The Mercury Capsule Attitude Control System

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Abstract

THIS PAPER presents a description of the attitude control system of the Mercury capsule and indicates the manner in which automatic and manual subsystems are used to complement each other to provide suitable redundancy of control. The automatic system is described in some detail, and the performance of the system is partially demonstrated by sample flight test data.

System requirements

In accordance with the basic design concepts of the Mercury capsule, the manual and automatic control systems were developed to provide a redundant and integrated method of controlling the capsule attitude. The systems were designed to meet the requirements of ballistic and orbital flight, for normal and abort missions. Since the orbital mission includes all modes of control, it will serve as a basis for the system description. This mission profile is shown in Fig. 1, and its attitude control system requirements are summarized as follows:

(a) Provide a 180° yaw maneuver following separation from the booster, and achieve a zero-roll, minus-34° pitch attitude. In this attitude the retro-rockets are properly aligned and beacon transmission from the cylindrical portion of the capsule is not blocked by the heat shield.

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(b) Maintain attitude with ±10° accuracy until time of retrograde rocket firing.

(c) Maintain attitude with ±5° accuracy during retrorocket firing.

(d) Achieve re-entry attitude of +1.5° pitch, then maintain it until 0.05g deceleration is experienced.

(e) Provide re-entry roll rate of 10° per second to minimize touchdown dispersion, and limit pitch and yaw rate oscillation to 2° per second during re-entry.

The control system may be divided into automatic, semi-automatic, and manual subsystems, all of which utilize the decomposition of hydrogen peroxide for generation of thrust necessary for rotation of the capsule.

As shown in Fig. 2, two completely separate and independent fuel supplies are provided. One is primarily for the automatic control system and the other for the manual control system, although each may be used by auxiliary means.

The automatic control system, which has the capability of meeting all attitude control requirements throughout the mission, consists of an attitude reference utilizing two horizon scanners and two attitude gyros, three rate-sensing gyros, and control logic, which commands on-off operation of reaction control thrust. On pitch and yaw axes, 1-pound and 24-pound thrusters provide angular accelerations of 0.5 deg./sec.^{2} and 12 deg./sec.^{2}, respectively. On the roll axis, 1-pound and 6-pound thrusters provide 0.5 and 3 deg./sec.^{2}, respectively.

The reaction control system is supplied by Bell Aerosystems; the horizon scanners are manufactured by Barnes Engineering; and the remainder of the electronics, the Automatic Stabilization and Control System (ASCS), is

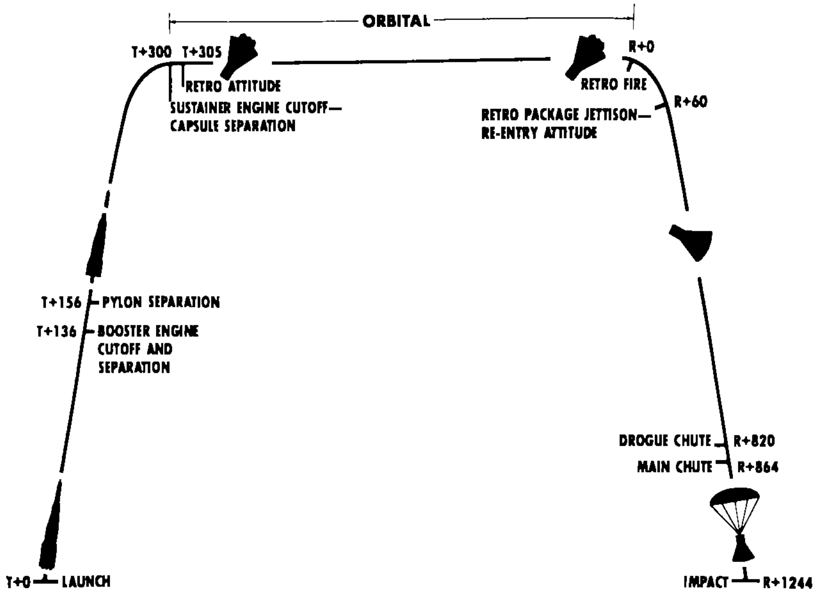

Fig. 1—Mission profile.

