THE ANNULAR SUSPENSION AND POINTING (ASP) SYSTEM FOR SPACE EXPERIMENTS AND PREDICTED POINTING ACCURACIES

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### Abstract

An annular suspension and pointing (ASP) system consisting of pointing assemblies for coarse and vernier pointing is described. The first assembly is attached to a carrier spacecraft (e.g., the space shuttle) and consists of an azimuth gimbal and an elevation gimbal which provide "coarse" pointing. The second or vernier pointing assembly is made up of magnetic actuators for suspension and fine pointing, roll motor segments, and an instrument or experiment mounting plate around which is attached a continuous annular rim similar to that used in the annular momentum control device (AMCD). The rim provides appropriate magnetic circuits for the actuators and the roll motor segments for any instrument roll position. The results of a study to determine the pointing accuracy of the system in the presence of crew motion disturbances are presented. Typical 3σ worst-case errors are found to be of the order of 0.001 arc-second.
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SUMMARY

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for coarse and vernier pointing is described. The first assembly is attached to a car-
rier spacecraft (e.g., the space shuttle) and consists of an azimuth gimbal and an elevation
gimbal which provide "coarse" pointing. The second or vernier point assembly is
made up of magnetic actuators for suspension and fine pointing, roll motor segments, and
an instrument or experiment mounting plate around which is attached a continuous annular
rim similar to that used in the annular momentum control device (AMCD). The rim pro-
vides appropriate magnetic circuits for the actuators and the roll motor segments for any
instrument roll position. The results of a study to determine the pointing accuracy of the
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INTRODUCTION

Requirements exist for an apparatus which can provide fine pointing for a variety of
solar-, stellar-, and Earth-viewing scientific instruments during extended space shuttle
orbital missions. As a by-product of analytical and experimental work on an annular
momentum control device (AMCD), discussed in reference 1, a concept for such an appa-
ratus, an annular suspension and pointing (ASP) system, has been conceived. The purpose
of this report is to introduce this concept, to explain the hardware configuration, and to
give results of an analytical study of pointing performance in the presence of crew motion
forces and moments applied to the carrier at a crew station. Disturbances caused by
gravity gradient torques, aerodynamic torques, and other environmental torques were
considered negligible relative to the magnitude of the crew motion disturbances. Sensor-
and actuator-noise disturbances were neglected in order to determine ultimate pointing
accuracies. When possible, the analysis has used normalized configuration and perfor-

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mance variables to simplify use of the results for arbitrary size, mass, and inertia of both the ASP system itself and the experiment or instrument mounted to it.

SYMBOLS

$A, A_1, A_2$ coefficient matrices

$B_1, b_2, b$ input matrices

$\{c\}$ vector location of center of mass of vernier pointing assembly in $X_r, Y_r, Z_r$ system

$\{c_{xr}, c_{yr}, c_{zr}\}$ components of $\{c\}$ (figs. 5 and 6)

$\{d_c\}$ displacement from carrier center of mass to intersection of coarse gimbals axes

$E$ expected value operator

$F_{xc}, F_{yc}, F_{zc}$ crew motion forces acting along $X_c, Y_c, and Z_c$

$F_{xr}, F_{yr}, F_{zr}$ magnetic bearing forces along $X_r, Y_r, and Z_r$

$f(t)$ forcing function of normalized crew motion forces and moments applied at crew station

$H(s)$ crew motion filter transfer function

$h_1, h_2, h_3, h_4$ crew motion filter state variables

$I_v$ inertia of vernier pointing assembly

$I_{XX}, I_{YY}, I_{ZZ}$ inertias of carrier about $X_c, Y_c, and Z_c$ (subscript $c$ has been dropped for convenience)

$L$ transformation matrix

$M_{xc}, M_{yc}, M_{zc}$ crew motion moments acting along $X_c, Y_c, and Z_c$

$m_v$ mass of vernier pointing assembly
\( P, P^* \) origin of \( X_r', Y_r', Z_r' \) and \( X_r, Y_r, Z_r \) systems, respectively

\( r \) radius of annular suspension system rim

\( s \) Laplace variable

\( t \) time

\[ U = \frac{1}{c_{zr,o}^2} \]

\[ u(t) = \frac{v(t)}{c_{zr,o}} \]

\( v(t) \) unity power spectral density white noise

\( X_b, Y_b, Z_b \) instrument-fixed coordinate axes

\( X_c, Y_c, Z_c \) carrier coordinate axes

\( X_g, Y_g, Z_g \) coarse gimbal axes

\( X_i, Y_i, Z_i \) inertial coordinate axes with origin at carrier center of mass

\( X_p, Y_p, Z_p \) coordinate axes parallel to \( X_c, Y_c, \) and \( Z_c \) but displaced \( \{d_c\} \)

\( X_r, Y_r, Z_r \) coordinate axes displaced along \( Z_r' \) from \( X_r' \) and \( Y_r' \)

\( X_r', Y_r', Z_r' \) coordinate axes rotated from \( X_g, Y_g, \) and \( Z_g \) through \( \psi_r \)

\( X_t, Y_t, Z_t \) inertial coordinate axes with origin at vernier pointing assembly center of mass

\( x_s \) complete state variable

\( x_1 \) state vector of vernier pointing assembly and carrier

\( x_2 \) state vector of crew motion filters

\( \delta_{x_r}, \delta_{y_r}, \delta_{z_r} \) normalized centering errors
\[
\delta \ell = \frac{c_{zr} - c_{zr,0}}{c_{zr,0}} \\
\delta \epsilon = \frac{c_{yr} - c_{yr,0}}{c_{yr,0}} \\
\delta \nu = \frac{c_{xr} - c_{xr,0}}{c_{xr,0}} \\
\epsilon = \frac{c_{yr}}{r} \\
\eta^2 = \frac{m_v c_{zr}^2}{I_v} \\
\nu = \frac{c_{xr}}{r} \\
\rho_1 \quad \text{damping ratios where } i = \phi_t, \theta_t, x_r, y_r, \text{ and } z_r \\
\rho_1, \rho_2 \quad \text{crew motion filter parameters} \\
\Sigma \quad \text{covariance matrix} \\
\overline{\Sigma} \quad \text{steady-state covariance matrix} \\
\sigma \quad \text{standard deviation} \\
\tau_1, \tau_2 \quad \text{crew motion filter parameters} \\
\phi_c, \theta_c, \psi_c \quad \text{carrier attitude angles} \\
\phi_t, \theta_t \quad \text{vernier pointing angles} \\
\psi_g, \theta_g \quad \text{coarse gimbal angles} \\
\psi_r \quad \text{instrument roll angle} \\
\omega_i \quad \text{natural frequencies where } i = \phi_t, \theta_t, x_r, y_r, \text{ and } z_r
\( \omega_1, \omega_2 \)  
crew motion filter cutoff frequencies

Subscripts:

\( n \)  
normalized

\( o \)  
measured value

\( \alpha \)  
ratio of actual to measured value

\( \theta_t, \phi_t \)  
rotation angles of vernier pointing assembly

Superscript:

\( T \)  
transpose of matrix

Dots over symbols denote differentiation with respect to time.

