NASA-TM-112521

043053

AAS 97-065

POINTING AND SCANNING CONTROL OF OPTICAL INSTRUMENTS USING ROTATING UNBALANCED MASSES

Carlee A. Bishop and John Y. Hung*
Michael E. Polites and Dean C. Alhorn†

Correct pointing direction and scanning motions are essential in the operation of many flight payloads, such as balloon-borne telescopes and space-based X-ray and gamma-ray telescopes. Rotating unbalanced mass (RUM) devices have been recently proposed, implemented and successfully tested to produce a variety of scanning motions. Linear scans, raster scans, and circular scans have been successfully generated on a gimbaled payload using pairs of RUM devices. Theoretical analysis, computer simulations, and experiments have also been used to study the feasibility of using RUM devices to control instrument pointing direction, in addition to generating scanning motion. Dynamic modeling of a gimbaled payload equipped with a pair of RUM devices has been studied, and preliminary testing indicates that the pointing control is indeed feasible. However, there is also great potential for significant performance improvements through more advanced control system analysis, modeling and design.

In this paper, modeling and control methods are described to achieve simultaneous scanning and pointing control of a gimbaled payload using rotating unbalance mass (RUM) devices. The model development work builds upon the results of Polites et al.[1-3] and also some modeling approaches from robotics research[4]. Results of some preliminary experiments are discussed and some nonlinear control methods[5-7] will be proposed.

INTRODUCTION

Remote sensing of gamma ray and X-ray sources poses unique attitude control challenges for balloon or space borne telescopes. The challenges include scanning and pointing of the telescope optical systems. Scanning is small localized motion accomplished by electronically or physically changing or moving the optics of the sensor. Pointing is motion that turns the telescope in a given direction for target acquisition and centering a scan on the target. An innovative new type of actuator called the rotating unbalanced mass (RUM) device was recently developed at the National Aeronautics and Space Administration (NASA) by Dr. Michael Polites[1,2] to accomplish the scanning requirements of these optical systems. The RUM device proved efficient at scanning for

* Department of Electrical Engineering, Auburn University, Auburn, Alabama 36830.
† Astrionics Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama 35812.

gamma ray or X-ray imaging during ground testing[3]. The next challenge is to use the RUM device to accomplish the pointing necessary for target acquisition and proper imaging. This paper presents preliminary research accomplished in the area of pointing control using the RUM device. This research, combined with earlier scanning research provides comprehensive control of balloon/space borne telescopes using the RUM actuator. The following areas are covered in this paper: Background information on the special scanning requirements of gamma ray and X-ray optics and how this scanning is accomplished using the RUM device. Next, modeling and control methods are described to achieve simultaneous scanning and pointing control of a gimbaled payload using rotating unbalance mass (RUM) devices. The model development work builds upon the results of Polites et al.[1-3] and also some modeling approaches from robotics research[4]. Results of some preliminary experiments are discussed and some nonlinear control methods[5-7] will be proposed.

BACKGROUND INFORMATION

The RUM device was originally developed to provide an efficient means of scanning space and balloon borne telescopes. The following sections provide background information on the unique requirements of gamma ray and X-ray detectors and how they influenced the development of the RUM device.

Optical Requirements for Gamma Ray and X-ray

This section presents the needs of the user based on optical requirements of this special remote sensing equipment.

Space and Balloon-Borne Systems. Gamma ray and X-ray detectors require a balloon-borne or space borne platform for several reasons[8]:

1. Atmospheric absorption prevents much of the radiation from ever reaching ground based telescopes. Figure 1 depicts the electromagnetic (EM) frequencies reaching the surface of the Earth and those absorbed or blocked by the atmosphere. X-ray and gamma ray radiation is blocked at rather high altitudes (approximately 25 to 30 thousand feet) making it very difficult if not impossible to detect these radiation sources from ground based sensors. In order to detect gamma ray or X-ray sources accurately, the imaging system must be above the level of the atmosphere that is distorting and blocking the radiation.
2. Images of astronomical objects are blurred when light travels through the turbulent and clumpy air around the Earth.
3. Ground based telescopes receive stray light interference from cities and from atmospheric auroras.
4. Angular resolution is dramatically increased when using space based optical telescopes. Space telescopes can generally distinguish details separated in angle ten times better than ground based systems.

