Telecommanded Inertially Referenced Attitude Control System (TIRACS)

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A telecommanded attitude control system for sounding rockets was developed to make the most effective use of real-time experimental data for accurate position updating. The system used a low-cost inertial reference complemented by semiautomatic and manual "joy stick" telecommanded maneuver corrections. Experiment and control system attitude data were presented in a simple but functional form to enable fast and efficient corrective action by the operator. The successful flight of the system in October 1975 demonstrated the advantages of a "man in the loop" and the feasibility of inexpensive accurate attitude control by telecommand.

Introduction

TELECOMMAND has been used in various forms for the attitude control of sounding rocket payloads. However, in most cases the philosophy has been to limit the commands to relatively simple event timing, selection of preprogrammed targets,[1] variation of maneuver rates, and small angular offsets.[2] The advantages of even such limited real-time remote control are obvious, but the logical extension of such a system to incorporate a man in the loop with full "joy stick" control for large maneuvers generalky has been regarded as unrealistic with operational flight times in the order of 8 min.

The specification and design of a low-cost, inertially referenced, three-axis attitude control system at DFVLR for the ASTRO 7[3] payload in the German national program, coincided with the development of a multichannel digital telecommand and slant range system by the telemetry group. The payload experiment of the Max Planck Institute at Heidelberg consisted of a uv polychromator and ir and visible photometers and was intended to observe zodiacal light. The availability of real-time star recognition from the experiment sensors enabled relatively inexpensive attitude updating of the control system and resulted in the development of TIRACS.

The development of the control system required a consideration of the technical and economic criteria of simple, real-time attitude reduction from experiment data and updating by telecommand. Information links, interfaces, and testing techniques were of considerable significance to the optimal use of a man in the loop.

Telecommand

Telecommand provides the means, during flight, to modify the sequence, timing, operations, and maneuvers of a sounding rocket payload. The advantage of telecommanded updating over onboard automatic systems lies in the greater range of general-purpose facilities for real-time data analysis which may be used on the ground for producing the flight corrections. These facilities may include a trained operator, special-purpose logic units, or even general-purpose computers. The most important problem for a given mission is to determine which functions may be remotely controlled profitably and what logic should be used.

The most rewarding area for incorporation of telecommand is in the utilization of experiment data for pointing bias correction. The majority of experiments in the field of astronomy consist of narrow-field-of-view sensors, which are required to be aligned to point sources or scanned across regions in which known bright sources exist.

The normal technique for single targets is to use an inertial platform as a coarse reference, followed by a star sensor and possibly a set of rate-integrating gyros, where the target is too far from a reference star or has no usable emission in the star sensor wavelength. The experiment sensor by its nature always will produce information if pointed at its intended target, and, except in the case of rapidly changing or weak sources where long integration times are necessary, the output is usable for attitude measurement. A coarse inertial reference is, of course, still necessary, and this may be provided by any of the relatively cheap roll stable platforms, which will confine the target to a quadrant of less than $6° \times 6°$. Where the experimental field of view is smaller than this, a raster scan or search pattern must be initiated. The experimental data must be processed to indicate the experiment pointing error, and the control system then may be corrected for any offset. As the payload is by this time effectively under zero g conditions, the inertial sensor is operated in its most favorable environment, and for most cases subsequent platform drift will not exceed the experiment field of view. In the case of large-amplitude scans, there is also a high probability that identifiable sources will be seen, remembering that the inertial sensor confines the instantaneous area of uncertainty to a few degrees. With two separate fixes, the platform bias may, in most cases, be calibrated accurately. A star sensor and rate-integrating gyros certainly will give less drift and smaller limit cycle amplitude but, without external correction, will not remove any bias due to misalignment of experiment and control sensor axes, and the use of such sensor can double the cost of the attitude control system (ACS) flight hardware.