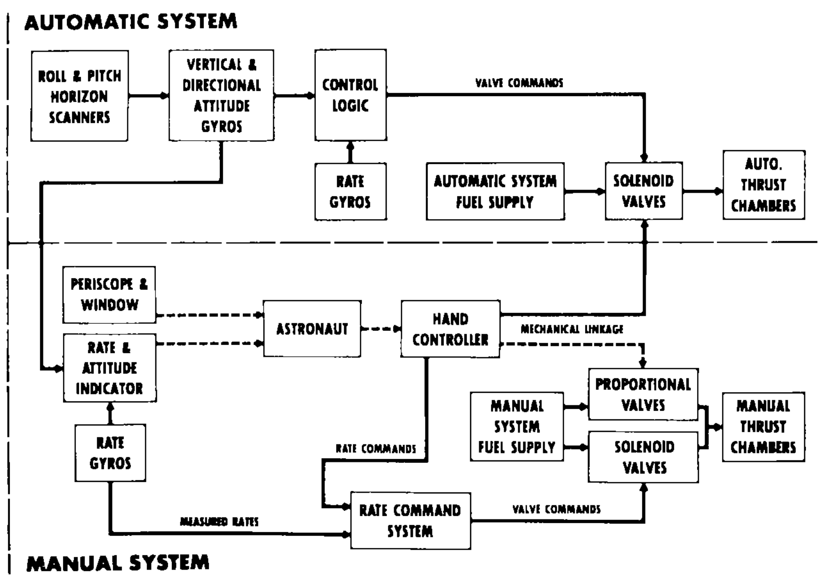

Fig. 2—Mercury attitude control systems.

supplied by the Minneapolis-Honeywell Regulator Co.

Manual control

The manual control system consists of a three-axis hand controller, which is connected by mechanical linkage to throttling valves. These valves provide fuel flow such that output thrust is essentially proportional to controller deflection and has a maximum value of 24 pounds for pitch and yaw control and 6 pounds for roll control. Several sources of attitude information are available to the astronaut. A 360° view of the horizon may be seen through the periscope, and a window gives direct but more limited view of the earth. In addition, a more quantitative display is provided by the rate and attitude indicator. The displayed attitude information is derived from the ASCS attitude gyros, and the rate signals are taken from a separate set of rate gyros. These same rate gyros are a part of the Rate Stabilization and Control System (RSCS). This semi-automatic system will, if selected by the astronaut, provide angular rates proportional to controller deflection, and in the absence of rate commands provides rate damping about all three axes. Like the ASCS, the RSCS is an on-off system which actuates solenoid-controlled valves, but it uses fuel from the manual system supply.

One other manual system, known as "fly-by-wire" (FBW), is also available to the astronaut as a means of utilizing the automatic fuel supply in case of a malfunction of the ASCS. Microswitches actuated by the hand-controller linkage energize low and high level solenoid valves of the automatic fuel system. Low level thrust is obtained at approximately ⅓ of total controller travel; high level thrust is obtained at ¾ total deflection.

It can be seen, therefore, that each of the independent hydrogen peroxide fuel supplies may be used by two separate systems of attitude control.

The physical locations of major systems, including the control system components, are shown in Fig. 3. Gyros and ASCS electronic equipment are mounted on shelves which are located on each side of the astronaut. The RSCS electronics package is located under the astronaut's right arm; the hand controller and linkage are also displayed. The pitch and yaw thrusters are located in the cylindrical section of the capsule, and the roll thrusters are located on the sides of the capsule near the maximum diameter. The horizon scanners are also mounted in the cylindrical section of the capsule.

The astronaut's instrument panel is shown in Fig. 4. At the top is the rate and attitude indicator. This instrument was designed to minimize eye motion by placing rate and attitude needles for each axis in close proximity. The instrument is located so that the rate indicator can be used in conjunction with either the window or periscope display. The ASCS/RSCS selector switches and reaction control fuel supply valves are on the left console. Automatic, semiautomatic, and manual control modes may be selected on any or all of the three axes, and superposition of manual and automatic control is possible.