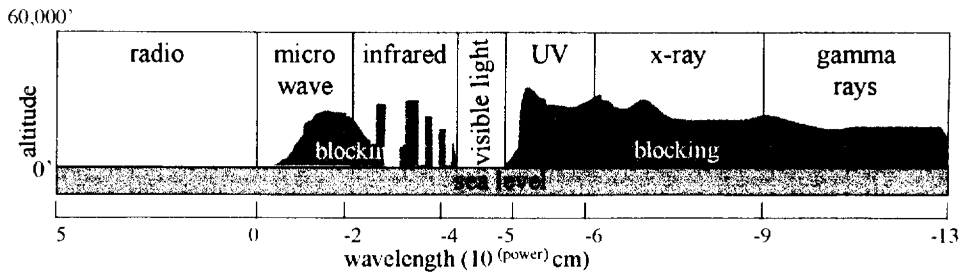

Figure 1 Atmospheric Blocking of EM Radiation[8]

Special Optics. Gamma rays and X-rays penetrate the normal 'mirror' optics of standard telescopes without being detected. Gamma ray detectors require unique hardware such as used in the spark detector shown in Figure 2. Gamma ray detectors track the gamma-ray photon as it passes close to the nucleus of an atom in the target. The photon disappears and a pair of electrons take its place. The electrons absorb the photons energy and retain much of its trajectory leaving trails of ions in the detector.

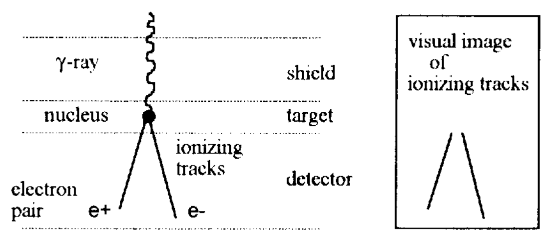

Figure 2 Spark Chamber Gamma Ray Detector[8]

Similarly, the X-ray detector requires special optics such as the grazing incidence telescope shown in Figure 3. It uses highly polished glass tubes to direct the X-ray radiation by placing them at high incidence angles to the source. Applying Snell's Law to gamma-ray and X-ray radiation provides the incidence angles needed for proper focusing of the image.

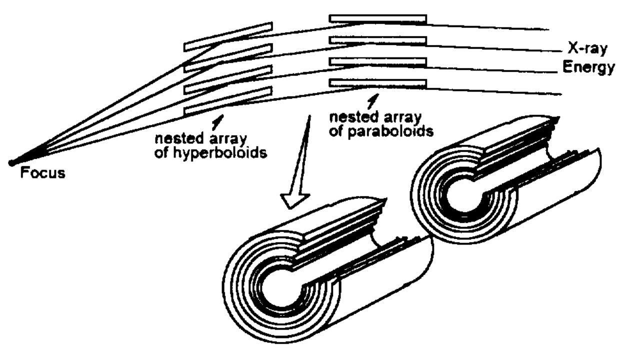

Figure 3 Grazing Incidence X-Ray Detector[8]

Scanning. The special optics and the sources to be detected present some unique control requirements for the imaging process. First, the limited field of view (FOV) requires that the imaging device be scanned to give proper dimension to the image[9]. Referring to Figure 4, a simple example of electro-optical scanning would include a one dimensional scan of an object orthogonal to the flight path of an aircraft. The motion of the aircraft generates the second dimension of the image and is an example of physical scanning.

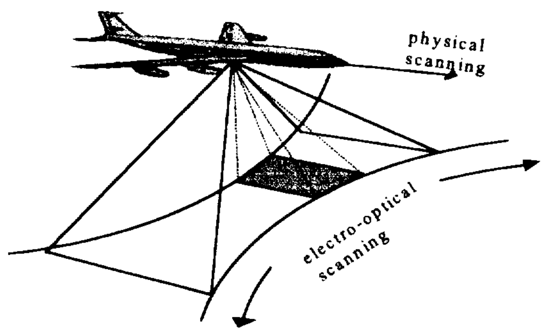

Figure 4 Scanning Example

Second, since gamma ray and X-ray radiation are always present as background radiation, it is necessary to distinguish between background radiation and source radiation when imaging a gamma ray or X-ray source. Scanning "on target" and "off target" identifies the flux coming from the background so it can be compared to that coming from the source[10]. Typical scanning patterns include linear, circular, and raster scanning as depicted in Figure 5[1,9,10]. Gamma ray and X-ray detectors generally require adjustable scan periods and radii to meet user needs.