The notation \([\ ]\) denotes a matrix.

DESCRIPTION OF ANNULAR SUSPENSION AND POINTING SYSTEM

General Description and Operational Use

The annular suspension and pointing (ASP) system includes two assemblies with connecting interfaces, each assembly having a separate function. (See fig. 1(a).) The first assembly is attached to the carrier vehicle and consists of an azimuth gimbal and an elevation gimbal which provide "coarse" pointing of the payload instrument by allowing two rotations of the instrument relative to the carrier vehicle. The second or vernier pointing assembly is made up of magnetic actuators for suspension and fine pointing, roll motor segments, and an instrument mounting plate around which a continuous annular rim is attached which provides appropriate magnetic circuits for the actuators and the roll motor segments. The vernier pointing assembly is attached to the elevation gimbal and provides vernier attitude fine pointing and roll positioning of the instrument as well as six-degree-of-freedom isolation from carrier motion disturbances. In addition, the second assembly has a rim centering mode in which axial and radial rim position sensors located at each actuator station (four stations are assumed throughout this report) are used to center the rim axially and radially between actuator pole faces. This mode allows coarse gimbal slewing for retargeting, for Earth pointing, or for backup coarse gimbal pointing.
Nominal operation of the ASP system for solar or stellar pointing first involves coarse gimbal pointing with coarse (wide field of view) sensors onboard the ASP system (or with sensors onboard the carrier vehicle and relative gimbal angle information). The rim centering mode is activated during gimbal slewing. After coarse alinement, coarse roll positioning is accomplished by means of the rim roll motor and a relative roll sensor located on the rim together with a carrier sensor or a sensor onboard the ASP system. After coarse attitude alinement, vernier fine pointing is initiated. For this mode, errors obtained from fine (narrow field of view) attitude sensors located on the ASP system, either as part of the instrument or remote, are nulled by small magnetic-suspension- and fine-pointing-actuator torques applied to the annular rim. Also, translation rim centering is accomplished for this mode.
Nominal operation of the ASP system for Earth pointing initially involves establishing the correct azimuth, elevation, and roll attitudes and attitude rates (slewing) in the rim centering mode. After appropriate smooth instrument slewing is established, vernier pointing (similar to that described for solar and stellar pointing) is accomplished. For extensive Earth pointing usage an alternative coarse gimbal arrangement (fig. 1(b)) may be preferable in which an elevation and a lateral gimbal provide simpler crosstrack capability when the carrier vehicle is in an inverted position relative to the local vertical.

Upon completion of a pointing task, connection of appropriate interfaces (data, power, cryogenic) between the payload mounting surface and the first assembly takes place. These interfaces could be maintained during a pointing task if the pointing degradation caused by the interface connection (wire, tubing, etc.) were tolerable.

Description of Coarse Gimbals

The azimuth (or lateral) and elevation gimbals which provide coarse pointing each include mechanical bearings, a torque motor, a tachometer, and a position readout potentiometer. These components interface with the control computer to form two closed-loop servosystems.

Description of Vernier Pointing Assembly

The vernier pointing assembly is shown schematically in figure 2 and is similar to the suspension system discussed in reference 1. Electromagnets (attached to the eleva-
tion or the lateral gimbal) working in opposed pairs (both radial and axial) are used to provide fine pointing forces on the rim of the instrument mounting plate. The command forces originate from rim position sensors attached to the lateral or the elevation gimbal while in the rim centering mode or from instrument pointing error sensors for the axial actuators while in the vernier pointing mode. The radial actuators are always maintained in the rim centering mode. Roll positioning is provided by a linear noncontacting roll torque motor (not shown) which produces forces tangential to the rim. Roll angle is determined from a linear sensor located along the periphery of the rim. Thus it is seen that the instrument mounting plate is completely isolated from the elevation gimbal when there are no interface connections, and the only forces produced on it, as long as the electromagnet gaps are maintained, are those produced by the electromagnets themselves, in response to command signals.

Mission Configuration

The ASP system is shown attached to a carrier vehicle in figure 3. The vehicle is assumed to be manned, and the location of the crew station and the ASP system can be defined with reference to the principal axes $X_c$, $Y_c$, and $Z_c$ which are a carrier-fixed coordinate system with origin at the carrier center of mass.

DESCRIPTION OF MATHEMATICAL MODEL

Coordinate Systems

The carrier and coarse gimbal coordinate systems are shown in figure 4. The system $X_1, Y_1, Z_1$ is inertial and is nominally centered at the carrier center of mass. The system $X_c, Y_c, Z_c$ is body fixed with origin also at the carrier center of mass. Carrier attitude is given by a set of Euler angles $\phi_c, \theta_c, \psi_c$ with a $X_c, Y_c, Z_c$ rotation sequence. These angles are considered small throughout this report. The system $X_p, Y_p, Z_p$ is body fixed and is centered at the intersection $P$ of the coarse gimbal axes which are displaced $\{d_c\}$ from the carrier center of mass. The coarse gimbal axes are defined as $X_g, Y_g, Z_g$ and are rotated through the azimuth angle $\psi_g$ and the elevation angle $\theta_g$, as shown in figure 4.

Figure 5 illustrates the vernier pointing assembly coordinates. The coordinate system $X'_r, Y'_r, Z'_r$ with origin at $P$ is rotated from the system $X_g, Y_g, Z_g$ through the instrument roll angle $\psi_r$. Located a distance along $Z'_r$ from $P$ is the nominal position of the instrument mounting plate $P^*$, which is the origin of the coordinate system $X_r, Y_r, Z_r$ (fig. 5). This system is parallel to $X'_r, Y'_r, Z'_r$. The vector $\{c\}$ locates the nominal position of the $X_t, Y_t, Z_t$ coordinate system which is inertial and nominally parallel to the $X'_r, Y'_r, Z'_r$ coordinate system. Finally, the system $X_b, Y_b, Z_b$ is an instrument-fixed system, rotated from the $X_t, Y_t, Z_t$ system by the vernier pointing angles $\phi_t$ and $\theta_t$ with a $X_t, Y_t$ rotation sequence.
Figure 3.- Mission configuration.

Figure 4.- Carrier and coarse gimbal coordinate systems.

Figure 5.- Vernier pointing assembly coordinate systems.
Derivation of Mathematical Model

The mathematical model used in this report consists of two structural models. One model consists of the equations of motion of the vernier pointing assembly, and the second model consists of the equations of motion of the carrier. Lumped mass perturbation equations are derived for the vernier pointing assembly and the carrier. The vernier-pointing-assembly X- and Y-axis inertias are assumed equal. It is assumed that the motion of the vernier pointing assembly does not affect the carrier since the carrier should be much larger in inertia and mass. The carrier attitude is assumed to be controlled by such devices as control moment gyroscopes (CMG) or annular momentum control devices (AMCD). The carrier is excited by three crew motion forces and three crew motion moments acting at a crew station. The crew motion forces and moments are modeled by band-limited white-noise processes. Therefore the linearization used in modeling makes the system amenable to analysis by means of linear stochastic control theory to determine the statistical properties of various signals in the system. Only rigid-body dynamics are considered. Crew motion inertia changes are neglected.

