COB672 THE DESIGN OF A STABILIZED GONDOLA FOR A GAMMA RAY TELESCOPE - PROJECT MASCO

Petrônio Noronha de Souza, Raphael de Almeida Fonseca, Thyrso Villela Neto, Mário Kataoka Filho
Instituto Nacional de Pesquisas Espaciais - INPE
Caixa Postal 515, 12227-010, São José dos Campos, SP, Brasil - E-mail: petros@dem.inpe.br

This paper describes the mechanical structure and the attitude control system of the gondola that carries the MASCO experiment. This is a gamma ray telescope that flies suspended by a balloon at an altitude of 40 km. The gondola is a truss structure that shall survive the landing loads and fulfill several requirements concerned with the mechanical interfaces and constraints of the transportation, launching and recovery. An attitude control system has the objective of pointing and stabilizing the telescope moving the gondola in azimuth and the telescope in elevation. There are several targets to be observed during the flight and the telescope must hold the attitude for more than one hour towards each one. Several types of sensors and actuators are employed. The system is computer controlled and the control software comprises several modes of operation according to the phase of the mission and the angular distance from the target.

Keywords: *Balloon-borne experiment, Gamma ray telescope, Structural design, Attitude control system*
Balão estratosférico, Telescópio, Raios Gama, Projeto estrutural, Sistema de controle da atitude

THE DESIGN OF A STABILIZED GONDOLA FOR A GAMMA RAY TELESCOPE - PROJECT MASCO

Petrônio Noronha de Souza, Raphael de Almeida Fonseca, Thyrso Villela Neto, Mário Kataoka Filho
Instituto Nacional de Pesquisas Espaciais - INPE
Caixa Postal 515, 12227-010, São José dos Campos, SP, Brasil - E-mail: petros@dem.inpe.br

Abstract

This paper describes the mechanical structure and the attitude control system of the gondola that carries the MASCO experiment. This is a gamma ray telescope that flies suspended by a balloon at an altitude of 40 km. The gondola is a truss structure that shall survive the landing loads and fulfil several requirements concerned with the mechanical interfaces and constraints of the transportation, launching and recovery. An attitude control system has the objective of pointing and stabilizing the telescope moving the gondola in azimuth and the telescope in elevation. There are several targets to be observed during the flight and the telescope must hold the attitude for more than one hour towards each one. Several types of sensors and actuators are employed. The system is computer controlled and the control software comprises several modes of operation according to the phase of the mission and the angular distance from the target.

Keywords

Balloon-borne experiment, Gamma ray telescope, Structural design, Attitude control system
Balão estratosférico, Telescópio, Raios Gama, Projeto estrutural, Sistema de controle da atitude

1. INTRODUCTION

The MASCO (which stands for MÁscara COdificada - Portuguese for Coded Mask) project (Villela *et al.*, 1995) is a balloon-borne gamma ray telescope in development at the National Institute for Space Research (INPE - Brazil). This experiment is a low energy gamma ray telescope that employs a Modified Uniformly Redundant Array - MURA coded mask (Gottesman *et al.*, 1989). The telescope will fly in a gondola suspended by a balloon at an altitude of approximately 40 km and should remain there a minimum of 15 and a maximum of 48 hours followed by the descending phase suspended by a parachute to be recovered. The project is divided in two main parts: detector system and stabilized platform. The entire system is represented in Fig. 1 in a block diagram.

The detector system consists in a 41 cm-diameter, 5 cm-thick NaI(Tl) crystal coupled to 19 photomultipliers. The imaging device is a 19x19 element square MURA-based extended mask mounted in a single mask-antimask configuration.

The mask can rotate 90 deg once or remain with constant velocity during the observation, in an one-piece mask-antimask configuration. This is the first experiment to use such a mask pattern (MURA) and configuration for astrophysical purposes. The anticoincidence is provided by plastic scintillators on the sides and by a NaI(Tl) crystal at the bottom. The scientific data are stored on board and sent to ground through an electronic system developed at INPE with a minimum rate of 96 kbps. The angular resolution of the detector system is approximately 14' over a 13 deg field-of-view, which requires that the expected pointing accuracy of the attitude control system should be better than that in order to allow the accomplishment of the scientific goals.

