the eye. Independently, these two sensors are not affected in the same manner by all external forces. For example, the semicircular canals of the inner ear are basically acceleration sensing organs, i. e., they sense the rate of change of velocity. (Yet, they are not sensitive to linear acceleration!¹⁴) As was cited earlier in discussion of nystagmus, the eye is sensitive and responsive to linear velocity. This difference in response to the same force by the ear and eye is significant because it emphasizes the unreliability of the human as either a velocity or acceleration detector.

Centripetal acceleration (and hence centrifugal force) increases as the product of the angular velocity squared times the radius of rotation. Experiments to determine the effect of linear acceleration on nystagmus by varying angular velocity have confirmed that the cupula is not a reliable detector of linear acceleration.¹⁰

Since the three semicircular canals are orthogonal, the brain is furnished data on both the direction and magnitude of skull angular velocity relative to space. This velocity signal then drives the eyes to compensate, similar to a velocity servo-control system. However, this compensation signal generally only lasts for the few seconds during which there is a rate of change of velocity (i. e., acceleration). Thus seriously misleading signals can arise during relatively long durations of angular movement when the acceleration drops to zero, causing the inner ear to believe that the head is at inertial rest.⁶ In addition, there is a severe Coriolis effect in a linearly rolling spacecraft, due to the short distance (radius) from the roll axis.

At the moment of roll initiation as shown in Figure 2, the eye is twisted violently round in the anti-compensatory direction through a large angle and all useful compensatory response is temporarily abolished. This critical period of violent twisting occurs both on entering and recovering from a roll maneuver as well as during other periods of angular acceleration.⁶

From a deleterious viewpoint, acceleration of rolling appears to be more severe than linear roll velocity. Furthermore, conditions of

acceleration will likely be more frequent than periods of constant angular velocity in spacecraft, even in unscheduled emergencies such as occurred with Gemini VIII.

Physiological/Psychological Interface

Tables I and II (Figures 3 and 4) summarize a dramatic series of events which could have claimed the lives of two astronauts. The scope of interest has thus far been limited to only the physiological parameters affected by this perilous experience. However, to completely separate the psychological from the physiological is difficult when these aspects of the emergency are considered:

1. The astronauts were performing a first-time activity, never accomplished by man previously.
2. Neither astronaut had previous space-flight experience.
3. Both men had been completely occupied with mandatory tasks for seven continuous hours prior to the emergency. (It has been suggested that had the docking maneuver been delayed until the astronauts had had an opportunity to sleep and also further familiarize themselves with spacecraft operation, the men would have been better equipped to meet the demands of the emergency.)
4. There had been no terrestrial simulation of roll acceleration simultaneously with weightlessness (particularly in performance of a first-time event with life at stake!).
5. Once the spacecraft was separated from the Agena, both vehicles were tumbling in a different pattern. The Agena periodically disappeared from the viewing window of GT-8, and since the Agena was loaded with hypergolic rocket propellants, a slight impact of the two vehicles would have resulted in an explosive disintegration of both.
6. Command pilot Armstrong's pulse was reported to have been 156 beats per minute for a sustained period.

When these unique aspects are considered in toto, the impact of the psychological on physiological reaction is obvious.

Results

The physiological limitations of man, when he is subjected to accelerated spacecraft rolling, include a high susceptibility to a series of symptoms which are deleterious to an astronaut's ability to pilot a spacecraft.

Deleterious Symptoms

Several deleterious manifestations of vestibulo-ocular disturbance are almost certain to occur during a period of accelerated rolling in a spacecraft. Five symptoms of vestibulo-ocular disturbance which have a high probability of occurrence in a situation similar to the emergency of Gemini VIII are discussed.