Vernier pointing control is provided by the eight magnetic forces $F_{xr,1}$, $F_{xr,3}$, $F_{yr,2}$, $F_{yr,4}$, and $F_{zr,i}$ ($i = 1, 2, 3, and 4$) shown in figure 6. (Numerical subscripts refer to the four electromagnets on the rim of the instrument mounting plate.) The instrument roll control system is not shown and is not considered in the mathematical model because it does not affect the pointing accuracy in the linearized analysis. The objective of the control system is to minimize centering errors $\delta_{xr}$, $\delta_{yr}$, and $\delta_{zr}$ and
vernier pointing errors $\phi_t$ and $\theta_t$ (from offset nominal mean values). Since the analysis is linear, these mean values are taken to be zero. This is accomplished by using the magnetic forces which are synthesized as linear functions of pointing-angle errors and error rates and relative displacements and velocities between the vernier pointing assembly and the carrier (centering errors and error rates). In this study such a design, which also minimizes the norm of the control force vector, is accomplished. Detailed derivation of the equations of motion and the control system is given in the appendix. Normalization is used wherever possible in the derivation.

The equations of motion for the complete closed-loop system can be written in the following state-variable form:

$$\dot{x}_1(t) = A_1 x_1(t) + B_1 f(t)$$

where the 16 by 16 matrix $A_1$ and the 16 by 6 matrix $B_1$ are defined in the appendix, and the 16-dimensional state vector is

$$x_1(t) = \begin{pmatrix} \phi_t, \dot{\phi}_t, \delta_{x_1}, \delta_{y_1}, \delta_{z_1}, \phi_{c,n}, \dot{\phi}_{c,n}, \theta_{c,n}, \dot{\theta}_{c,n}, \psi_{c,n}, \dot{\psi}_{c,n} \end{pmatrix}^T$$

where: $\phi_t$ and $\theta_t$ are the vernier pointing angle errors; $\delta_{x_1}, \delta_{y_1},$ and $\delta_{z_1}$ are the centering errors normalized by the nominal $Z_r$-axis center-of-mass offset $c_{zr,0}$; and $\phi_{c,n}$, $\theta_{c,n}$, and $\psi_{c,n}$ are the carrier attitude angles also normalized by $c_{zr,0}$. The normalized six-dimensional crew motion disturbance vector $f(t)$ is defined as

$$f(t) = \frac{1}{c_{zr,0}} \begin{pmatrix} F_{xc}, F_{yc}, F_{zc}, M_{xc}, M_{yc}, M_{zc} \end{pmatrix}^T$$

where $F_i$ and $M_i$ ($i = xc, yc,$ and $zc$) are the crew motion forces and moments acting parallel to $X_c$, $Y_c$, and $Z_c$.

**DISTURBANCE MODEL**

The carrier is excited by force and moment inputs generated by the movement of the crew members at the crew station. The crew activities considered here are

1. Console operation 1
2. Console operation 2
3. Hand washing
Some of these activities do not require appreciable translation of the center of mass of the crew member (e.g., console operation), whereas other activities (e.g., compressive walking and handrail) require considerable translation of the center of mass. A detailed description of each activity may be found in reference 2.

The crew motion forces and moments have been approximated by zero-mean band-limited white-noise processes in reference 2. Each crew motion force and moment is generated by passing a unit power spectral density white-noise process through a linear filter which is represented by the general transfer function (ref. 2)

\[
H(s) = \frac{\tau_1 s (\tau_2 s + 1)}{(s^2 + 2\rho_1 \omega_1 s + \omega_1^2)(s^2 + 2\rho_2 \omega_2 s + \omega_2^2)}
\]  

(4)

Therefore a total of six filters, three for the forces and three for the moments, are required to describe the crew motion disturbances for each crew activity.

In order for the system to be amenable to analysis through application of linear stochastic control theory, it is necessary to represent this transfer function in state-space form. There are many ways to represent the above transfer function in state-variable form. One way is to write the transfer function (eq. (4)) as a cascade of two transfer functions, each having numerator dynamics. This avoids the presence of large numbers in the system matrix which can cause numerical difficulties in computing the steady-state covariance matrix. The result is

\[
\begin{bmatrix}
\frac{dh_1}{dt} \\
\frac{dh_2}{dt} \\
\frac{dh_3}{dt} \\
\frac{dh_4}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 \\
-\omega_1^2 & -2\rho_1 \omega_1 & 1 & \tau_2 \\
0 & 0 & 0 & 1 \\
0 & 0 & -\omega_2^2 & -2\rho_2 \omega_2
\end{bmatrix}
\begin{bmatrix}
h_1 \\
h_2 \\
h_3 \\
h_4
\end{bmatrix} +
\begin{bmatrix}
0 \\
\tau_1 \tau_2 \\
\tau_1 \\
-2\rho_2 \omega_2 \tau_1
\end{bmatrix} v(t)
\]

(5)
where the crew motion disturbance (force or moment) is \( h_1(t) \). The crew motion filter state equations are given by

\[
\dot{x}_2(t) = A_2 x_2(t) + b_2 u(t) \quad f(t) = L x_2(t)
\]  

(6)

where \( x_2 \) is the 24 by 1 state vector of the six crew motion filters. The matrix \( A_2 \) (24 by 24) is formed by appropriate combination of the system matrices of all filters, and matrix \( L \) is the transformation from \( x_2 \) to the normalized crew motion disturbance vector \( f(t) \). The scalar \( u(t) = v(t)/c_{zr,o} \) is the input where \( v(t) \) is a zero-mean unity power spectral density white noise. Combining equations (1) and (6) yields

\[
\dot{x}_s(t) = A x_s(t) + b u(t)
\]

(7)

where

\[
A = \begin{bmatrix}
A_1 & B_1 L \\
0 & A_2
\end{bmatrix}, \quad b = \begin{bmatrix}
0 \\
b_2
\end{bmatrix}, \quad x_s = \begin{bmatrix}
x_1 \\
x_2
\end{bmatrix}
\]

METHOD OF SOLUTION

For the above linear system (eq. (7)) excited by white noise, the evolution of the covariance matrix can be written as (see ref. 3)

\[
\frac{d\Sigma(t)}{dt} = A \Sigma(t) + \Sigma(t) A^T + bUb^T
\]

(8)

where \( \Sigma(t) = E[x_s(t) x_s^T(t)] \) and \( U = 1/c_{zr,o}^2 \) (covariance intensity of \( u(t) \)). For steady state (where \( A \) is stable),

\[
A\Sigma + \Sigma A^T + \frac{bb^T}{c_{zr,o}^2} = 0
\]