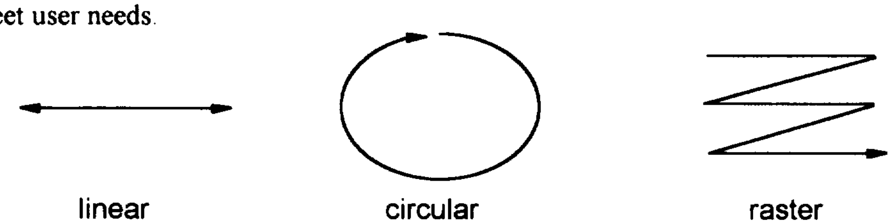

Figure 5 Typical Scanning Patterns

Traditional Scanning Methods. The special make up of gamma ray and X-ray detectors prevent them from being electro-optically scanned. Physical scanning is the only option for these detectors. Prior scanning techniques incorporated torque motors, reaction wheels, control moment gyros or reaction control devices to generate the desired scan patterns. A detailed description of these components is covered in reference[11]. Basic operation and advantages/disadvantages of each are described as follows:

1. Momentum control devices actively vary the angular momentum of small masses within the spacecraft to change attitude. Reaction wheels and control moment gyros are momentum control devices. Reaction wheels vary spin speed to effect a change in the angular momentum. They provide highly accurate, fast response attitude control. They are complex and expensive, however, and have a large power consumption in the scanning mode of operation. Control moment gyros (CMG) vary spin direction to effect a change in angular momentum. The advantages and disadvantages are similar to reaction wheels.
2. Reaction control devices are basically jet thrusters. The thrusters apply a force at a distance from the center of mass (CM) to effect a torque about the CM. They can produce fast responses but have limited use since they require propellant which is exhaustible. Because of their nonlinear 'on-off' behavior, they are difficult to control and very inefficient for scanning use since excessive propellant is required.
3. Torque motors provide the simplest means of attitude control. Electronic motors apply torque to a gimbaled system by 'pushing' against the gimbal platform. The 'pushing', however, can cause instability for balloon-borne gondola systems[12]. Torque motors require excessive power during scanning operation and they cannot be used for free flying spacecraft because there is no platform to 'push' against[1].

The RUM Device

All of the traditional methods of scanning have serious drawbacks including excessive weight, cost, and limited lifetime. The primary motivation for developing the RUM device was reducing payload mission requirements. Major factors influencing space and balloon-borne payloads are efficiency, low cost, and reliability; the RUM device was developed to meet all these requirements. Simulation and prototype test results have shown that the RUM device has a great advantage over reaction wheels and torque motors in the areas of weight and power consumption[1,3]. This section presents a brief overview of the RUM concepts. References [1] and [3] provide excellent explanations of the RUM device.

Basic Concept. The concept of scanning using rotating unbalanced masses is a geometry and physics problem involving the mechanical properties of the system. The RUM device consists of a mass on a lever arm rotating at a constant angular velocity. The mass rotation generates a centripetal force that has constant magnitude but changing direction. This force applied through a distance from the center of mass generates a torque about the center of mass that also has time varying direction. The time varying toque produces the necessary scan motion which can be circular, linear, or raster depending on the configuration of the RUM devices[1]. In developing this concept, several assumptions were made:

1. The center of mass is along the line of sight.
2. The line of sight is the axis of minimum principle moment of inertia (I_{min}).
3. The other two principle moments of inertia are equal (I_{max}).

4. Localized RUM motion (i.e. small angle of movement of the experiment).
5. Constant RUM velocity (constant ω_R).
6. The RUM device is treated as a simple actuator decoupled from the experiment dynamics except as an input to the system.
   Note: Assumptions 7 and 8 specifically apply to only balloon-borne systems.
7. The Experiment is attached to the gondola by a 2 axis gimbal system.
8. Balloon rotations are isolated from the experiment by a separate azimuth control system.

Based on these assumptions, a linearized equation of motion for the balloon-borne gondola system is developed in the next section.

Equations of Motion. For the balloon-borne gondola system configured with a RUM device as depicted in Figure 6, torque about the center of mass (CM) of the experiment is given by Equation 1[1]. The masses are 180° out of phase from each other and rotate in the same direction.