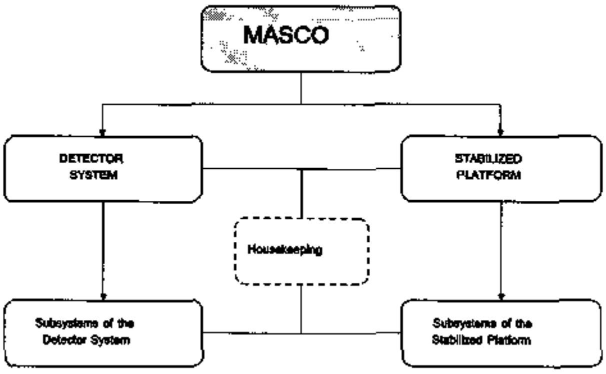

Fig. 1: Block diagram of the MASCO project.

2. THE STABILIZED PLATFORM

The stabilized platform consists in an aluminum alloy truss structure (gondola) manufactured with squared tubes that contains the detector system (the telescope itself), the attitude control system for stabilization of the platform and pointing of the telescope (in azimuth and elevation) and all other subsystems required for the flight. These include the navigation monitoring system (GPS based), the power supply system (batteries), the ballast control, the interface with the parachute and balloon, the telemetry and tellecomand system, the mass storage device for the data of the experiment, etc..

2.1 Gondola structure

The gondola structure is divided in three modules that can be separated from each other keeping their shape and strength. The first one, in the bottom, is the electronics module. It holds all the electronic equipments as much as the batteries and the ballast. The second module is the telescope module. It holds the elevation shaft that rotates the telescope. The third module comes in the top and holds the decoupling mechanism that provides the interface between the gondola and the parachute/balloon assembly. Each module is a welded structure but the joining between two modules is accomplished by bolts. This design satisfies the transportation, mechanical design and assembly and recovery requirements. The design of the gondola structure is subject to several constraints that are described below.

Mass: The size of the balloon (and consequently its price, the quantity of gas required and the difficulty to launch) is a function of the mass to be suspended. This means that some sort of optimization should be considered during the structural design in order to minimize its mass.

Transportation and launching: The structure should be transported by truck and suspended by a crane for the launching. Each step imposes a length limitation due to the size of the truck and crane available.

Mechanical design and assembling: The mechanical design should provide a large quantity of interfaces for all mechanical and electronic parts that must stay on board. In order to organize the assembling operations, tests and maintenance, it is necessary to have an electronic bay that can be separated from the rest of the structure. The telescope itself has other demands regarding its field-of-view and the openings required during assembling/disassembling, tests, operation and recovery.

Recovery: There is no control over the place where the structure lands. This always happens in remote areas with restricted or without access for trucks and cranes. In this situation the gondola shall be disassembled and removed manually in parts to an open space that allows the use of hoisting and transportation aides.

Loads: During its launching and operation, the structure will be under four different load cases:

(1) when it is entirely assembled and seated on its base (1*g* static upwards from the bottom);

(2) when it is suspended by its top by the balloon or in the laboratory (1*g* static upwards from the top);

(3) when the parachute opens (10*g* transient upwards from the top);

(4) when it touches the ground, the impact is reduced by some damping devices (crushable blocks of aluminum honeycomb) assembled in the bottom and in all sides of the gondola (not shown in Fig. 2). The actual direction of the acceleration generated by this impact is unknown but, for the sake of dimensioning, it is considered as being vertical. The value of the acceleration is obtained from the final speed of the gondola (calculated considering its total mass and the size of the parachute) and the mechanical properties of the aluminum honeycomb blocks. The dimensioning of the damping blocks indicates an acceleration of 8 *g*.