(9)

where \( \Sigma = \lim_{t \to -\infty} \Sigma(t) \). Thus the matrix \( \Sigma c_{zr,o}^2 \) can be obtained by solving the steady-state covariance equation (eq. (9)). Except for \( \phi_t, \dot{\phi}_t, \theta_t, \) and \( \dot{\theta}_t \), all other components of the state vector \( x_s \) are normalized by \( c_{zr,o} \). Thus, it is necessary to divide
the appropriate diagonal elements of $\Sigma c_{zr,0}^2$ by $c_{zr,0}^2$ to obtain the variances of $\phi_t$ and $\theta_t$. The variances of all other variables are given by the appropriate diagonal elements of $\Sigma c_{zr,0}^2$. Since $\Sigma$ is a symmetric matrix, equation (9) represents a system of $\frac{n(n+1)}{2}$ simultaneous linear algebraic equations where $n$ is the dimension of $A$. A number of methods are available for the solution of this equation without having to invert a high dimensional matrix (of order $\frac{n(n+1)}{2}$). In particular, the method of reference 4 was found to be efficient and accurate and was therefore used to obtain the numerical results. The control forces are simply linear transformations of the state vector; therefore the covariance matrix for the control forces can be easily obtained from $\Sigma$.

**DISCUSSION OF ANALYTICAL RESULTS**

The objective of this study is to investigate the pointing performance of the ASP system when the carrier is subjected to random force and moment crew motion inputs at the crew station. To that effect a linearized model of the vernier pointing system was developed, and a pointing control system was designed on the basis of the nominal (measured) values of the parameters: $m_{v,0}$, $I_{v,0}$, $\nu_0 = c_{xr,0}/r$, $\epsilon_0 = c_{yr,0}/r$, $c_{zr,0}$, $\eta_0^2$, and $r/c_{zr,0}$. This model was coupled to the stabilized carrier model, which in turn was coupled to the crew motion filters excited by white noise.

In the absence of errors in the measurement of $c_{xr,0}$, $c_{yr,0}$, and $c_{zr,0}$, the steady-state standard deviations $\sigma_{\theta t} = \sqrt{E(\theta_t^2)}$ and $\sigma_{\phi t} = \sqrt{E(\phi_t^2)}$ are zero (eqs. (A18) and (A19)). However, when errors $\delta v$, $\delta e$, or $\delta \ell$ are present, $\sigma_{\theta t}$ and $\sigma_{\phi t}$ are no longer zero. The standard deviation of the total pointing error (for small $\theta_t$ and $\phi_t$) is given by

$$\sigma_{\theta \phi} = \sqrt{\sigma_{\theta t}^2 + \sigma_{\phi t}^2}$$

Thus, it is meaningful to compute $\sigma_{\theta \phi}$ as a function of the parameters $\delta v$, $\delta e$, $\delta \ell$, $I_{v,\alpha}$, $m_{v,\alpha}$, $\eta_0^2$, and $r/c_{zr,0}$ and the control system parameters $\rho_1$ and $\omega_1$ ($i = \phi_t$, $\theta_t$, $xr$, $yr$, and $zr$). For the purpose of the present study, it was decided to keep the nondimensional parameters $\eta_0^2$ and $r/c_{zr,0}$ and the control system parameters $\rho_1$ ($i = \theta_t$, $\phi_t$, $xr$, $yr$, and $zr$) and $\omega_1$ ($i = \phi_t$ and $\phi_t$) fixed. It was decided to make $\omega_{xr} = \omega_{yr} = \omega_{zr} = \omega_{xyz}$ a variable, which took on various values. The values of these
parameters used in computation are given in table I. The parameters used for the carrier, including the locations of the crew station and the instrument station, were those approximating the NASA space shuttle. The carrier parameters are given in table II. As mentioned previously, 10 crew motion activities were considered. The parameters of the crew motion filters for each activity are listed in table III.

As pointed out previously, the quantity \( c_{Zr,o} \sigma_{\theta \phi} \) is obtained by solving the steady-state covariance equation. It was found numerically that \( \sigma_{\theta \phi} \) was directly proportional to \( \omega_{XYZ} \); therefore the quantity \( \sigma_{\theta \phi} c_{Zr,o} / \omega_{XYZ} \) is suitable for computing the pointing error as a function of \( \delta \epsilon, \delta \nu, \) and \( \delta \ell \). Also of interest are the centering errors \( \delta x_r, \delta y_r, \) and \( \delta z_r \). Since the matrix computed is \( \overline{c}^2_{Zr,o} \) rather than \( \overline{c} \), one can readily obtain the centering error standard deviations \( \sigma_{x_r}, \sigma_{y_r}, \) and \( \sigma_{z_r} \) from the appropriate diagonal elements of the matrix \( \overline{c}^2_{Zr,o} \). As a design ground rule the 3\( \sigma \) values of these variables should never exceed the magnetic actuator gap (e.g., 0.25 cm) for any crew activity. Finally, a suitable normalization for the control forces was found to be \( c_{Zr,o} \frac{r}{r_{\text{Iv},o}} \) which results in the dimension of acceleration (m/sec\(^2\)); for example, \( F_{Zr,1,n} = F_{Zr,1} c_{Zr,o} \frac{r}{r_{\text{Iv},o}} \).

In order to find worst-case errors, the coarse gimbal angles \( \psi_g \) and \( \theta_g \) were given seven different (combination) values (table I). Experiments were first carried out for \( \delta \epsilon = \delta \nu = 0 \) for \( \epsilon_o \) and \( \nu_o \) ranging from -0.5 to 0.5, and \( \delta \ell \) was varied from -0.1 to 0.1 (±10 percent error in measurement of \( c_{Zr} \)). It was assumed that \( m_{V,a} = I_{V,a} = 1 + \delta \ell \); that is, the same error was made in the measurements of \( c_{Zr}, m_v, \) and \( I_v \). It was found that for each crew activity and for each combination of coarse gimbal angles, the quantity \( \sigma_{\theta \phi} c_{Zr,o} / \omega_{XYZ} \) varied almost linearly with \( \delta \ell \) and was symmetric about the point \( \delta \ell = 0 \). Next, with \( \delta \ell, \epsilon_o, \) and \( \nu_o \) constant at various values, \( \delta \epsilon \) and \( \delta \nu \) were varied between -0.1 and 0.1 (±10 percent) for each coarse gimbal angle. It was found that the effect of errors in measuring the \( X_r \) and \( Y_r \) offsets (\( \delta \nu \) and \( \delta \epsilon \)) of the center of mass of the vernier pointing assembly was rather small compared with the effect of error in measuring the \( Z_r \) offset (\( \delta \ell \)). For all the crew activities considered, the effect of \( X_r \) and \( Y_r \) measurement errors of up to 10 percent was to increase the pointing error by less than 20 percent; therefore, it was considered sufficient to compute \( \sigma_{\theta \phi} c_{Zr,o} / \omega_{XYZ} \) as a function of \( \delta \ell \) with \( \delta \nu = \epsilon_o = 0 \) for \( \epsilon_o \) and \( \nu_o \) fixed at their worst-case value, 0.5.