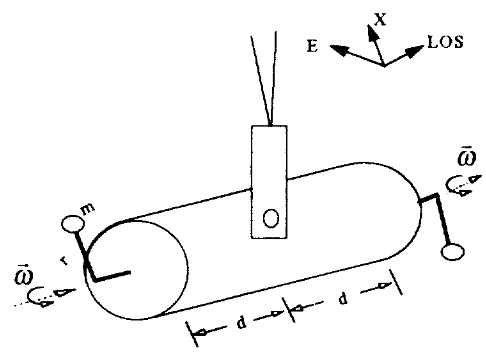

Figure 6 Balloon-borne experiment in a circular scan

$$\begin{bmatrix} T_{LOS} \\ T_E \\ T_X \end{bmatrix} = 2m\omega_R^2 rd \begin{bmatrix} 0 \\ -\sin(\theta_R) \\ +\cos(\theta_R) \end{bmatrix} \tag{1}$$

where:

$T_{(LOS,E,X)}$ = torque about the line of sight (LOS), elevation (E), or cross-elevation (X) axis respectively,
m = mass on end of lever arm of RUM,
r = length of lever arm,
d = distance from CM to attachment point of RUM,
ω_R = angular velocity of rotating mass,
$\theta_R = \omega_R \bullet t$ = angular position of rotating mass.

Using these torques in the linearized equation of motion given by Equation 2 and integrating twice gives the steady state scan motion given by Equation 3.

$$\begin{bmatrix} \ddot{\theta}_{LOS} \\ \ddot{\theta}_E \\ \ddot{\theta}_X \end{bmatrix} = \begin{bmatrix} I_{\max}^{-1} & 0 & 0 \\ 0 & I_{\max}^{-1} & 0 \\ 0 & 0 & I_{\min}^{-1} \end{bmatrix} \begin{bmatrix} T_{LOS} \\ T_E \\ T_X \end{bmatrix} \tag{2}$$

where: $\ddot{\theta}_{(\,)}$ = angular acceleration about the respective axis.

$$\begin{bmatrix} \theta_E \\ \theta_X \end{bmatrix} = \frac{2mrd}{I_{\max}} \begin{bmatrix} +\sin(\theta_R) \\ -\cos(\theta_R) \end{bmatrix} \tag{3}$$

where: $\theta_{(E,X)}$ = angular rotation about the elevation and cross-elevation axis respectively. This results in the circular scanning motion depicted in Figure 5. The radius of the scan is given by Equation 4 and the period of the scan is given by Equation 5. Note that the radius and period of the scan are independent of each other. This is a valuable design benefit, making it possible to adjust the period of the scan without changing the radius of the scan and visa versa.

$$\rho = \frac{2mrd}{I_{\max}} \tag{4}$$

$$T_{period} = \frac{2\pi}{\omega_R} \tag{5}$$

For the balloon-borne experiment configured as depicted in Figure 7, torque about the center of mass of the experiment is given by Equation 6 and results in the steady state scan motion given by Equation 7 resulting in the linear scan motion depicted in Figure 5.

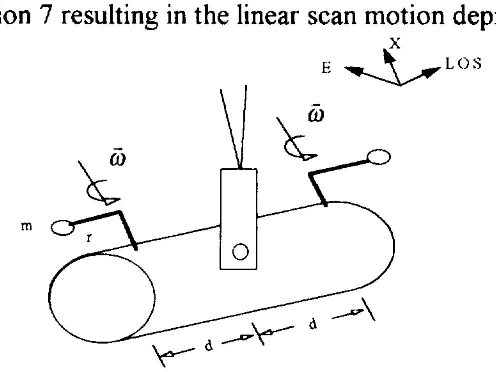

Figure 7 Balloon-borne experiment in a linear scan

$$\begin{bmatrix} T_{LOS} \\ T_E \\ T_X \end{bmatrix} = 2m\omega_R^2 rd \begin{bmatrix} 0 \\ 0 \\ \cos(\theta_R) \end{bmatrix} \quad (6)$$

$$\theta_X = -\frac{2mrd}{I_{max}}\cos(\theta_R) \quad (7)$$

The raster scan is generated by using the linear scan configuration and superimposing complementary motion from an auxiliary control system (ACS) that will be described in the next section. The development is similar for the free flying spacecraft and the gimbaled space platform experiment. See Reference [1] or [3] for details.

Auxiliary Control System. An auxiliary control system is needed to supplement the RUM devices and is usually made of traditional control devices such as reaction wheels, torque motors, etc. The auxiliary control system is used for the following pointing and scanning purposes:

1. Target acquisition.
2. Keeping the center-of-scan on target.
3. Producing the complementary motion for raster scanning.

