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### MARSHALL SPACE FLIGHT CENTER
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### POINTING AND SCANNING CONTROL OF INSTRUMENTS
### USING ROTATING UNBALANCED MASSES

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# INTRODUCTION

Motions of telescopes, satellites, and other flight bodies have been controlled by various means in the past. For example, gimbal mounted devices can use electric motors to produce pointing and scanning motions. Reaction wheels, control moment gyros, and propellant-charged reaction jets are other technologies that have also been used. Each of these methods has its advantages, but all actuator systems used in a flight environment face the challenges of minimizing weight, reducing energy consumption, and maximizing reliability. Recently, Polites invented [1] and patented [2] the Rotating Unbalanced Mass (RUM) device as a means for generation scanning motion on flight experiments. RUM devices have been successfully used to generate various scanning motions [3]. The basic principle: a RUM rotating at constant angular velocity exerts a cyclic centrifugal force on the instrument or main body, thus producing a periodic scanning motion. A system of RUM devices exerts no reaction forces on the main body, requires very little energy, and is very simple to construct and control. These are significant advantages over electric motors, reaction wheels, and control moment gyroscopes.

Although the RUM device very easily produces scanning motion, an auxiliary control system may be required to maintain the proper orientation, or pointing of the main body. It has been suggested that RUM devices can be used to control pointing dynamics, as well as generate the desired periodic scanning motion. The idea is that the RUM velocity will not be constant, but will vary over the period of one RUM rotation. The thought is that the changing angular velocity produces a centrifugal force having time-varying magnitude and direction. The scope of the present research project is to further study the pointing control concept, and to implement a microcontroller program to control an experimental hardware system.

This report is subdivided into three themes. The basic dynamic modeling and control principles are described first. Then, the controller implementation and preliminary test results are discussed. Finally, suggestions for future work are presented.

## DESCRIPTION OF THE DYNAMIC MODEL AND CONTROL

A sketch of a RUM system is shown in Figure 1. Two RUM devices are mounted on the main body so as to produce a circular scan with respect to the line-of-sight (LOS) vector. The RUMs rotate in the same direction, but are synchronized and positioned 180° apart to eliminate reaction forces at the center of mass. (In a zero-gravity environment, a single RUM is adequate.)
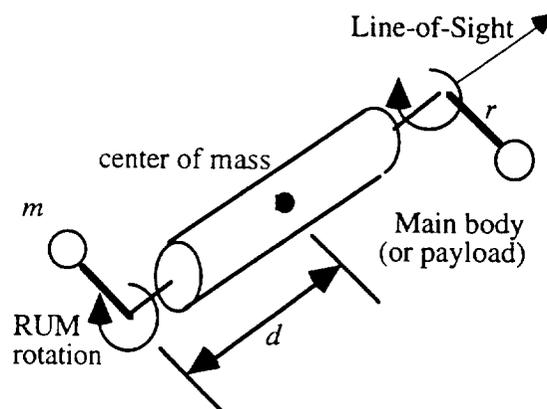


Figure 1. Sketch of a body using 2 RUMs to generate scanning.

A basic model describing the main body and RUM device dynamics is summarized below.

## Nomenclature

| | |
|---|---|
| $m$ | RUM mass |
| $r$ | RUM radius of rotation |
| $d$ | distance between RUM and payload center of mass, measured along the LOS. |
| $I$ | main body inertia |
| $\theta_E$ | main body elevation angle |
| $\theta_X$ | main body cross-elevation angle |
| $\theta_R$ | RUM angular position |

The local coordinate system is shown in Figure 2. The axis $\vec{P}_1$ is aligned with the main body line-of-sight (LOS). Axis $\vec{P}_2$ is associated with the main body elevation angle $\theta_E$, while the main body cross-elevation angle $\theta_X$ is associated with axis $\vec{P}_3$. All three axes pass through the main body center of mass. The RUM device rotates at constant speed.
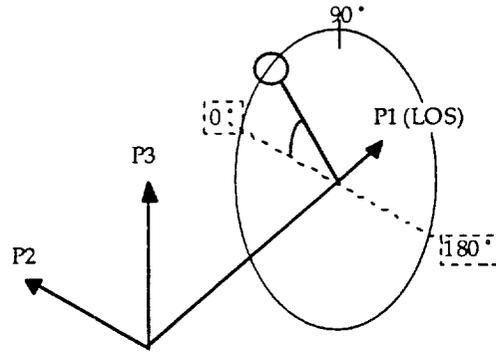