Despite the control capability of the astro-

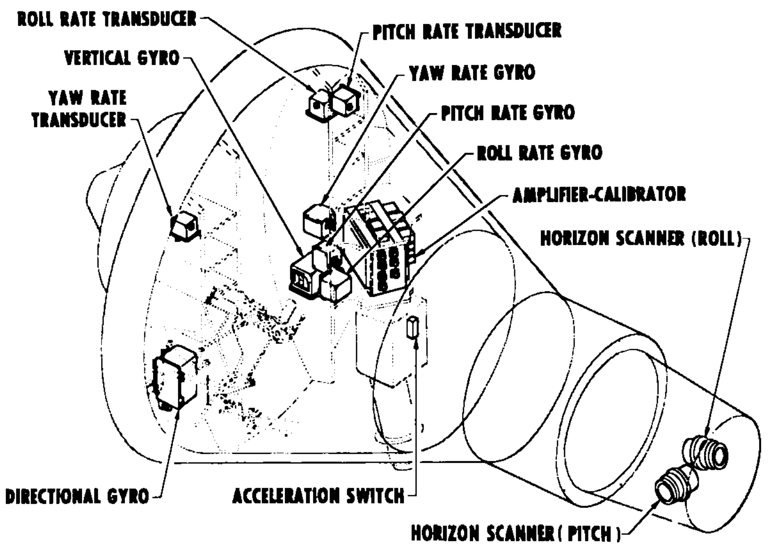

Fig. 3—Automatic stabilization and control systems.

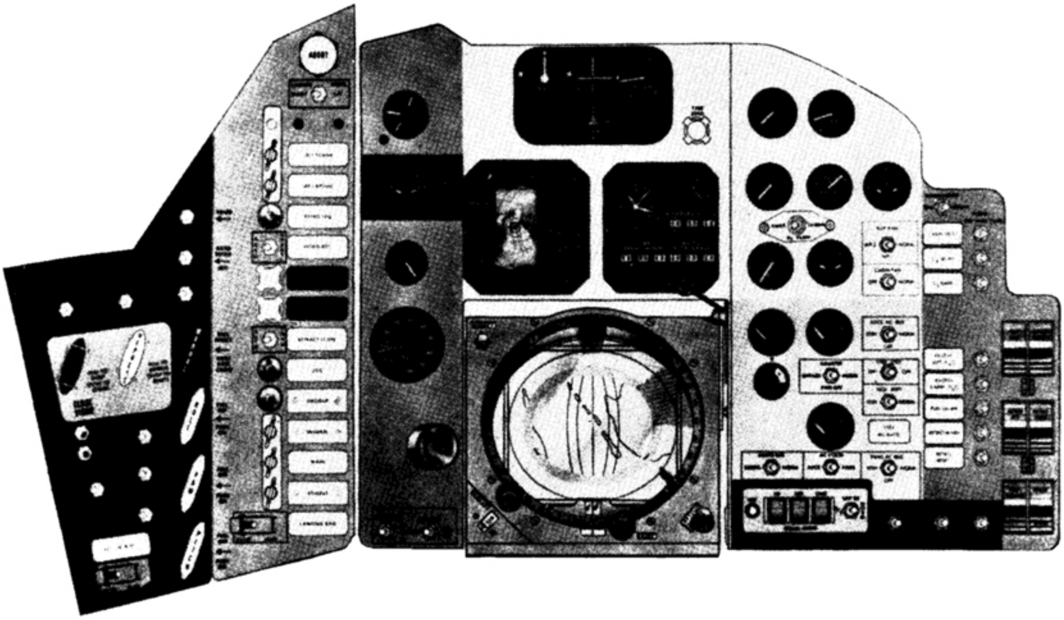

Fig. 4—Mercury capsule instrument panel.

naut, normal attitude control is provided by the ASCS, and of course in unmanned flights it must operate unassisted. This system, therefore, will be described more extensively and some early flight test results will be presented.