The aforementioned technique would appear to be complicated and time-consuming; however, one is not confined to a coarse accuracy better than a few degrees, and the only ACS sensor required is a cheap platform. Assuming availability of telecommand equipment, the maximum utilization of experiment data in real time can enable considerable cost savings in high-accuracy sensors and provide a means to correct system errors in flight. The system may be used further to compensate for any flight variables and make optimal use of the limited flight time.

ASTRO 7 Maneuver Requirement

The ASTRO 7 experiment was required to scan a region of zodiacal light and then calibrate on a known reference source. The basic maneuver comprised three $\pm 40°$ scans, centered on the ecliptic and with a constant zenith distance of $80°$, followed by calibration on one of several selected stars. The error budget of the inexpensive MIDAS analog platform and

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the narrow field of view of the experiment sensor (1° half-cone) necessitated a raster scan of 6° ×6° in 1.5° steps, to insure observation of the desired reference star. Figure 1 illustrates the maneuver provided by an onboard programmer, which, in the event of disturbance of the up-down link, would have achieved most of the scientific objectives. Additional experimental requirements, such as a 25-sec hold on the ecliptic and acquisition of several stars, were made relatively easy by the use of telecommand.

Ground Control Loop

Given a requirement for telecommand of a payload and reliable up-down links, the design of the data processing, display, and control logic on the ground is of paramount importance. Although a completely automatic ground system, such as an on-line computer, could be used, the most versatile and cost-effective control element, for many applications, is a man. The design of any control system requires a systematic analysis of all of the control loops, and this is possible only with a knowledge of the transfer functions of all of the components of the system. Although this normally is not difficult with hardware, the addition of a man in the system loop poses a variety of problems.

The strongest arguments against the use of a man in any control loop concern the physiological requirements of human control and the possible unpredictability of man in a panic situation. Both problems are basically a question of cybernetics, or the communication links between the man and the machine, and may be minimized by careful design of ground equipment and adequate training of the operator.

In everyday motion control, man has at his disposal a variety of input sensors comprising vision, hearing, and senses of linear and angular acceleration. Data from these sensors are fed to the brain, which has been programmed from experience, and the output is in the form of rate demands. The use of a computer or man in the ground loop generates similar requirements for suitable input data and adequate programming or training for all possible situations. An inadequately programmed computer is no less of a problem than a confused man. The choice, then, may be based on a comparison of the high cost, speed, and accuracy of a computer vs the low cost, speed, and accuracy of a man.

The choice of a man as a dynamic element of the TIRACS system was based mainly on cost, as no suitable computer was available, and, if one had been, the programming and engineering effort of incorporation into the system was considered to exceed the likely benefit in this application. The disadvantages of speed and accuracy of a man were minimized by automatic aids in the data display and command processing, which simplified the function of the operator and made optimum use of his abilities as an adaptive element.

Data Displays

The major requirement of a data display for real-time attitude control is to give the operator the feeling of motion of the rocket. The ideal display is a visual presentation of the star background which can convey the impression of pitch, yaw, and roll motion. As only pitch and yaw were of primary importance on ASTRO 7, an extremely simple display consisting of an *x-y* plotter was used. The plotter chart was marked with all major stars of interest and the programmed maneuver. The effect of this display was remarkable, as the movement of the plotter pen over the star chart produced the necessary subjective sensation in the operator, of looking out of the rocket along the experiment axis at the stellar background. Once platform errors were obtained from the experiment, it was relatively simple to displace the desired targets the necessary amount. The only disadvantage with this display was concerned with system lags as the display indicated instantaneous, and not demanded attitude. This problem was minimized by limiting manual rate demands and hence instantaneous system errors.

Indications of roll position, rates, program, and telecommand signals were available on analog meters. Experiment data were displayed on an *x*-time chart recorder with a calibration to enable quick confirmation of reference stars.