Disorientation. The Coriolis forces discussed earlier are responsible for producing varying degrees of disorientation and confusion. The geometric location of the astronauts' heads in the Gemini spacecraft makes the following quotation particularly significant: "Radial motion in the vicinity of the roll axis and the distortion of the environment due to change in resultant force both in magnitude and direction would probably cause the onset of illusions and mental confusion."¹¹

A complication concerning disorientation is that the symptom may be undetected by the person involved and only noticeable to objective observers. Therefore, even if astronauts were to testify that they were not disoriented, greater significance would be placed on an analysis of the sequence of decisions, the timing required for each decision, and the logical quality of each decision occurring during a questionable period of time such as accelerated spacecraft rolling. For example, even though Armstrong and Scott demonstrated outstanding and courageous action during great peril, the timing between events in Table I suggest that, had they not been in a rolling maneuver, less time would have been required to reach some of the decisions. Far from being critical of admirable response by the astronauts, this observation simply highlights a physiological limitation in any human being.

Dizziness. As previously mentioned, the Soviet cosmonauts experienced unpleasant dizzy sensations during moderate or sharp movements of the head and therefore restricted their movements or made smooth movements as they performed required operations. This dizziness was not necessarily associated with roll maneuvers, and Coriolis forces were even eliminated as the cause.¹⁸

Dizziness is virtually a certainty during periods of angular acceleration in any axis, but it is most likely to occur in roll or pitch.

Impaired Vision. While the eyes normally "compensate" for skull rotation, there is evidence demonstrated during flight, especially during early stages of roll (i.e., 180° per second) or sustained during acceleration in the roll mode, that the expected compensatory response may be virtually eliminated for several seconds (or longer in acceleration) due

to anti-compensatory response. Presumably, consequent failure of retinal image stabilization could cause serious impairment of visual acuity.⁷ (Actually, a battle ensues, out of phase, between the compensatory and anti-compensatory responses which precludes image stabilization.)

The eye rotation shown in Figure 2 occurs upon entry and during recovery from rolling maneuvers, and the visual image of the outside world is rotating fast over the retina, presumably with consequent blurring of the image and risk of misinterpretation of the target's relative movement.⁶ This blurring of the image is undoubtedly why interpretative or impressionistic photography of amusement concessions such as a roller coaster frequently picture a blurred scene.

Significantly, astronaut Armstrong was quoted as having said in debriefing interviews that during the emergency of Gemini VIII he could not "see" the circuit breakers which controlled the malfunctioning OAMS rocket engine. These breakers were located above his eye level. Apparently in response to Armstrong's report, the circuit breakers were relocated on the instrument panel for Gemini IX and subsequent flights. Whether this problem was due to image slipping or Coriolis-induced nystagmus (resulting from head movement) has not been discussed in official NASA reports released to date. Nevertheless, impaired vision is to be expected during accelerated rolling.

Nausea. Astronauts in both the Mercury and Gemini programs have experienced nausea. However, this reaction to vestibulo-ocular disturbance has occurred only after the spacecraft have landed in the water and displayed their well-known instability as ocean-going vessels. No orbital experiences of nausea have been reported in American manned spaceflight.

On the other hand, nearly all terrestrial testing to simulate rotational conditions in space results in nausea for the participants. This reaction is particularly frequent when simulating roll or pitch maneuvers. While nausea can be classified as a physiological phenomenon, it is influenced by psychological factors, and perhaps the select sample of astronauts are less affected by the psychological elements than the more heterogeneous group of personnel who have been tested on the ground.

Since nausea can be directly attributed to disturbance of the vestibulo-ocular system and since it further is a discomforting occurrence for anyone, it is concluded that nausea is a probable and deleterious result of spacecraft roll acceleration.

Panic. Whether or not panic can be properly classified as a physiological symptom of

vestibulo-ocular disturbance, panic is certainly nurtured and stimulated by the other symptoms discussed earlier. Furthermore, panic produces physiological reactions that secondarily influence these same symptoms.

Danger to physical well-being or loss of life existed in the emergency of Gemini VIII. This fact is confirmed by the American Institute of Aeronautics and Astronautics presentation of its 1966 Astronautics Award to astronauts Armstrong and Scott "for their outstanding contributions and accomplishments in the technology of manned space flight at great personal risk." Panic would have been difficult to preclude in such danger whether the spacecraft was rolling or stabilized. Therefore, panic cannot be considered a primary symptom or result of vestibulo-ocular disturbance, but in spacecraft missions where sustained disturbance could occur, panic is a probable secondary result.