Automatic control

Fig. 5, a block diagram of the ASCS, shows it to consist of a set of rate gyros having outputs at discrete rates rather than proportional rates, a set of two two-degree-of-freedom attitude gyros, an 0.05g accelerometer switch, and a major electronics unit known as the amplifier-calibrator. Within the "amp-cal" are four major sections: mode logic, control logic, gyro slaving loops, and attitude repeater servos. The amplifiers and logic systems use solid state devices throughout; approximately 500 diodes and transistors are required. The mode logic responds to commands from capsule wiring and places the ASCS in an appropriate mode of control. The control logic maintains attitude control in one of several modes: orientation, orbit, retro-fire, or rate damping. The attitude repeater servos take the attitude gyro output synchro signals representing pitch, roll, and yaw angles, and drive multiple outputs: attitude sector switches for control logic, potentiometers for telemetry, and synchros for attitude indication to the astronaut. It is by biasing the pitch axis repeater that pitch attitude is changed from orbit to re-entry attitude.

As shown in Fig. 6, the slaving loops are used to slave the vertical gyro gimbals to the roll and pitch horizon scanners, to slave the directional gyro roll gimbal to the vertical gyro roll gimbal, and to slave the yaw gimbal of the directional gyro to a yaw reference signal derived from the vertical gyro slaving loop. This yaw reference signal is taken from the input to the roll (inner) gimbal torquer, since the average torquing rate of this gimbal is proportional to the yaw angle of the capsule. This may be more readily visualized from the vertical gyro gimbal diagram of Fig. 7.

In its normal, or zero yaw angle condition, which is shown as (a) in Fig. 7, the vertical gyro inner gimbal requires no torquing rate to maintain the spin axis vertical. For a 90° yaw angle of the capsule, shown as (b) in Fig. 7, the horizon scanner slaves the inner gimbal at the orbital rate in order to maintain a vertical spin axis. At any intermediate yaw angle, the

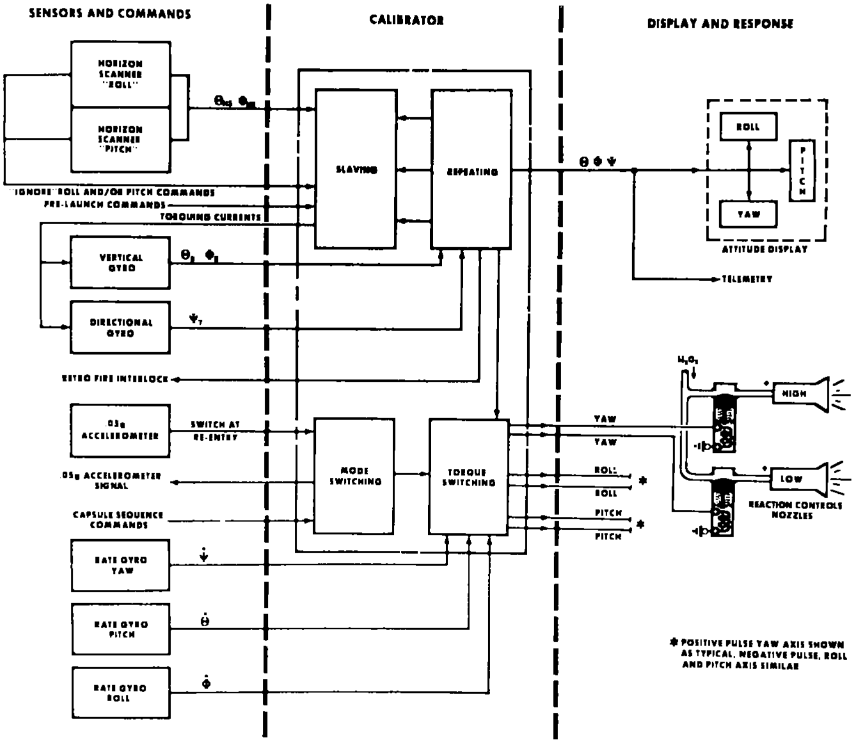

Fig. 5—Functional block diagram of ASCS.

torquing rate is proportional to the sine of the angle. For small yaw angles, therefore, the roll gimbal torquing signal, when multiplied by $(1/\Omega)$, is approximately equal to the capsule yaw angle and is the yaw reference to which the directional gyro is slaved. For economy of electrical power, the slaving loops are energized approximately eight minutes of every half-hour in orbit.

The control logic, which is made up of transistor and diode circuits not critically dependent on voltage, receives the step function outputs of the attitude repeaters and the discrete rate signals from the ASCS rate gyros. Using these step-wise indications of attitude and rate conditions, along with the output of the mode switching section defining the current phase of the mission, "decisions" are made which result in the actuation of appropriate reaction control valves.