Ground Command Generation

As mentioned previously, an onboard programmer was fitted in the flight system to reduce the effects of failure of the telecommand. To prevent major disturbances of the payload during switching from flight programmer to ground command, it was essential for the instantaneous signals of flight and ground systems to be the same. The ground logic, which is illustrated in Fig. 2 and was identical for pitch, yaw, and roll, was based on an amplifier/integrator. In the "tracking" mode, the amplifier produced the same command output as the flight program received by telemetry. In the "manual" mode, the capacitor held the level tracked unless driven in either direction by the joy stick. In tracking mode, the joy

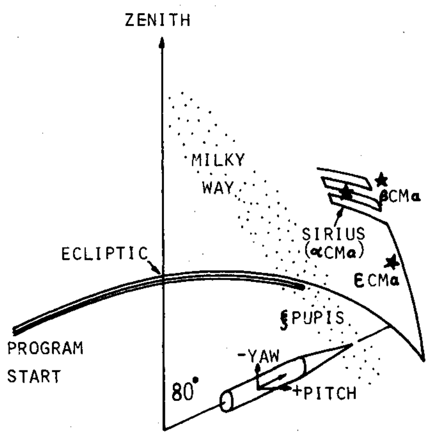

Fig. 1 ASTRO 7 program maneuver.

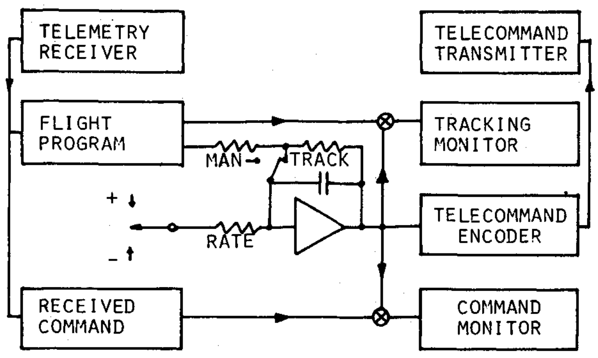

Fig. 2 Telecommand tracking logic.

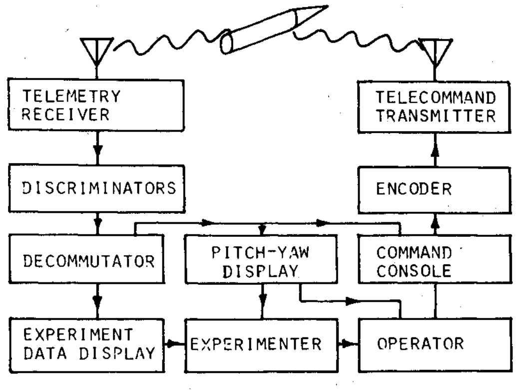

Fig. 3 Telecommand ground station logic.

stick also could be used for offsetting the tracking level. Additional logic indicated correct operation of the tracking and command loops.

Figure 3 illustrates the overall command logic of the ground station. ACS telemetry was processed by the command console to provide the *x-y* display and program tracking. From the displayed information, the command operator and experimenter generated the maneuver commands, which were encoded and transmitted to the payload.

Telecommand Link

The most important requirement of the TIRACS was an accurate and reliable analog telecommand system. The ground system consists of a channel multiplexer and encoder, which sequentially converts each input channel into a 34-bit word. Each word consists of two synch bits and eight 4-bit elements comprising two clock and two data bits, as shown in Fig. 4. The resulting word therefore contains only 16 data bits, of which up to six must be used for channel address and parity; however, the format permits reliable tracking by the flight decoder even in the event of significant clock rate changes.