For each coarse gimbal angle and for each \( \omega_{XYZ} \) considered, the quantity \( \sigma_{\theta \phi} c_{Zr,o} / \omega_{XYZ} \) was found to be a nearly linear function of \( \delta \ell \) almost symmetric about the point \( \delta \ell = 0 \). For a nominal design with \( c_{Zr,o} = 1 \) m and \( \omega_{XYZ} = 0.0025 \) rad/sec, \( \sigma_{\theta \phi} c_{Zr,o} / \omega_{XYZ} \) can be normalized with respect to these nominal quantities. Therefore
the quantity \( 3\bar{\sigma}_{\theta\phi} = 3\sigma_{\theta\phi} \frac{c_{zr,o}}{c_{zr,o}} \frac{\omega_{xyz}}{\omega_{xyz}} \) with dimension arc-second is used for reporting the results. For each crew activity, and for the seven sets of coarse gimbal angles, \( 3\bar{\sigma}_{\theta\phi} \) lies within a band as shown in figure 7 for the activity compressive walking. The same pattern was found to exist for the rest of the crew activities. Maximum value of \( \bar{\sigma}_{\theta\phi} \) occurred for \( \delta\ell = 0.1 \) for each crew activity. Maximum values of \( 3\bar{\sigma}_{\theta\phi} \) for all 10 crew activities considered in this study are given in table IV. In order to obtain the maximum \( 3\sigma \) pointing error for a particular case with \( c_{zr,o} \) and \( \omega_{xyz} \) different from the nominal values, one need only multiply \( 3\bar{\sigma}_{\theta\phi} \) by \( \frac{1}{c_{zr,o}} \frac{\omega_{xyz}}{0.0025} \) where \( c_{zr,o} \) and \( \omega_{xyz} \) are the actual values. The coarse gimbal angle at which the worst pointing error occurred was different for each crew activity. The maximum pointing error occurred for the crew activity shower, for which \( 3\bar{\sigma}_{\theta\phi} \) was 0.001337 arc-second. For all crew

![Figure 7.- 3\sigma pointing error for compressive walking.](image-url)
activities considered, the maximum $3\sigma$ values of the centering errors ($3\delta_x, 3\delta_y,$ and $3\delta_z$) were well below 2.5 cm for the nominal design ($\bar{\omega}_{xyz} = 0.0025 \text{ rad/sec}$). They were lower for higher values of $\bar{\omega}_{xyz}$. The maximum of the $3\sigma$ values of the normalized control forces (e.g., $F_{zr,1c_{zr,0}/I_{v,0}}$) was found to be $1.883 \mu \text{m/sec}^2$ which occurred for the crew activity shower. The actual maximum $3\sigma$ values of the force in newtons can be obtained simply by multiplying this value by $I_{v,0}/rc_{zr,0}$.

**EARTH TRACKING**

In order to track a fixed point on the Earth's surface from an orbiting spacecraft, instruments mounted to the ASP system instrument mounting plate would be required to rotate relative to the carrier vehicle (assumed to rotate at orbit rate) exhibiting the bell-shaped attitude rate curve. For a 200-km orbit the peak rate can be shown to be approximately $2.2 \text{ deg/sec}$ with peak acceleration of approximately $0.06 \text{ deg/sec}^2$. For an instrument inertia with respect to the coarse gimbal axes of 15 000 kg-m$^2$, this represents a required torque of approximately 16 N-m. It is anticipated that both the maximum rate and the maximum torque will be easily achievable with the ASP system and that Earth tracking with the ASP system, preferably with the gimbal configuration of figure 1(b), will be achievable with vernier pointing occurring simultaneously during tracking.

**CONCLUSIONS**

It is concluded on the basis of the steady-state analysis presented and within the assumptions presented that ultimate (perfect sensors) $3\sigma$ accuracies of an annular suspension and pointing (ASP) system are of the order of 0.001 arc-second for the cases studied. These cases were for inertial pointing (stellar targets) and crew motion disturbances. For Earth tracking it is concluded that the torques required across the vernier pointing assembly isolation gaps are easily within magnetic actuator capabilities and that simultaneous Earth tracking and vernier pointing should present no problem for the ASP system.

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October 8, 1975
APPENDIX

DERIVATION OF EQUATIONS OF MOTION AND CONTROL SYSTEM DESIGN

In this appendix, linearized equations of motion are derived for the vernier pointing assembly and the stabilized carrier. The two models are subsequently interconnected, and a minimum-norm vernier pointing control system is derived. The equations of motion contain the three main parameters of interest: 

\[ \delta \ell = \frac{(c_{zr} - c_{zr,0})}{c_{zr,0}}, \]
\[ \delta \epsilon = \frac{(c_{y_r} - c_{y_r,0})}{c_{y_r,0}}, \]
\[ \delta \nu = \frac{(c_{x_r} - c_{x_r,0})}{c_{x_r,0}} \]

where \( c_{x_r}, c_{y_r}, \) and \( c_{zr} \) are the coordinates of the payload instrument center of mass expressed in the coordinate system \( X_r, Y_r, Z_r \). The subscript \( o \) denotes the measured value of the variable used for control system design. Other parameters of interest are \( I_v, \alpha = I_v/I_v,0 \) and \( m_v, \alpha = m_v/m_v,0 \), which are the ratios of the actual and the measured values of the payload inertia and mass. The main objective of the analysis is to investigate the statistical properties of the pointing accuracy when errors are present in measuring \( c_{x_r}, c_{y_r}, c_{zr}, m_v, \) and \( I_v \). The control system design is based on the measured values of these quantities.

The major assumptions used in modeling were stated in the main text. As stated therein, the instrument roll control system does not affect the linearized analysis and therefore is not considered. The roll angle \( \psi_r \) is assumed to be zero. The vernier pointing system is acted on by eight forces as shown in figure 6.