Two examples of the control logic are shown by the phase plane diagrams of Fig. 8. In the upper portion of the figure the "retrograde attitude hold" mode is displayed. The control logic applies high positive or negative torque depending upon the combination of existing rates and attitudes. In this example, the positive disturbance torque initially adds to the control torque to reduce the negative rate. Following a period of zero control torque, negative torque is applied. The phase plane trajectory then continues to converge toward zero rate and attitude, but may reach an equilibrium point at 3° of error if the disturbance torque is sufficiently great.

In the lower portion of Fig. 8 is shown the orbit mode of control. In this mode, only attitude error signals are used to develop a series of torque pulses which increase in width as attitude error increases. These pulses produce sufficient impulse to damp original rates of 0.5° per second and provide a convergent limit cycle oscillation, which will normally exceed the ±3° boundaries only intermittently. The typical steady state oscillation shown has a period of approximately four minutes and requires less than 0.4 pound of fuel per hour. As a precaution, however, the

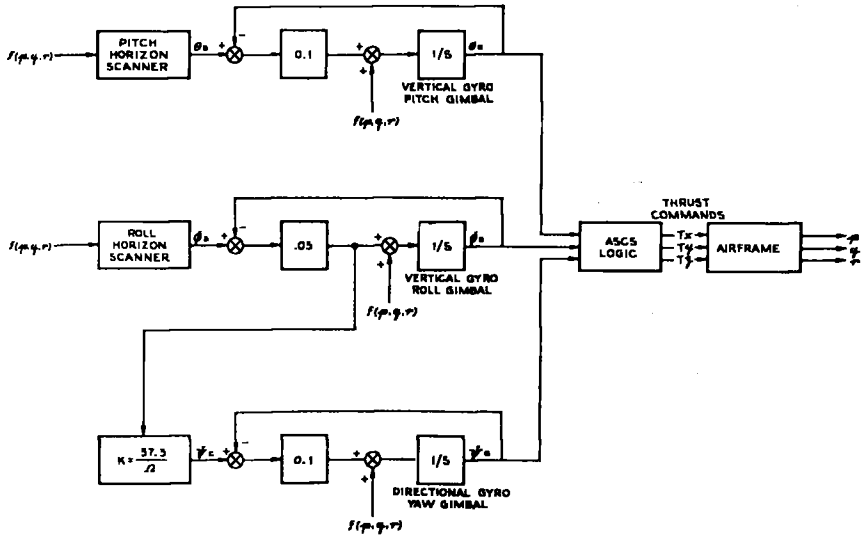

Fig. 6—Mercury yaw reference system.

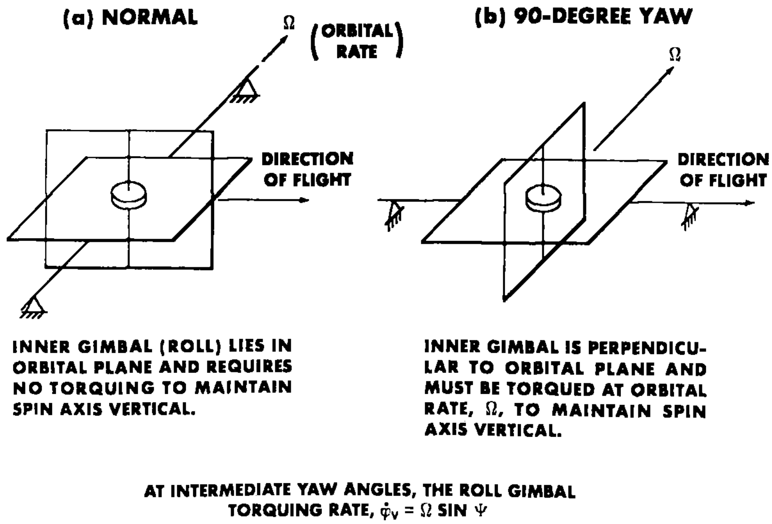

Fig. 7—Mercury vertical gyro orientation.