If one considers the effect of a transmission error in a position or rate command loop, it is apparent that the resulting disturbance to the payload attitude or maneuver could be extremely detrimental to the overall performance and wasteful of control system gas. For this reason, each encoded word is transmitted twice sequentially. Although this again reduces the data rate by 50%, the flight logic then may check the received data for each channel before passing it to the control system. The ground and flight logic is remarkably simple and is illustrated in Figs. 5 and 6. The received demodulated signal is decoded, and each word is stored and compared with the following. Each word identical with that immediately preceding it is passed to the output memory, where the address decoder relays the appropriate output to the channel digital-to-anglog converter. The advantage of this system is that each telecommanded channel holds the last received correct information, and therefore intermittent or sustained transmission failures have the minimum degrading influence on the control system performance.

As the maneuver requirements of ASTRO 7 enabled the use of an onboard program unit as backup, additional fail-safe logic was included in the telecommand channels. In the event of excessivly low received signal strength or if any channel received no correct data in a preset time period, the whole system or appropriate output channel automatically would switch to the onboard program. In such circumstances, the operator would have the choice of continuing to command by the operational channels or reverting completely to the onboard program.

The modulation form used was frequency shift keying (FSK) because of its inherently low error probability. The logic 1 and 0 were represented by 5 and 4 kHz with a bit rate of 1 kHz, respectively, and with this was mixed a reference frequency of 17 kHz, which was used by the slant range system. The resultant telecommand system provided an extremely reliable remote command of pitch, yaw, and roll position offsets.

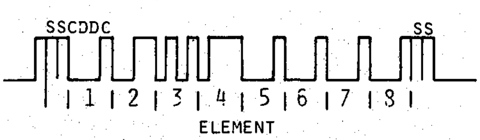

Fig. 4 Telecommand word format.

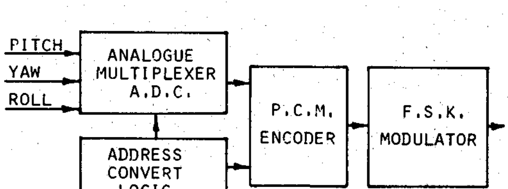

Fig. 5 Telecommand ground encoder.

Control System Logic

The inertial reference was provided by a MIDAS analog roll-stabilized platform, which is a relatively inexpensive device with accuraties of 2° or 3° in average sounding rocket use. The system was position-controlled from the gimbal pickoffs with rate damping derived by lead-lag networks. The use of derived rate proved the greatest limitation to "tightness" of the system because of the noise spectrum of the platform. Use of position instead of rate commands was determined by the gimbal coupling of the platform, which produces somewhat nonlinear derived rate terms.

The system block diagram in Fig. 7 illustrates the processing and summing of pitch, yaw, and roll platform signals with programmer or telecommand offsets and the resolving of pitch and yaw to body-fixed control jet axes. The telecommand digital-to-analog converters contain the fail-safe relays for selecting onboard programmer in the event of command failure.

Testing

Initial development involved the use of an analog computer, three-axis simulator to check the gain, and stability margins for all possible flight conditions. This was followed by single-axis air-bearing tests, with inertias and thrusts adjusted to simulate flight conditions.

Because of the gimbal coupling and the requirement for optimum maneuver characteristics under telecommand and program, the complete control system then was mounted on a three axis air bearing, and the full flight sequence was performed. These tests indicated several shortcomings in the computer simulation and confirmed the exact maneuver

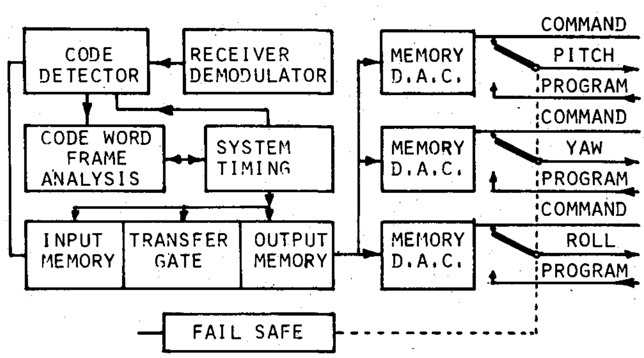

Fig. 6 Telecommand flight logic.