Figure 8 shows the test configuration of the gimbaled system using torque motors for the ACS. The elevation and cross-elevation axis are controlled independently with low frequency/low amplitude torques where as the RUM devices are controlled by high frequency/high amplitude torques[1]. Low pass filtering keeps the ACS from fighting the motion generated by the RUM devices.

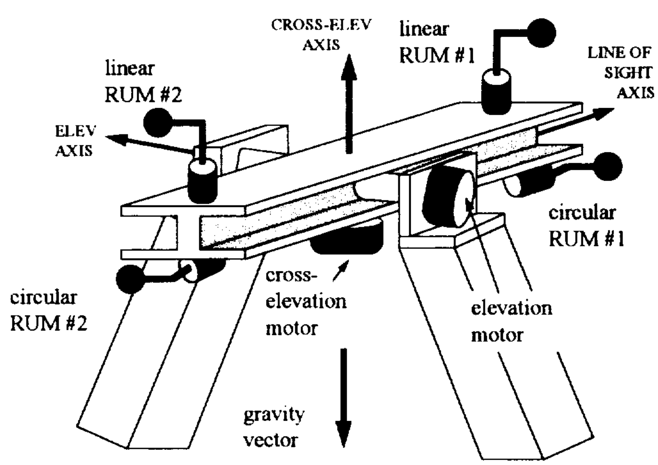

Figure 8 Test Configuration

WORK DONE TO DATE ON POINTING CONTROL

It has been suggested by Dr. Polites that the RUM device can be used for not only scanning motion but also for pointing motion. The research work conducted through the NASA/ASEE Summer Faculty Fellowship Program during the summer of 1996 produced promising results in the area of RUM actuated pointing control[7]. The goals of the research program included further dynamical analysis of the experimental system and development of microcontroller code to achieve pointing control. The following two sections cover dynamical analysis and control analysis of the RUM actuated pointing system.

Dynamical Analysis

The dynamical analysis centered around the basic concept that a time varying RUM velocity (ω_R) will produce a centripetal force having both time varying magnitude and direction[2,7]. This force can generate a torque about the center of mass that also has time varying magnitude and direction. Figure 9 shows a comparison between a constant ω_R torque profile and a time varying ω_R torque profile. Note that a net torque can be generated, depending on how the RUM velocity is varied, which in turn can generate the necessary pointing motion.

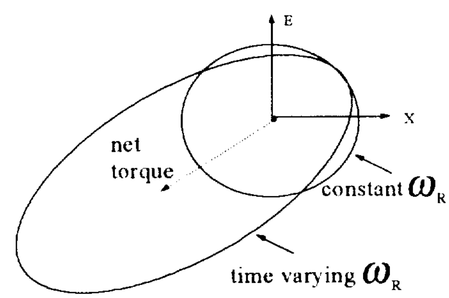

Figure 9 Torque Profile about the Center of Mass

The gimbal mounted experiment is configured in the circular scan mode to ensure both the elevation axis and cross-elevation axis have 'steering' opportunities. In other words, for the circular scan configuration, RUM rotation generates torques about both the elevation and cross elevation axis as compared to the linear scan configuration where torque is generated about only one axis. Dynamical analysis starts with Equation 8 which represents the equations of motion for constant RUM velocity resulting from combining Equations 1 and 2. Assuming reaction forces from the acceleration of the RUM masses are small, pointing control will be achieved by varying RUM velocity, (ω_R), in Equation 8.

$$\ddot{\theta}_E = -\frac{2dmr}{I_E}\sin(\theta_R)\omega_R^2$$
$$\ddot{\theta}_X = \frac{2dmr}{I_X}\cos(\theta_R)\omega_R^2 \quad (8)$$

Equation 8 yields some interesting observations[7]:

1. The elevation and cross-elevation angle dynamics are functions of RUM position (θ_R) and velocity (ω_R).
2. The control input, ω_R , varies based on the position of the RUM (i.e. is weighted by $\sin(\theta_R)$ and $\cos(\theta_R)$ for elevation and cross-elevation respectively).
3. The control input, ω_R , enters the equation of motion as a squared term. Negative ω_R has the same effect as positive ω_R and must rely on the sign changes of cosine and sine factors to effect positive and negative accelerations.

These observations are used in the next section to develop the control input necessary for pointing motion.