Symbols

The following symbols are used in this appendix in addition to some of the symbols used and defined in the main text:

- \( D_1 \) cross-product matrix of \( d_{xc}, d_{yc}, \) and \( d_{zc} \)
- \( D_2 \) cross-product matrix of \( x^*_c, y^*_c, \) and \( z^*_c \)
- \( (d_{xc}, d_{yc}, d_{zc}) \) coordinates of crew station in \( X_c, Y_c, Z_c \) system
- \( f_c \) normalized crew motion force vector
- \( g_1, g_2, g_3 \) expressions defined in equation (A16)
- \( I_c \) matrix of carrier inertias
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\( m_c \) mass of carrier

\( t_c \) normalized crew motion moment vector

\( \begin{pmatrix} x^*_c, y^*_c, z^*_c \end{pmatrix} \) coordinates of \( P^* \) in \( X_c, Y_c, Z_c \) system

\( \begin{pmatrix} x^*_1, y^*_1, z^*_1 \end{pmatrix} \) coordinates of \( P^* \) in \( X_1, Y_1, Z_1 \) system

\( \begin{pmatrix} x_{t, cg}, y_{t, cg}, z_{t, cg} \end{pmatrix} \) center-of-mass location of vernier pointing assembly in \( X_t, Y_t, Z_t \) coordinate system

\( \begin{pmatrix} x^*_t, y^*_t, z^*_t \end{pmatrix} \) coordinates of point \( P^* \) fixed with respect to carrier in \( X_t, Y_t, Z_t \) system

\( \begin{pmatrix} x^*_t, y^*_t, z^*_t \end{pmatrix} \) coordinates of the center of instrument mounting surface in \( X_t, Y_t, Z_t \) system

\( \beta_c \) normalized carrier attitude vector

\( \delta \xi \) normalized centering error vector

\( \Lambda_\beta \) defined in equation (A24)

\( \lambda \) defined in equations (A10) and (A25) with appropriate subscripts

\( \mu \) defined in equation (A17) with appropriate subscripts

\( \xi_c \) normalized coordinates of \( P^* \) in \( X_1, Y_1, Z_1 \) system

\( \xi^*_c \) normalized coordinates of \( P^* \) in \( X_t, Y_t, Z_t \) system

Subscripts:

\( \phi_c, \theta_c, \psi_c \) carrier attitude angles

Superscript:

\(-1\) inverse of matrix
APPENDIX

Equations of Motion of Vernier Pointing Assembly

The dynamics of rotation for the two degrees of freedom are

\[
I_{\phi_t} = F_{zr,4}(r - c_{yr}) - F_{zr,2}(r - c_{yr}) - (F_{zr,1} + F_{zr,3})c_{yr} + (F_{y\gamma,2} + F_{y\gamma,4})c_{zr} \quad (A1)
\]

\[
I_{\dot{\phi}_t} = F_{zr,1}(r + c_{xr}) - F_{zr,3}(r - c_{xr}) + (F_{zr,2} + F_{zr,4})c_{xr} - (F_{x\gamma,1} + F_{x\gamma,3})c_{zr} \quad (A2)
\]

The translation of the center of mass of the vernier pointing assembly is given by

\[
\ddot{x}_{t, cg} = \frac{1}{m_v}(F_{x\gamma,1} + F_{x\gamma,3}) \quad (A3)
\]

\[
\ddot{y}_{t, cg} = \frac{1}{m_v}(F_{y\gamma,2} + F_{y\gamma,4}) \quad (A4)
\]

\[
\ddot{z}_{t, cg} = \frac{1}{m_v}(F_{zr,1} + F_{zr,2} + F_{zr,3} + F_{zr,4}) \quad (A5)
\]

where \(x_{t, cg}, y_{t, cg}, \) and \(z_{t, cg}\) are coordinates of the center of mass expressed in the \(X_t, Y_t, Z_t\) system.

When \(\theta_t\) and \(\phi_t\) are small, the coordinates of the center of the instrument mounting surface are given in the \(X_t, Y_t, Z_t\) system by

\[
x'_t = x_{t, cg} - c_{zr}\theta_t
\]

\[
y'_t = y_{t, cg} + c_{zr}\phi_t
\]

\[
z'_t = z_{t, cg} - c_{zr}
\]

Substitution of equations (A3), (A4), and (A5) in these equations yields

\[
\ddot{x}'_t = \frac{1}{m_v}(F_{x\gamma,1} + F_{x\gamma,3}) - c_{zr}\ddot{\theta}_t \quad (A6)
\]
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\[ \ddot{y}_t = \frac{1}{m_v}(F_{yr,2} + F_{yr,4}) + c_{zr}\dot{\phi}_t \quad (A7) \]

\[ \ddot{z}_t = \frac{1}{m_v}(F_{zr,1} + F_{zr,2} + F_{zr,3} + F_{zr,4}) \quad (A8) \]

Controller Design

The desired behavior of \( \theta_t, \phi_t, x'_t, y'_t, \) and \( z'_t \) can be written in the following form:

\[ \begin{cases} 
\ddot{x}_t' = -\lambda_{xr} \\
\ddot{y}_t' = -\lambda_{yr} \\
\ddot{z}_t' = -\lambda_{zr} \\
\ddot{\phi}_t = -\lambda_{\phi t} \\
\ddot{\theta}_t = -\lambda_{\theta t}
\end{cases} \quad (A9) \]

where

\[ \begin{aligned}
\lambda_{xr} &= 2\rho_{xr}\omega_{xr}(\dot{x}_t' - \dot{x}_t^*) + \omega^2_{xr}(x'_t - x_t^*) \\
\lambda_{\phi t} &= 2\rho_{\phi t}\omega_{\phi t}\dot{\phi}_t + \omega^2_{\phi t}\phi_t
\end{aligned} \quad (A10) \]

where \( \rho_{xr}, \rho_{\phi t}, \omega_{xr}, \) and \( \omega_{\phi t} \) are the desired damping ratios and natural frequencies; and \( x_t^* \) is the \( x \)-component of the position of the corresponding point \( P^* \) fixed relative to the carrier transformed to the coordinate system \( X_t, Y_t, Z_t \). The quantities \( \lambda_{yr}, \lambda_{zr}, \) and \( \lambda_{\theta t} \) are similarly defined. One way of designing a control system is to ignore the coupling from \( \theta_t \) and \( \phi_t \) to \( x'_t \) and \( y'_t \) while designing \( x'_t \) and \( y'_t \) loops. This retains the ease in the analytical treatment of the system. Design of the \( z'_t \) loop poses no coupling problem. From equations (A6), (A7), and (A8) let

\[ F_{xr,1} + F_{xr,3} = -m_v,0\lambda_{xr} \quad (A11) \]

\[ F_{yr,2} + F_{yr,4} = -m_v,0\lambda_{yr} \quad (A12) \]

\[ F_{zr,1} + F_{zr,2} + F_{zr,3} + F_{zr,4} = -m_v,0\lambda_{zr} \quad (A13) \]
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The remaining equations for designing $\theta_t$ and $\phi_t$ loops allow exact compensation. From equations (A1) and (A2),

\[
F_{zr,4}(r - c_{yr,o}) - F_{zr,2}(r + c_{yr,o}) - (F_{zr,1} + F_{zr,3})c_{yr,o} + (F_{yr,2} + F_{yr,4})c_{zr,o} = -I_{v,o} \lambda_{\phi_t} \tag{A14}
\]

\[
F_{zr,1}(r + c_{xr,o}) - F_{zr,3}(r - c_{xr,o}) + (F_{zr,2} + F_{zr,4})c_{xr,o} - (F_{xr,1} + F_{xr,3})c_{zr,o} = -I_{v,o} \lambda_{\phi_t} \tag{A15}
\]