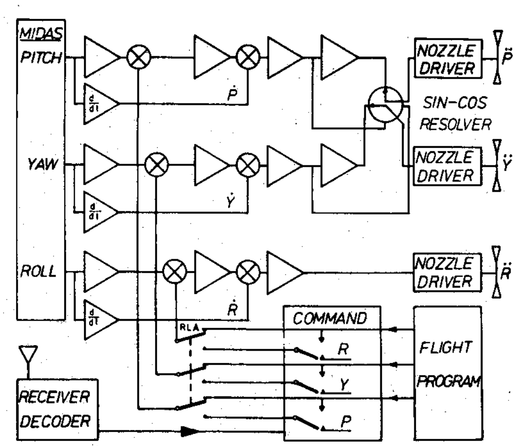

Fig. 7 TIRACS schematic diagram.

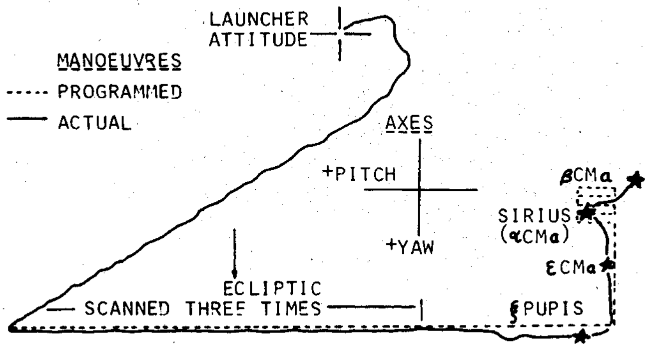

Fig. 8 ASTRO 7 flight maneuver.

dimensions and directions. The dynamic tests were backed up by an analog computer simulation to increase the experience of the operator under widely differing initial conditions; however, most of the platform and dynamic equations were simplified for this purpose.

Acceptance testing fulfilled two requirements: proving that the maneuvers were correct, and training the operator and the experimenter for the star-acquisition sequence. Complete flight simulations were performed, and a simulated star was acquired by telecommand from the command container situated some 100 m from the dynamic test area. These dynamic tests were of considerable value, as they simulated most nearly the psychological conditions of the actual launch.

Flight Results

The ASTRO 7 vehicle was launched on Oct. 9, 1975. The first two yaw scans were performed entirely by the onboard programmer, and during this time period the command system was checked and the telemetry system adjusted for reference drift. On commencement of the third yaw maneuver, the command link was enabled, and the onboard program was tracked and transmitted to the ACS. On reaching the ecliptic, the ground logic was switched from tracking to manual mode for 25 sec which held the payload stationary. On reverting to track mode, the payload immediately caught up to the program.

During the three 80° yaw scans, a series of polarizing and color filters was cycled in the experiment and prevented easy star recognition; however, at +340 sec flight time, these filters were stopped, and stars were recognizable on the u.v. and visible channels. While maintaining tracking mode, a small offset of 3° was fed into the pitch channel, and ξ pupis was identifed a little over 1° from the expected position. Using the measured error from this star, ϵ CMa also was seen shortly after, and, because of the small error in both pitch and yaw, it was decided not to use the time-consuming raster scan for αCMa (Sirius).

After a manual maneuver through Sirius, a further offset was made to the corrected position of βCMa, and this was centered in the experiment field of view with sufficient time for calibration, before the payload re-entered the Earth's atmosphere. Figure 8 illustrates the flight maneuver as recorded on the *x-y* plotter.

Conclusion

TIRACS demonstrated the feasibility of real-time, large-angle, telecommanded position control with a combination of semiautomatic and manual "joy stick" operation. The information displays and control logic, although simple, enabled confident and fast attitude correction by the operator. Further development of the system is proceeding to incorporate a stellar television camera as an attitude sensor and a microprocessor logic unit.

Acknowledgment

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