Control Analysis

Dr. Polites originally proposed to use a control signal that introduces periodic variations in the RUM rate ω_R. The basic approach for determining the control input is to start with a nominal RUM velocity and vary it slightly about each axis. The nominal velocity will provide the scanning motion necessary with the rate variation will provide the change in the net torque necessary for pointing motion. The control input is defined in Equation 9 as:

$$\omega_R = \omega_{ro} + \Delta\omega_X \cos(\theta_R) - \Delta\omega_E \sin(\theta_R) \quad (9)$$

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.

Since the control input is based on the position of the RUM, the rate variations must be 'timed' properly to effect the desired input. The sine and cosine terms in Equation 9 weight the rate variations to give them the proper 'timing'.
Substituting the control input into the dynamical model of Equation 8 and eliminating small higher order terms results in the elevation and cross-elevation axis acceleration approximations in Equation 10.

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

$$\ddot{\theta}_X \approx \frac{2dmr}{I_X}\left(\omega_{ro}^2 \cos(\theta_R) + \frac{\omega_{ro}}{2}\Delta\omega_X \right) \qquad (10)$$

$$\Uparrow \qquad\qquad \Uparrow$$

scanning pointing

There are several interesting observations made from this analysis:

1. The first sinusoidal terms cause the periodic 'scanning' motion of the main body.
2. The second terms affect the 'pointing' motion.

Therefore, pointing control can be accomplished by introducing periodic RUM rate variations $\Delta\omega_X$ and $\Delta\omega_E$ for cross-elevation and elevation axis errors, respectively, without interfering with the scanning motion controlled by ω_{ro}. The control developed around this model required a pointing controller and a RUM speed controller as shown in Figure 10. Note that this is the control system for a single RUM device. Control for the second RUM device is identical with the exception that the second RUM is 180° out of phase with the first RUM.

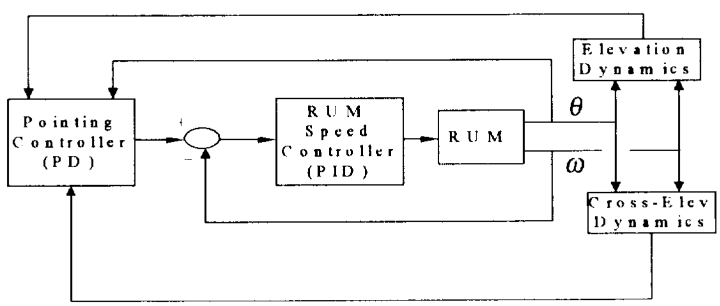

Figure 10 Control System Overview

The pointing controller uses a proportional derivative control design (PD) to provide gimbal control via coupling to the RUM speed controller which uses proportional - integral - derivative (PID) control. The elevation and cross elevation torque motors are disabled leaving the RUM devices for actuation of pointing and scanning motion. The test results are shown in Figure 11 for a small impulse disturbance input in the elevation axis.

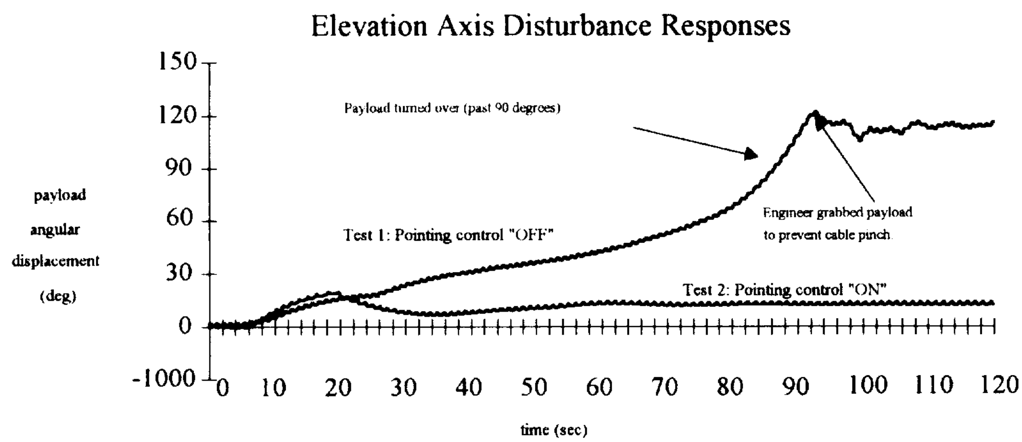

Figure 11 Pointing Control Test Results

Pointing control test result observations:

1. Scanning motion is shown as high frequency oscillation on the plots.
2. Without pointing control, the system has no disturbance rejection.
3. With pointing control off, the system demonstrates a non-linear behavior even before it turns over 90°. A linear system would have displayed a ramp-type response to an impulse input instead of the exponential type response shown. This seems to indicate there is some coupling between the RUM dynamics and the motion of the experiment beyond simple scanning or pointing movement.
4. There is a large steady state error (approximately 10°) with pointing control on.
5. Further testing indicated there was a small stability margin.

