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DYNAMIC MODELS OF INSTRUMENTS USING ROTATING UNBALANCED MASSES

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INTRODUCTION

The motion 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 together with traditional servomechanisms have been successfully used to generate various scanning motions: linear, raster, and circular [3]. The basic principle can be described: 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 to rotate the RUMs, and is simple to construct. 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 has been 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 kept 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 this ongoing research project is to study the pointing control concept, and recommend a direction of study for advanced pointing control using only RUM devices.

This report is subdivided into three section. Three dynamic models and one proposed control principles are described first. Then, the results of model analyses and some experiments are discussed. Finally, suggestions for future work are presented.

DYNAMIC MODELS AND CONTROL

A sketch of one 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.)

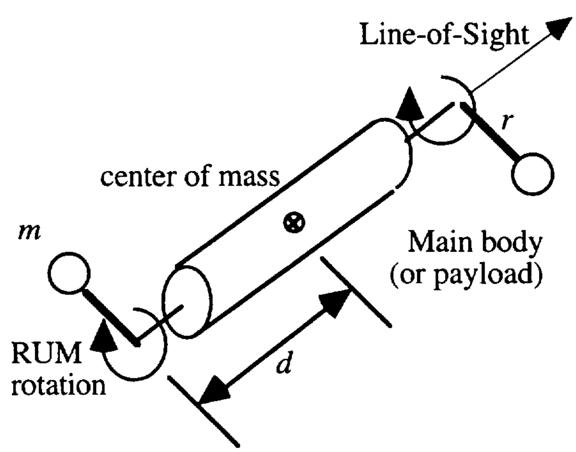

Figure 1. Sketch of a body using 2 RUMs to generate scanning.

Several models describing the main body and RUM device dynamics are summarized below. Key parameters and variables are defined as follows:

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
θ_E	main body elevation angle
θ_X	main body cross-elevation angle
θ_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 θ_E, while the main body cross-elevation angle θ_X is associated with axis $\vec{P}_3$. All three axes pass through the main body center of mass.

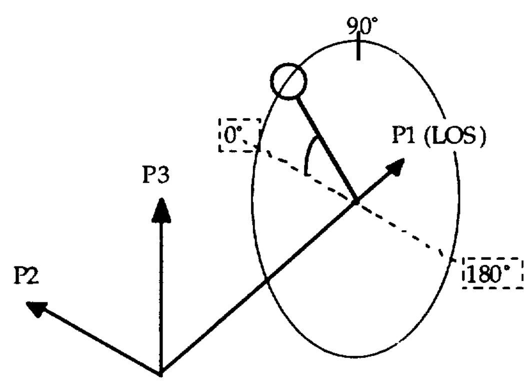

Figure 2. Coordinate system

Torque Developed by RUMs

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 or moment exerted about the main body center of mass is doubled. The torque vector can be decomposed into elevation and cross-elevation components, expressed by the following relationship [1]:

$$\begin{bmatrix} T_E \\ T_X \end{bmatrix} = 2dmr\omega_R{}^2 \begin{bmatrix} -\sin\theta_R \\ \cos\theta_R \end{bmatrix} \tag{1}$$

Observation of the actual experiment motion verifies that the centrifugal forces generated by RUMs are the dominant effects when RUM angular velocity is constant [3]. 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. Further analysis of the RUM system suggests that a more complete model of the developed torques is of the following form [8]:

$$\begin{bmatrix} T_E \\ T_X \end{bmatrix} = 2dmr\begin{bmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{bmatrix}\begin{bmatrix} \dot{\omega}_R \\ \omega_R^{\;2} \end{bmatrix} \tag{2}$$

In other words, the torque on the main body about the center of mass is a function of RUM angular velocity (squared) AND the RUM acceleration.