Permanence of Effects

Fortunately, the effects of vestibulo-ocular disturbance to date have been transitory. Extended space missions which might last for months or even years could produce in astronauts some effects analogous to a sailor's "sea legs" in which accommodation to rotational stimuli would be developed for long periods of time. However, if this were to occur, the effects would undoubtedly be considered as beneficial rather than deleterious, at least while the astronaut was in space.

Recommendations

Accelerated spacecraft rolling produces deleterious effects for an astronaut. Because such rolling maneuvers may either be necessary or unavoidable in future space missions, the effects can be reduced in severity by giving special consideration to the astronaut or the spacecraft or both.

Astronaut Selection Criteria

Both the United States and the Soviet Union have used tests to screen candidates for tendencies toward airsickness. While the Soviets feel that their current ground test methods make it possible to predict (to a limited degree) the possibility of vestibular disturbance in flight, the methods of vestibular examination have proven insufficient for determining the type and extent of possible vestibular disturbances.¹⁸ In fact, the vestibular reactions of the cosmonauts in the "Voskhod" spaceship were disappointing to the medical personnel who had tested all three of the cosmonauts for an extended period prior to the flight.

The United States Navy has likewise screened its pilots, in an experimental program, by including a Coriolis vestibular reaction during preflight to detect and eliminate those who are likely to have strong tendency to airsickness.¹ In a similar program designed to detect differences in nystagmic response between the weightless state and normal gravity, only candidates who showed a high tolerance for vestibular stimulation were utilized.⁵

Notwithstanding the two test programs just described, there may be more logic in selecting personnel for extended space missions involving rotational maneuvers who have labyrinthine defective histories than those with normal vestibular response. In an experiment to study the effects of prolonged rotation on postural equilibrium, personnel with normal vestibular capability were compared with others who had defective vestibular responses. Ironically, those with defective capability showed better adaptation to prolonged rotation than the subjects with normal histories!³

It is recommended that additional testing of vestibular response versus accommodation be performed. Hopefully, this further work would yield conclusive criteria for selection of personnel who would have the minimum likelihood of deleterious disturbance in spaceflight.

Astronaut Conditioning

Just as there is conflicting evidence in the literature regarding the efficacy of selection criteria for minimizing deleterious effects of vestibulo-ocular disturbance, so the literature disagrees on the possibility of conditioning personnel to withstand exposure to rotational stimuli. In one experiment where nystagmus persisted as long as rotation continued, the conclusion drawn was that there is apparently no accommodation on the part of the vestibular apparatus.²

Results of another experiment indicated that adaptation to a rotating system by making the necessary compensations to overcome Coriolis effects has been successfully demonstrated. However, such compensations are learned responses requiring dynamic exposure and correction for time periods in excess of four hours.¹⁵ Obviously, this four-hour conditioning period would have little appeal or usefulness in a situation such as occurred in Gemini VIII. Furthermore, the rotation in this experiment was in the yaw plane at a maximum rate of 12 rpm,

A third test produced results indicating that adaptation to rotational stimuli may be only a partial answer for conditioning astronauts. Since a logical extension of adaptation to roll maneuvers may be to have space stations produce

artificial gravity by a constant roll rate, this study showed that adaptation will not alone compensate. There must be additional countermeasures, i. e., the astronauts will have to be trained to limit or avoid specific types of activity.⁴

One example of an activity which astronauts should be conditioned to avoid is the rotation of the head about the roll axis. This can be to some extent achieved by continuously directing the head and eyes toward a fixed point, thereby constraining the angular movement of the skull. This constraint will also avoid the highly undesirable cross-coupling effect (so-called Coriolis effects in the canals) due to rotating the skull in the pitch plane while experiencing post-rotational effects in other planes. Furthermore, the unwanted persistence of post-rotational ocular nystagmus in the roll plane would be substantially prevented.⁶

Future space missions will require greater physical activity and will thereby introduce a more severe environment for vestibulo-ocular disturbance. Perhaps the extensive and lengthy NASA astronaut training program already includes both adaptation and avoidance disciplines for this reaction. If not, such conditioning is recommended.