ASCS is programmed to revert to the maneuvering or "orientation mode" of control if attitude errors continute to increase beyond the values corresponding to the outer orbit mode pulses.

Other control modes are the orientation mode, which utilizes both high and low thrust and is employed during the capsule maneuvers, such as the 180° yaw rotation after separation, and the rate damping mode, used for re-entry. In the latter mode, both high and low torques are used, in response to rate gyro output signals.

System performance

Flight testing to date has consisted of five ballistic trajectory flights and three orbital missions. In general, the control systems have performed as designed, that is, satisfactory attitude control has been provided despite the occurrence of reaction control malfunctions. Fig. 9 illustrates the system performance during the first manned ballistic flight, with Commander Shepard at the controls. A portion of the yaw axis flight test data is shown in Fig. 9. Following

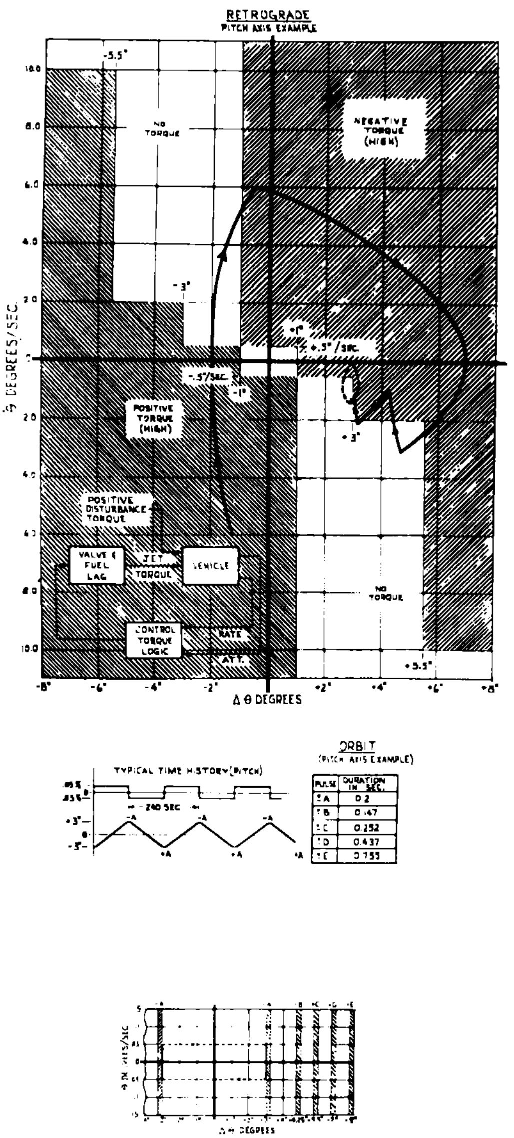

Fig. 8—Phase plane diagrams.

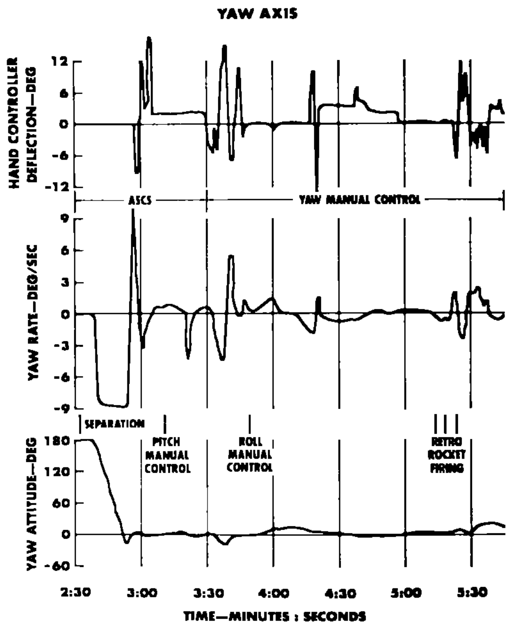

Fig. 9—Mercury 7 capsule flight test data.

capsule separation, the ASCS provides a five-second rate damping, then the 180° yaw maneuver. The ASCS then drops into the orbit mode of control for a short period. In accordance with the flight plan, manual control is achieved by turning off the automatic fuel supply in a pitch, yaw, roll sequence.