Equations (A13), (A14), and (A15) can be rewritten in the following form:

\[
\begin{bmatrix}
1 & \nu_o & 0 & \nu_o \\
0 & -\epsilon_o & 1 & -\epsilon_o \\
0 & 1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
F_1 \\
F_2 \\
F_3 \\
F_4
\end{bmatrix}
= \begin{bmatrix}
-I_{v,o} \left( \frac{\lambda_{\phi_t} + \eta_o \mu_{xr}}{r} \right) \\
-I_{v,o} \left( \frac{\lambda_{\phi_t} - \eta_o \mu_{xr}}{c_{zr,o}} \right) \\
-I_{v,o} \left( \frac{\eta_o \mu_{zr}}{r} \right)
\end{bmatrix} = \begin{bmatrix}
g_1 \\
g_2 \\
g_3
\end{bmatrix} \tag{A16}
\]

where

\[
F_1 = F_{zr,1} - F_{zr,3} \\
F_2 = F_{zr,1} + F_{zr,3} \\
F_3 = F_{zr,4} - F_{zr,2} \\
F_4 = F_{zr,4} + F_{zr,2}
\]

\[
\eta_o^2 = \frac{m_{v,o} c_{zr,o}^2}{I_{v,o}} \\
\mu_{xr} = \frac{1}{c_{zr,o}} \lambda_{xr} \\
\mu_{yr} = \frac{1}{c_{zr,o}} \lambda_{yr} \\
\mu_{zr} = \frac{1}{c_{zr,o}} \lambda_{zr} \tag{A17}
\]

These are three linear equations in four unknowns, and more than one solution exists for this problem. The solution which minimizes the norm $\left( F_1^2 + F_2^2 + F_3^2 + F_4^2 \right)^{1/2}$
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and which equivalently minimizes \( \left( F_{zr,1}^2 + F_{zr,2}^2 + F_{zr,3}^2 + F_{zr,4}^2 \right)^{1/2} \) can be obtained by using the pseudoinverse to get

\[
F_1 = g_1 - \nu_0 g_3 \\
F_2 = F_4 = \frac{1}{2} g_3 \\
F_3 = g_2 + \epsilon_0 g_3
\]

Substitution of these expressions into equations (A1), (A2), (A6), (A7), and (A8) and simplification yield

\[
\ddot{\phi}_t = -\frac{1}{I_{v,\alpha}} \lambda \phi - \frac{\eta_0}{I_{v,\alpha}} \delta \mu \gamma + \frac{\eta_0}{I_{v,\alpha}} \epsilon \left( \frac{r}{c_{zr,o}} \right) \delta \epsilon \mu_{zr} \tag{A18}
\]

\[
\ddot{\theta}_t = -\frac{1}{I_{v,\alpha}} \lambda \theta - \frac{\eta_0}{I_{v,\alpha}} \delta \mu \nu - \frac{\eta_0}{I_{v,\alpha}} \nu_0 \left( \frac{r}{c_{zr,o}} \right) \delta \nu \mu_{zr} \tag{A19}
\]

\[
\ddot{x}_t^{\prime} = -\frac{1}{m_{v,\alpha}} \mu \gamma - (1 + \delta \lambda) \dot{\phi}_t \tag{A20}
\]

\[
\ddot{y}_t^{\prime} = -\frac{1}{m_{v,\alpha}} \mu \nu + (1 + \delta \lambda) \dot{\theta}_t \tag{A21}
\]

\[
\ddot{z}_t^{\prime} = -\frac{1}{m_{v,\alpha}} \mu_{zr} \tag{A22}
\]

**Equations of Motion of Carrier**

The carrier equations of motion consist of three degrees of freedom of translation and three degrees of freedom of rotation. The carrier attitude is assumed to be stabilized by control moment gyroscopes (CMG). The equations of motion for the stabilized rotational dynamics are

\[
\ddot{\beta}_c = I_c^{-1} t_c - \Lambda_\beta + I_c^{-1} D_1 f_c \tag{A23}
\]

where \( \beta_c = \frac{1}{c_{zr,o}} \left( \phi_c, \theta_c, \psi_c \right)^T \) is the normalized carrier attitude vector and

\[
\Lambda_\beta = \frac{1}{c_{zr,o}} \left( \lambda_{\phi_c}, \lambda_{\theta_c}, \lambda_{\psi_c} \right) \tag{A24}
\]
APPENDIX

where

\[
\lambda_{\phi C} = 2\rho_{\phi C} \omega_{\phi C} \dot{\phi}_C + \omega_{\phi C}^2 \phi_C \tag{A25}
\]

with \( \rho_{\phi C} \) and \( \omega_{\phi C} \) being the desired carrier damping ratio and natural frequency.

The quantities \( \lambda_{\theta C} \) and \( \lambda_{\psi C} \) are similarly defined. The matrix of carrier inertias is defined by

\[
I_C = \begin{bmatrix}
I_{XX} & 0 & 0 \\
0 & I_{YY} & 0 \\
0 & 0 & I_{ZZ}
\end{bmatrix}
\]

Finally,

\[
D_1 = \begin{bmatrix}
0 & -d_{zc} & d_{yc} \\
d_{zc} & 0 & -d_{xc} \\
-d_{yc} & d_{xc} & 0
\end{bmatrix}
\]

where \( f_c = \frac{1}{c_{zr,0}} \begin{bmatrix} F_{xc} \\ F_{yc} \\ F_{zc} \end{bmatrix} \) and \( t_c = \frac{1}{c_{zr,0}} \begin{bmatrix} M_{xc} \\ M_{yc} \\ M_{zc} \end{bmatrix} \)

where \((d_{xc}, d_{yc}, d_{zc})\) are the coordinates of the crew station expressed in the system \(X_C, Y_C, Z_C\).

The dynamics of the translation of point \( P^* \) fixed relative to the carrier consist of (1) a component due to the translation of the carrier center of mass and (2) a component due to the rotation of the carrier and the displacement of the point \( P^* \) from the carrier center of mass. These are given by

\[
\ddot{x}_C = -D_2 I_C^{-1} t_c + D_2 \Lambda \beta - D_2 I_C^{-1} D_1 f_c + \frac{1}{m_C} f_c \tag{A26}
\]

where \( \dot{x}_C = \frac{1}{c_{zr,0}} \begin{bmatrix} x_1^* \\ y_1^* \\ z_1^* \end{bmatrix}^T \) is the normalized coordinate vector of \( P^* \) expressed in the inertial system \( X_1, Y_1, Z_1 \) and

\[
D_2 = \begin{bmatrix}
0 & -z_c^* & y_c^* \\
z_c^* & 0 & -x_c^* \\
-y_c^* & x_c^* & 0
\end{bmatrix}
\]

where \((x_c^*, y_c^*, z_c^*)\) are the coordinates of point \( P^* \) expressed in the carrier-fixed system \( X_C, Y_C, Z_C \) and \( m_C \) is the mass of the carrier.
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The position of \( P^* \), which is fixed relative to the carrier, in coordinate system \( X_t, Y_t, Z_t \) can be obtained by premultiplying \( \xi_c \) by the matrix \( R = R_2(\theta_g)R_1(\psi_g) \) where