Spacecraft Design Principles

The vestibular system, the neck rotation proprioceptors, and the visual system form a major part of the control system which maintains the eye stationary relative to a target, e. g., the spacecraft instrument panel. Figure 5 depicts this interrelationship of control.

In manned systems, the spacecraft designer makes assumptions regarding optimum control modes to be allocated to the astronaut. There are many functions which represent gray areas rather than clear-cut man or machine activities. Since the rotational environment is more deleterious to man than to machines, the designer is obliged to become knowledgeable concerning the limitations that vestibulo-ocular disturbance imposes on the human before he finalizes the functional allocation for the spacecraft.

Spacecraft motion cues, i. e., those that are sensed by the vestibular system, can be helpful to astronaut performance. However, as the frequency of disturbance from normality increases, the usefulness of motion cues diminishes and can result in confusion, irritation, and disorientation.¹⁷ This non-linearity of usefulness of such cues is a complication in spacecraft design as well as in mission planning because automatic controls must be employed in an increasing degree as the environment for the astronaut becomes more severe.

Although the roll maneuver was an abnormal one for Gemini spacecraft, several principles for designing a vehicle to operate in constant roll (for artificial gravity) seem pertinent because they were not employed in the Gemini vehicle:¹¹

1. The crew compartment should be located as far as possible from the axis of rotation. (The Gemini astronauts were very near this axis.)

2. The work console instruments and controls should be designed so that left-right head rotations and up-down arm motions are minimized. (Armstrong had to reach up for the OAMS engine circuit breakers.)

3. The crew compartment should be windowless. (The Gemini vehicle required windows for numerous reasons such as photography, rendezvous, and docking operations.)

As a final principle for designers, an upper design limit on vehicle angular acceleration of 0.4 radians per second has been set forth as the standard to minimize canal sickness.¹¹

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TABLE I
EMERGENCY EVENTS OCCURRING DURING
FLIGHT OF GEMINI VIII
ON 16 MARCH 1966

Event Number	Event	Postlaunch Time (Hours, Minutes, Seconds)
1	Spacecraft roll initiated by unscheduled firing of OAMS Engine #8	7:00:41.0
2	OAMS Engine #8 stopped firing	7:00:46.0
3	OAMS Engine #8 started firing	7:00:50.0
4	OAMS Engine #8 stopped firing	7:03:20.0
5	OAMS Engine #8 started firing	7:07:20.0
6	Spacecraft decoupled from Agena	7:15:12.3
7	Attitude Control/Maneuver Electronics (ACME) disabled by pilot	7:15:50.0
8	OAMS circuit breakers disengaged (disconnecting all OAMS engines)	7:18:16.0
9	Engines in both Reentry Control Systems (RCS) fired to aid control	7:19:00.0
10	Astronauts report "partial control"	7:21 (approx)
11	Astronauts report "full control"	7:23:50.0

TABLE II
TECHNICAL DATA PERTINENT TO GEMINI VIII
EMERGENCY EVENTS (Courtesy of
Dr. J. C. Lee, Rocketdyne)

Datum Number	Datum
1	The maximum roll velocity during Events 1 through 6 of Table I was 20° per second.
2	Selective manual firing of OAMS Engines #3 and #4 to compensate for Engine #8 minimized the roll velocity during Events 1 through 6.
3	Maximum roll velocity during the emergency occurred between Events 6 and 8 when the roll rate reached 330-340° per second.
4	The maximum roll rate of 330-340° per second did not exist for more than 1 minute 9 seconds.
5	OAMS Engine #8 is rated at 25 pounds thrust and yields an acceleration of 2.5 to 3.0° per second per second.
6	The spacecraft diameter at the OAMS engine line is 14 feet approximately.
7	The firing of only one of the eight OAMS Yaw/Roll engines results in a combined yaw/roll maneuver by the spacecraft (see Figures 3 and 4). It is necessary to fire Engines #7 and #8 to produce a pure yaw maneuver, and likewise, both Engines #4 and #8 are required for a pure roll. Therefore, the spacecraft underwent a mixed yaw/roll maneuver (actually tumbled) during the firing of only Engine #8.