Another observation is that both models (1) and (2) are derived under the assumption that there are no other cross-coupling effects. A more complete model has been derived by Bishop, using techniques from robot dynamic modeling [9]. The form of that model is as follows:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} = T(q) \tag{3}$$

where

q:	4x1 vector of the cross-elevation, elevation, and two RUM position angles
$D(q)$:	4x4 matrix of inertia components
$C(q)$:	4x4 matrix of coriolis and centripetal force components
$T(q)$:	4x1 vector of applied torques

Bishop has also shown that the model can be reduced to three variables instead of four under the assumption that the two RUMs are perfectly synchronized. All three models (1), (2), and (3) predict similar scanning behavior. In fact, the model (1) can be recovered from both other models under suitable assumptions (e.g. small angular variations, ignoring cross-coupling, etc.).

Pointing Control Using RUM Rate Variation

Polites originally proposed to use a control signal that introduces periodic variations in the RUM rate ω_R. A heuristic explanation can be found in the report [4]. 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 also directed to the references [5] - [7].

Polites suggested that control input be defined as:

$$\omega_r = \omega_{ro} + \Delta\omega_X \cos\theta_R - \Delta\omega_E \sin\theta_R \tag{4}$$

where

ω_{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 ω_{ro}. Notice that the rate variations are periodic and are synchronized to the RUM position θ_R through the $\sin(\theta_R)$ and $\cos(\theta_R)$ factors.

Summary of Model Analyses & Experiments

Extensive computer simulations of the three models have been performed. Also, a study of the total angular momentum of the system has been conducted. In addition, several experiments on the NASA RUM test bed located at Marshall Space Flight Center have been conducted for comparison. All of this summer's studies have focused on a control input of the form shown in Eq. (4). The

RUM rate variations $\Delta\omega_X$ and $\Delta\omega_E$ have been held constant, so the studies and experiments address the open-loop behavior of the system. The following conclusions are drawn:

a. All three models (1), (2), and (3) predict periodic scanning behavior of the instrument, and agree reasonably well with experimental behavior.

b. The control input (4) alone has little noticeable effect on the experimental system's pointing. That is, significant changes in the average cross-elevation angle and average elevation angle are not possible using the control input (4) alone. This experimental observation is in agreement with behavior predicted by Bishop's simulations of model (3).

c. Bishop's model (3) shows that cross-coupling effects have a significant role in the system response. The control (4) may have a very small, long term effect on the pointing angles. The predicted effect is small, however, and may be easily washed out by imperfections in the present experiment (e.g. nonlinear frictions at the gimbals, gravity, cable tensions, etc.).

d. The model (2) also predicts a small effect on the instrument model pointing when control input (4) is used alone. It is concluded that reactions to the RUM accelerations and decelerations cannot be ignored.

e. Curiously, the model (1) predicts significant effect on the instrument pointing by using the control input (4) alone. This simulation result is not in agreement with either the experiment, or the simulations of models (2) and (3). However, the analyses of model (1) DOES give insight to how instrument pointing can be achieved by a modified control. In other words, the control input (4) may not be suitable alone, but may be effective if augmented by other control effort. This is explained further in the recommendations for future work.

f. Finally, angular momentum conservation does not appear to be violated. Angular momentum of a system set up for linear scan using RUMs has been performed this summer. The preliminary results leave the door open for pointing control using RUMs alone.

RECOMMENDATIONS FOR FUTURE WORK

Analysis of the basic model (1) and an angular momentum model suggests that pointing control of the system should be possible. However, the more detailed models (2) and (3) predict that cross-coupling and other nonlinear dynamics are significant and cannot be ignored. From the controller design viewpoint, it is suggested that these nonlinear effects be cancelled by feedback control. The idea is very similar to feedback linearizing control, which has been proven in robotic control (but is called "computed torque control") to give linear closed-loop dynamics to systems that are inherently nonlinear. In the RUM application, linear closed-loop dynamics are not the goal. Rather, closed-loop dynamics consistent with that predicted by the nonlinear model (1) are the goal. Hence it is recommended that further analytical study be focused on the design of a nonlinear controller to cancel the undesirable dynamic components. These undesirable components are described in the model (3).

Implementation of the recommended nonlinear controller may not be feasible on the present experimental system at Marshall Space Flight Center. A chief concern is the limited computational capability of the microcontroller system. Although modifications were made last summer to improve the sampling rate and accuracy of the calulations, it is recommended that an electronic control system based on a floating-pointing digital signal processor be developed for future experimental work.

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