Manual yaw control is observed at $t = 331$ seconds, and thereafter yaw rates are manually controlled to less than 3° per second, even during the retrorocket firing period. Average yaw error during the rocket firing period is approximately 6°, a satisfactory value for an orbital mission since the resultant down-range error would have been less than 10 nautical miles. This error had no appreciable effect on the ballistic trajectory of Capsule No. 7, however.

Captain Grissom's flight was equally successful, and he was the first to make use of the RSCS.

There followed the three orbital flights: one orbit unmanned, two-orbit with Enos aboard, and the three-orbit mission of Colonel Glenn. In all of these orbital flights the systems have operated satisfactorily, but their performance has been marred by one recurring malfunction. In every case, during the first or second orbit there has occurred an apparent orifice blockage of one or more of the one-pound thrust chambers. When this occurs in the orbit mode, the capsule continues to deviate from the desired attitude until it reaches, in the case of the yaw axis, a value of 30°. At this point the ASCS returns automatically to the orientation mode and utilizes the 24-pound thrusters to reduce the error to zero. The system then continues to cycle in and out of the orbit mode and consumes fuel at the rate of about eight pounds per hour.

After a number of such cycles were noted in Enos's flight, the decision was made to terminate the mission at the end of the second orbit. In the case of Colonel Glenn, however, attitude control could be maintained somewhat more efficiently by use of the Fly-By-Wire and Manual Proportional modes of control so that he was able to complete the three-orbit mission. During the retro-rocket firing period, Colonel Glenn did employ the ASCS as the primary means of maintaining attitude while also applying manual proportional control.

In addition to the continuing emphasis on system cleanliness, modifications to the orifice plate and to the thrust chamber catalyst bed are expected to overcome the thruster problem; tests of these modifications are currently underway.

Summary

In summary, it can be concluded that the Mercury control systems have provided both automatic and manual attitude control of the capsule. With respect to the solid-state electronics system, it can be said that a high degree of reliability has been achieved; there has been no in-flight failure of any of the control system electronics components.

Based upon Colonel Glenn's flight, it is apparent that future spacecraft can dispense with the "fully automatic" design of the Mercury capsule and revert to the concepts of providing effective manual control modes for astronaut control, and of including pilot-selectable automatic modes which provide pilot relief or precision control when they are required.

A question-and-answer period followed Mr. Twombly's presentation.

Mr. John Walker, Douglas Aircraft: During this final phase, when a pilot will be controlling, what will his field of view be from the Gemini?

Mr. Twombly: Regarding the field of view of the Gemini pilots, it is somewhat complicated to describe because it is not a simple rectangle. However, each astronaut, having a window in front of him, will be able to see roughly about ten to fifteen degrees off the left of center line, and in the vertical plane roughly about thirty to forty degrees off to the right, perhaps another thirty degrees.

Mr. Tom Hedrick, North American Aviation: My first question: Are you planning to present any information to the pilot for rendezvous other than range and range rate?

Mr. Twombly: Yes. The angle information from the rater will also be displayed to him in the form of cross-pointer meters, and of course the other indications are those of the velocity increments required and the on-board fuel.

Mr. Hedrick: My second question: Is the radar on an inertial platform or is it mounted on the capsule?

Mr. Twombly: The radar is fully mounted. It is a development of the Westinghouse Company. It is not a gimbal radar. Basically, the antennas are mounted, circled but not gimbaled.

Mr. Walker: I'm sorry, I mis-stated the question. Is it necessary to orient the radar at any time during the last phase?

Mr. Twombly: The question is: Is it necessary, or does maneuvering the Gemini require, that the astronaut lose his line-of-sight view of the target? The answer is, "No, it should not, in that maneuvering thrusters are provided both fore and aft, left and right, up and down, and his normal catch trajectory should be such that he should have his target in view at all times."

Mr. Ken Kiser, Douglas Aircraft: My first question is: What acceleration capability does the astronaut have in his final phase at right angles to the range vector?

Mr. Twombly: Half a foot per second squared.

Mr. Kiser: And the second question: Is the target completely passive, or does it point at him at all times?

Mr. Twombly: As presently conceived, the target is active only to the extent that it does have a radar transponder on board and does maintain a fixed orbital attitude.