FUTURE WORK / NECESSARY TECHNICAL STUDY

Work accomplished in the summer of 1996 indicates that pointing control can be accomplished using the RUM device as an actuator. There are several open issues that arise, however, when incorporating the RUM device and a RUM control algorithm to accomplish the pointing control. These issues are divided into two primary areas: Modeling issues and control issues.

Modeling Issues

The modeling approach taken thus far has been to use the RUM device as an actuator basically independent of plant dynamics. The dynamic model developed previously used the RUM device as strictly a torque input. This was a valid approach when the small angle and constant ω assumptions were valid. A different modeling approach may be necessary if these assumptions are not be valid. Time varying ω_R generates additional reaction force terms in the modeling of the RUM device that were neglected in the original dynamical analysis. A more accurate model should include these terms as shown in Equation 11.

$$\begin{bmatrix} \ddot{\theta}_{\mathrm{LOS}} \\ \ddot{\theta}_{\mathrm{E}} \\ \ddot{\theta}_{\mathrm{X}} \end{bmatrix} = \frac{2mrd}{I_{\max}} \begin{bmatrix} 0 \\ -\omega^2 \sin(\theta_R) + \frac{u}{J}\cos(\theta_R) \\ +\omega^2 \cos(\theta_R) + \frac{u}{J}\sin(\theta_R) \end{bmatrix} \tag{11}$$

$\Uparrow$ centripetal components $\quad$ $\Uparrow$ reaction components

where:

u = torque applied to the RUM (control input)

J = moment of inertia of the RUM

$\frac{u}{J} = \dot{\omega}_R$

Even this model, however, may not be completely accurate. Coupling between the system dynamics and the RUM dynamics would invalidate previous systems models. A systems approach to modeling should be used in order to account for the possible coupling of the RUM device to the experiment dynamics. Robotics provides a large body of knowledge which may be applicable to the proposed model. The physical makeup of the plant and RUM devices as seen in Figure 8 resembles the make-up of robotic mechanisms. Using a robotics approach will allow for the mechanics of the problem by addressing how individual components of the system interact. Applying well developed robotic kinematics and kinetics concepts to this problem provides a systematic approach to system modeling. Two important modeling formulations appear to be applicable: The Lagrange formulation and the Newton-Euler formulation[4].

Control Issues

Future research work must address several control issues that result from the development of equations of motion for a time varying RUM velocity. Even though Equation 11 may not be completely accurate, it brings up the following control issues that should be applicable in future research:

1. RUM control actuation is unique in a robotics sense. Robots generally use torques at the base and subsequent joints to generate motion at the end effector. In the RUM actuated system, the actuator is at an end effector equivalent and is used to generate motion about the base (or center of mass). Also, the RUM actuator is relying on

centripetal force to generate torques that cause movement at the center of mass of the experiment instead of using directly applied torques.

2. A nonlinear system model and large angular motion require a different control method. Well developed robotic control methods involving feedback linearization, adaptive control, or nonlinear trajectory control appear to be more appropriate than linear control methods[4-6,16].
3. The system displays "periodic controllability." Periodic controllability is a term coined by the authors to indicate the periodic nature of the control signal. The RUM device generates the sine and cosine terms in the centripetal and reaction components of Equation 11. These terms have a periodic effect on the "steering" opportunities for each axis. Floquet theory[13-15] has been applied to systems that contain periodic dynamics and may be applicable to the RUM actuated system.
4. Small stability margins require an in-depth stability analysis. One of the most useful and general approaches to nonlinear stability analysis is based on the Lyapunov theory[16].

Floquet theory combined with the Lyapunov theory provides a powerful tool for analyzing and controlling systems displaying 'periodic' dynamics.