Figure 2. Coordinate system

## Plant Dynamics

Position of the RUM device relative to the $\vec{P}_1$ axis is described by the vector:

$$\vec{\rho}(t) = r\cos[\theta_R(t)]\vec{P}_2 + r\sin[\theta_R(t)]\vec{P}_3 \tag{1}$$

Differentiating (1) twice yields the RUM mass acceleration vector. Centrifugal force is in the direction opposite the acceleration vector, and its magnitude is proportional to the RUM mass. Centrifugal force exerts a torque about the main body center of mass by acting through a moment arm of length $d$. In the system of Figure 1, the two RUM devices are controlled to rotate in synchronized fashion, but always pointing 180° opposite each other. Therefore, the total torque exerted about the main body center of mass is doubled. Angular acceleration of the main body is proportional to the torque, and can be expressed in elevation and cross-elevation components [1]:

$$\ddot{\theta}_E = -\frac{2dmr}{I_E}\sin(\theta_R)\omega_R^2$$

$$\ddot{\theta}_X = \frac{2dmr}{I_X}\cos(\theta_R)\omega_R^2 \tag{2}$$

Examination of the state-variable model yields a few interesting observations.

1. The elevation and cross-elevation angle dynamics are functions of the RUM position $x_3$, and RUM angular velocity $\omega_R$.

2. For each main body axis, the sine and cosine of RUM position can be considered as periodic weights on the "control input," namely the RUM angular velocity squared. The influence of the "input" on a particular axis dynamics varies with respect to RUM position.

## Pointing Control Using RUM Rate Variation

Note that the RUM angular velocity enters the main body axes dynamics in a squared function, so negative RUM angular velocities have identical effect as positive ones. Therefore, the acceleration and deceleration of the payload axes is only possible as the sine and cosine of RUM position lend changes in algebraic sign. Fortunately, such conditions occur periodically, since the RUM is turning at a nominal "constant" speed. Hence, as the RUM turns, alternating opportunities exist for each payload axis to be "steered." Polites originally proposed to use a control signal that introduces periodic variations in the RUM rate $\omega_R$. The logic of such an approach can also be analytically confirmed by applying the nonlinear control design technique known as input-output linearization. The interested reader is directed to the references [4] - [6]. However, a simpler heuristic explanation is offered here. The control input is defined as:

$$\omega_R = \omega_{ro} + \Delta\omega_X \cos\theta_R - \Delta\omega_E \sin\theta_R \tag{3}$$

where

$\omega_{ro}$ : a constant (nominal RUM rate of rotation)

$\Delta\omega_X$ : a rate variation to compensate for cross-elevation gimbal error

$\Delta\omega_E$ : a rate variation to compensate for elevation gimbal error

The RUM rate variations $\Delta\omega_X$ and $\Delta\omega_E$ are small relative to the nominal RUM rate $\omega_{ro}$. Notice that the rate variations are periodic and "synchronized" to the RUM position through the $\sin(x_3)$ and $\cos(x_3)$ factors. Consider the model (2), and substitute the control (3) in the elevation axis dynamics. Then, the elevation axis acceleration is given by:

$$\ddot{\theta}_E = -\frac{2dmr}{I_E}\sin\theta_R\left(\omega_{ro} + \Delta\omega_X \cos\theta_R - \Delta\omega_E \sin\theta_R\right)^2 \tag{4}$$

Expand the right-hand side, but retain only the low-order terms:

$$\ddot{\theta}_E \approx -\frac{2dmr}{I_E}\left(\omega_{ro}^2 \sin\theta_R + \omega_{ro}\Delta\omega_X \cos\theta_R \sin\theta_R - \omega_{ro}\Delta\omega_E \sin^2\theta_R\right) \tag{5}$$

Eq. (5) states that the elevation axis acceleration is influenced by three terms. Since the RUM rate variations are small, the expression can be further simplified. The second term can be omitted, since it is a higher-order "cross" term. A trigonometric identity can be applied to the third term to expose a low-order component. As a result, the elevation axis acceleration is approximately:

$$\ddot{\theta}_E \approx -\frac{2dmr}{I_E}\left(\omega_{ro}{}^2 \sin\theta_R - \frac{\omega_{ro}}{2}\Delta\omega_E\right)\qquad(6)$$