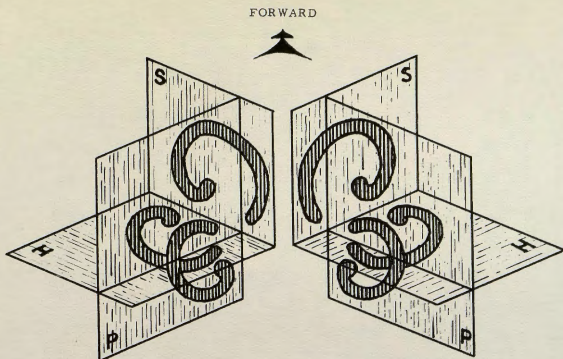


Figure 1. Diagram of semicircular canals: horizontal (H), superior vertical (S), posterior vertical (P) -- redrawn from reference 16.

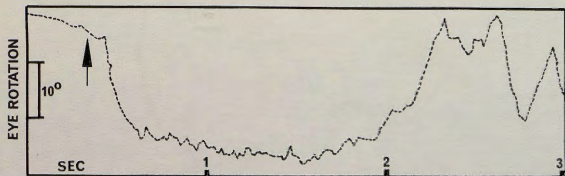


Figure 2. Rolling (torsional) eye movement during rapid roll maneuver (redrawn from reference 6).

^aActual record obtained from a pilot executing a 180° per second roll maneuver in an aircraft. The arrow indicates initiation of the roll. Downward deflection of the record is anti-compensatory eye rotation in the roll plane.

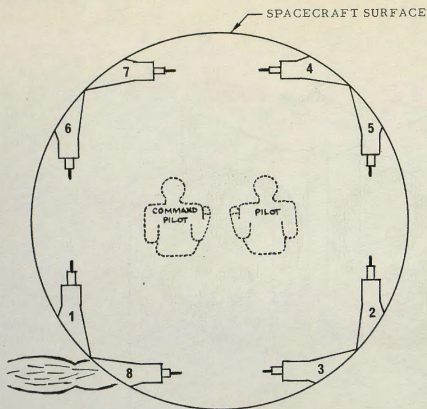


Figure 3. Orientation of OAMS 25-pound engines in the Gemini spacecraft (aft view).

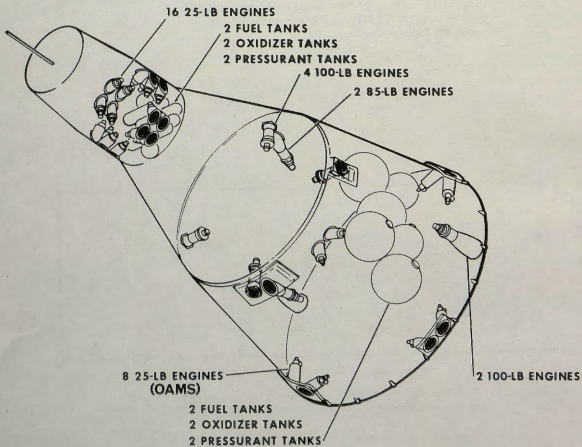


Figure 4. Gemini spacecraft propulsion

11-2-11

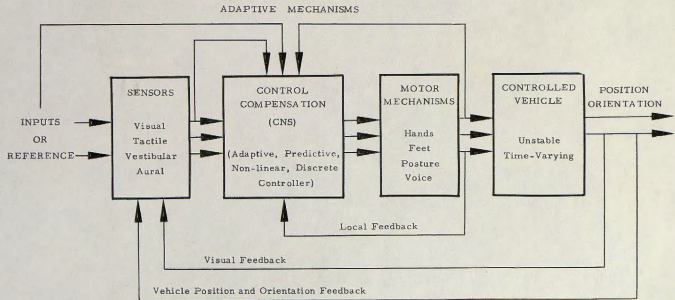


Figure 5. Block diagram of the man-vehicle control problem (redrawn from reference 17).