CONCLUSIONS AND ANTICIPATED CONTRIBUTIONS

This paper has presented preliminary research in the area of RUM actuated pointing control. The basic concept employed uses a time varying RUM velocity that produces torqes about the center of mass of the experiment having time varying magnitude and direction. These torques, in turn, effect pointing motion. Experimental testing indicates that pointing control is possible but there is considerable room for improvement. Future research must address several issues to improve pointing performance of the RUM actuated system. Modeling and control issues indicate a systems approach is necessary to account for "periodic controllability", stability factors, and possible coupling of the RUM device to experiment dynamics. With the great potential for improved performance, the following anticipated contributions are possible:

1. Eliminating the ACS will result in considerable benefits. The complexity of the hardware is reduced dramatically by the elimination of ACS devices such as reaction wheels or torque motors providing a more physically reliable system.
2. Elimination of the ACS devices also reduces the cost of implementation. Reaction wheels and control moment gyros are extremely complex and expensive.
3. Reducing ACS hardware reduces the weight of the overall system. Severe weight limitations are placed on balloon-borne and space borne systems because of the tremendous costs involved in transporting every pound of equipment. By eliminating the ACS system, a weight saving can lead to a cost savings or enable the optical system to be improved if more payload weight is available.

4. This research should enhance the applicability of RUM devices for other scanning and pointing systems. Examples cited by NASA researchers include spraying water in forest fires, spray painting with a fragile robot arm and medical scanners[3].
5. Unique contribution may be made to better understanding of robot control and modeling of nonlinear actuated systems.
6. New insight should be developed to the control of 'periodically controllable' systems.

REFERENCES

1. M.E. Polites, "New Method for Scanning Spacecraft and Balloon-Borne/Space-Based Experiments," *Journal of Guidance, Control and Dynamics*, vol. 14, No. 3, May-June 1991, pp. 548-553.
2. M.E. Polites, "Rotating-Unbalanced-Mass Devices and Methods of Scanning Balloon-Borne Experiments, Free-Flying Spacecraft, and Space Shuttle/Space Station Attached Experiments," U.S. Patent #5, 129,600, NASA, Washington, D.C. July 14, 1992.
3. D.C. Alhorn and M.E. Polites, "Rotating Unbalanced-Mass Devices for Scanning : Results from the Proof-of-Concept Test," *Guidance and Control 1994*, Vol. 86, *Advances in the Astronautical Sciences*, Edited by R.D. Culp and R.D. Rausch, American Astronautical Society, 1994.
4. A.J. Koivo, *Fundamentals for Control of Robotic Manipulators*, John Wiley & Sons, 1989
5. B. Friedland, *Advanced Control Techniques*, McGraw-Hill, 1995.
6. Z. Qu and D.M. Dawson, *Robust Tracking Control of Robot Manipulators*, IEEE Press, 1996.
7. J.Y. Hung, D.A. McGee, M.E. Polites, D. Alhorn, "Spacecraft Pointing and Scanning using Rotating Unbalance Masses," Project Summary Report, NASA/ASEE Summer Faculty Fellowship Program, Marshall Space Flight Center, Huntsville, AL, Aug 1996.
8. J. Cornell and J. Carr, Editors, *Infinite Vistas: New Tools for Astronomy*, New York, Charles Scribner's Sons, 1985.
9. M. Bass, Editor in Chief, *Handbook of Optics*, McGraw-Hill, Inc. 1995.
10. R.A. Sunyaev, etal, "Highlights from the KVANT Mission," *Advances in Space Research*, Vol 10, No. 2, 1990, pp. 41-46.
11. J.J. Sellers, *Understanding Space: An Introduction to Astronautics*, McGraw-Hill, Inc. 1994.
12. J.P. Ducarteron and J.P. Treilhou, "Resonance Frequencies of a Gondola Submitted to a Forced Rotation under a Stratospheric Balloon," *Advances in Space Research: Scientific Ballooning*, Vol 13, No. 2, Feb 1993, pp. 185-188.
13. P. Kuchment, *Floquet Theory for Partial Differential Equations*, Birkhauser, 1993.
14. J.S. Bibb, *Computation of Lyapunov-Floquet Transformation Matrices for General Periodic Systems,* Master's Thesis, Auburn University, December 1992.
15. P. Ramalingam, *Analysis and Control for Nonlinear Dynamics Systems with Periodically Varying Parameters*, Ph.D. Dissertation, Auburn University, August 1994.
16. J.-J.E. Slotine and W. Li., *Applied Nonlinear Control*, Prentice Hall, 1991.