Approximation (6) states that elevation axis acceleration has a sinusoidal component, as well as a term linear with respect to $\Delta\omega_E$. The sinusoidal component causes the periodic "scanning" motion of the main body, while the linear term affects the "pointing," or line-of-sight motion. The beauty of this approach is that the scanning dynamics are governed by the first term in (6), while the pointing is affected by the second term. Polites proposed that the variation $\Delta\omega_E$ be determined by a proportional + rate feedback controller based on an average elevation axis error. The line of reasoning for expressions (4)-(6) can be applied to the cross-elevation axis dynamics. In summary, the control of payload pointing can be achieved by introducing periodic RUM rate variations $\Delta\omega_X$ and $\Delta\omega_E$ for the cross-elevation and elevation axis errors, respectively.

## CONTROLLER IMPLEMENTATION

Experimental tests of the pointing control scheme have been developed in this research project. The NASA-developed experiment consists of a gimbal mounted payload with several RUM devices. The control electronics remain unchanged, but the Motorola 80196 controller code is modified to achieve pointing using only RUM devices, without intervention from auxiliary motors acting on the main body. The control input described described in (3) is implemented as a new floating-point subroutine (named MOD_RUM_COM). RUM rate variations $\Delta\omega_X$ and $\Delta\omega_E$ are generated by modified gimbal control subroutines. To improve the overall system performance, several measures have been designed and implemented to increase the sampling frequency. These include:

a) Implementing the gimbal control subroutine using integer arithmetic. In addition, the sampling frequency and controller gains are chosen to be powers of two, so that multiplication and division involving these numbers can be achieved very quickly using binary data shifts.

b) Sine and cosine functions are implemented using a table look-up scheme with linear interpolation. This method is approximately 10X faster than using the polynomial approximation implemented with floating-point. Yet the results are correct to 5-6 decimal places, compared to 4 decimal places using the polynomial approximation.

The new controller code computation time is around 2.5 msec, which is easily fast enough to achieve a sampling frequency of 256 Hz.

Preliminary tests of the system show that pointing control using RUMs is possible, but that further work is needed. If no RUM speed variations are used, the line-of-sight axis will drift away with the slightest disturbance. In contrast, small disturbances can be accommodated when the RUM speed variations are enabled, though the steady-state error is somewhat excessive. A record of experimental results needs to be collected in the near future for more detailed analysis.

## SUGGESTIONS FOR FUTURE WORK

Improvements in pointing control performance may be possible through several approaches. Two suggestion are described here:

1) Improved modeling and analysis - Observation of the experiment motion verifies that the centrifugal forces generated by RUMs are the dominant effects when RUM angular velocity is constant. But if the RUM angular velocity is not constant, then it appears that the main body

also reacts to the RUM motor torques as the RUM accelerates and decelerates during each rotation. More detailed analysis of the RUM system suggests that a more complete model of the main body angular accelerations is of the form:

$$\ddot{\theta}_E = \frac{2dmr}{I_E}\left(-\sin(\theta_R)\omega_R^2 + \cos(\theta_R)\ddot{\theta}_R\right)$$

$$\text{(7)}$$

$$\ddot{\theta}_X = \frac{2dmr}{I_X}\left(\cos(\theta_R)\omega_R^2 + \sin(\theta_R)\ddot{\theta}_R\right)$$

In other words, the accelerations of the main body about the center of mass are functions of RUM angular velocity (squared ) AND the RUM acceleration. Compare the acceleration models (2) and (7). Another observation is that these models are derived under the conditions that the elevation and cross-elevation angles are small. Experiments suggest consideration for large variations in these main body axes. It is recommended that a more complete model be examined or derived, perhaps using techniques from robot dynamic modeling [7].

2) Improved control design - Experimental results show that the stability margin of the RUM system is not very large. The gimbal controller subroutine that generates the RUM rate

variations $\Delta\omega_X$ and $\Delta\omega_E$ implements a PD-type controller. Steady-state performance should be improved with the addition of integral compensation, but simulation results have not been encouraging (small stability margin). Controller improvements based on nonlinear control theory might be examined. In addition, the synchronization of the control to the RUM motion should be studied for possible improvements.

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