\[
R_1(\psi_g) = \begin{bmatrix}
\cos \psi_g & \sin \psi_g & 0 \\
-\sin \psi_g & \cos \psi_g & 0 \\
0 & 0 & 1 
\end{bmatrix}
\]

\[
R_2(\theta_g) = \begin{bmatrix}
\cos \theta_g & 0 & -\sin \theta_g \\
0 & 1 & 0 \\
\sin \theta_g & 0 & \cos \theta_g 
\end{bmatrix}
\]

where \( \theta_g \) and \( \psi_g \) are coarse gimbal pointing angles as shown in figure 4. The instrument roll angle \( \psi_r \) is assumed to be zero. Thus \( \xi^*_c = R\xi_c = \frac{1}{c_{zr,0}}(x^*_t, y^*_t, z^*_t)^T \) is the representation of the position of a suspension point fixed on the carrier in the coordinate system \( X_t, Y_t, Z_t \).

The final step is to interconnect the vernier pointing system model to the carrier model. It has been assumed that the vernier pointing system does not affect carrier dynamics. The interconnection is done by premultiplying equation (A26) by \( R \) and subtracting the result from equations (A20), (A21), and (A22). This gives

\[
\delta \ddot{\xi} = -\frac{1}{m_{v,A}}\begin{bmatrix}
\mu_{xr} \\
\mu_{yr} \\
\mu_{zr}
\end{bmatrix} + (1 + \delta \ell) \begin{bmatrix}
\ddot{\phi}_t \\
0 
\end{bmatrix} + RD_2^{-1}t_c
\]

\[
- RD_2^\Lambda \delta A + RD_2^{-1}D_1f_c - \frac{1}{m_c}Rf_c \tag{A27}
\]

where

\[
\delta \xi = (\delta_x, \delta_y, \delta_z)^T = \left(\frac{x_t - x^*_t}{c_{zr,0}}, \frac{y_t - y^*_t}{c_{zr,0}}, \frac{z_t - z^*_t}{c_{zr,0}}\right)^T
\]

The complete closed-loop equations therefore consist of equations (A18), (A19), (A23), and (A27). This is a set of 16 linear constant coefficient differential equations with 6 forcing functions which are the components of the vector \( f \), where

\[
f = \frac{1}{c_{zr,0}}(F_{xc}, F_{yc}, F_{zc}, M_{xc}, M_{yc}, M_{zc})^T
\]

These equations can be written in the form of the following state-space model:

\[
\dot{x}_1(t) = A_1 x_1(t) + B_1 f(t) \tag{A28}
\]

where the state vector \( x_1(t) \) is defined in the main text (eq. (2)). The matrix \( A_1 \) is
\[
\begin{array}{cccccccccccccccc}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{b_{\phi}}{I_{v,\alpha}} & \frac{a_{\phi}}{I_{v,\alpha}} & -P_{1\theta_{yr}} & -P_{1\phi_{yr}} & 0 & 0 & 0 & 0 & 0 & Q_{1\beta_{ze}} & Q_{1\phi_{ze}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\frac{\lambda_{\phi}}{I_{v,\alpha}} & \frac{\lambda_{\phi}}{I_{v,\alpha}} & -P_{1\phi_{yr}} & -\lambda_{\phi} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]
The matrix $B_1$ is

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
H_{21} & H_{22} & H_{23} & J_{21} & J_{22} & J_{23} \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
H_{11} & H_{12} & H_{13} & J_{11} & J_{12} & J_{13} \\
0 & 0 & 0 & 0 & 0 & 0 \\
H_{31} & H_{32} & H_{33} & J_{31} & J_{32} & J_{33} \\
0 & 0 & 0 & 0 & 0 & 0 \\
K_{11} & K_{12} & K_{13} & 1/I_{XX} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
K_{21} & K_{22} & K_{23} & 0 & 1/I_{YY} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
K_{31} & K_{32} & K_{33} & 0 & 0 & 1/I_{ZZ} \\
\end{bmatrix}
\]

The numerical subscripts to $G$, $H$, $J$, and $K$ refer to $i,j$ elements of these matrices and

\[
P_1 = \frac{\eta_0^2 \delta l}{I_{v,\alpha}} \quad Q_1 = \frac{\eta_0^2}{I_{v,\alpha}} \epsilon_0 \left( \frac{r}{c_{Zr,0}} \right) \delta \epsilon \\
Q_2 = -\frac{\eta_0^2}{I_{v,\alpha}} \nu_0 \left( \frac{r}{c_{Zr,0}} \right) \delta \nu \\
\]

\[
\ell_{\alpha} = 1 + \delta l \quad a_{\phi t} = 2 \rho_{\phi t} \omega_{\phi t} \\
b_{\phi t} = \omega_{\phi t}^2
\]

The quantities $a_{\theta t}$, $b_{\theta t}$, $a_{x r}$, $b_{x r}$, $a_{y r}$, $b_{y r}$, $a_{z r}$, and $b_{z r}$ and the carrier attitude coefficients $a_{\phi c}$, $b_{\phi c}$, $a_{\theta c}$, $b_{\theta c}$, $a_{\psi c}$, and $b_{\psi c}$ are similarly defined. Finally,
\[ G = -RD_2 \]
\[ H = \left( \begin{array}{c} \frac{1}{m_c} R + RD_2 I_c^{-1} D_1 \end{array} \right) \]
\[ J = RD_2 I_c^{-1} \]
\[ K = I_c^{-1} D_1 \]

\[ \text{(A30)} \]

The matrices \( A_1 \) and \( B_1 \) depend on the parameters \( \eta_o^2 \), \( \frac{r}{c_{zr,0}} \), \( \epsilon_o = \frac{c_{y,0}}{r} \), \( \nu_o = \frac{c_{x,0}}{r} \), \( \delta \ell \), \( \delta \epsilon \), \( \delta \nu \), \( m_{\nu,0} \), and \( I_{\nu,0} \). The last five represent per unit errors in measuring the payload parameters.
REFERENCES


### Table I. System Parameters

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<th>Direction</th>
<th>Natural frequency, $\omega$</th>
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$\eta_0^2 = 3$
### TABLE II.- CARRIER PARAMETERS

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\(^a\text{If } \omega_2 = \rho_2 = 0, \text{ the term } (s^2 + 2\rho_2\omega_2 s + \omega_2^2) \text{ is deleted from equation (4).}\)
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\(^a\) If \( \omega_2 = \rho_2 = 0 \), the term \( s^2 + 2\rho_2\omega_2 s + \omega_2^2 \) is deleted from equation (4).
TABLE IV. - MAXIMUM 3σ POINTING ERRORS

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<th>$3\sigma_{\theta\phi}$, arc-second</th>
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</table>
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—National Aeronautics and Space Act of 1958

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