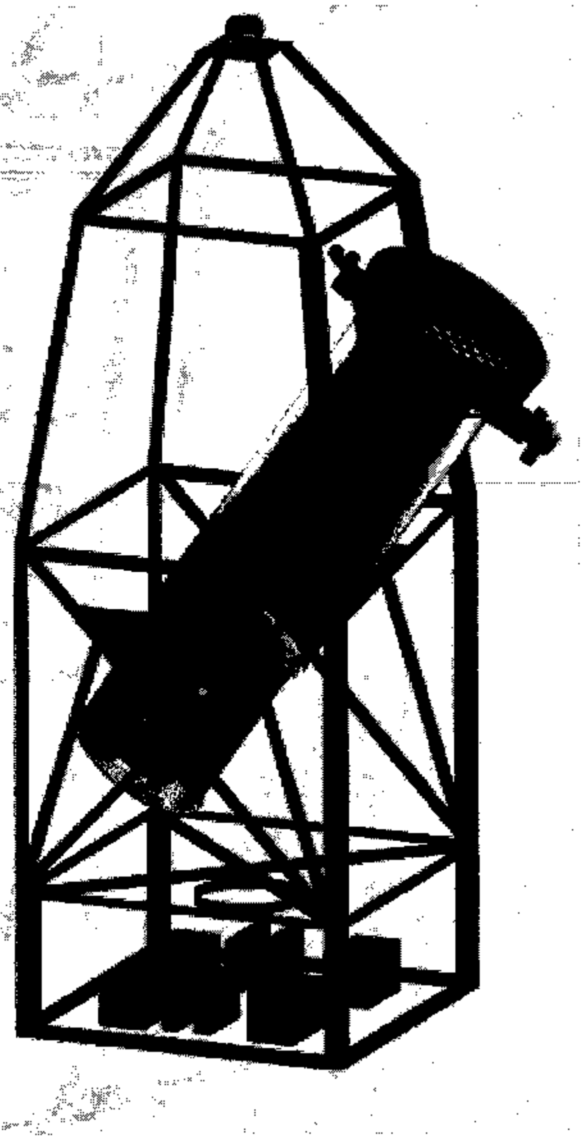

Fig. 2: The gondola of the MASCO telescope (some reinforcing beans are missing in this picture)

The first design of the structure which fulfilled all requirements described above had all tubes with the same cross section. The analysis and optimization of this structure was done using the commercial finite element code MSC/NASTRAN, Meijerink (1995). Fig. 3 shows the FEM model and Fig. 4 presents the deformation of the gondola for the load case 4. During the optimization process seven different cross sections were considered and fifteen design variables were defined (seven widths and wall thicknesses of the tube squared cross sections and the platform thickness).

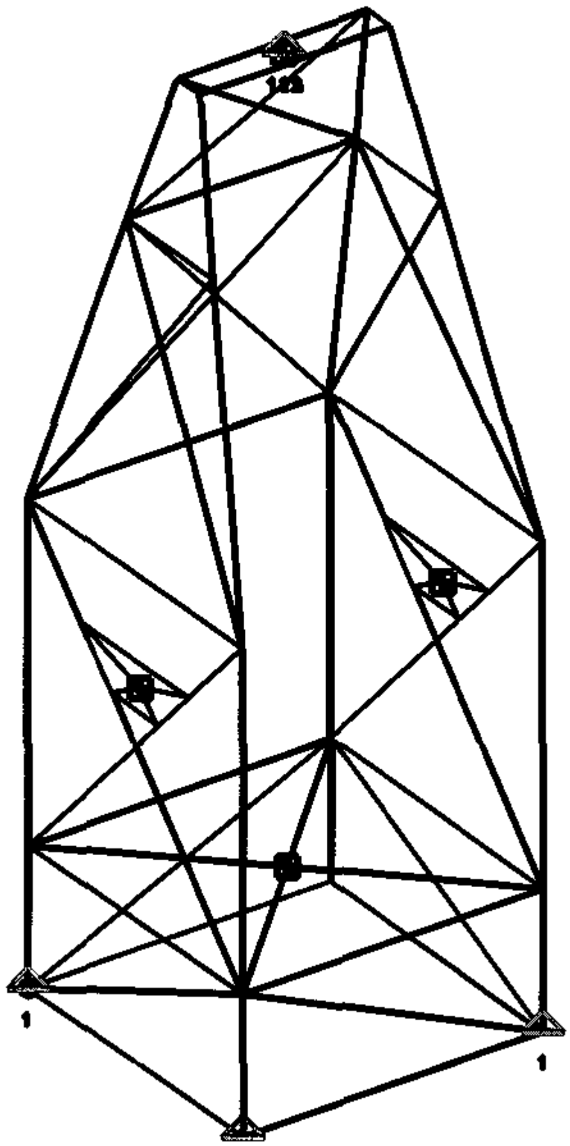

Fig. 3: Preliminary FEM model of the gondola structure.

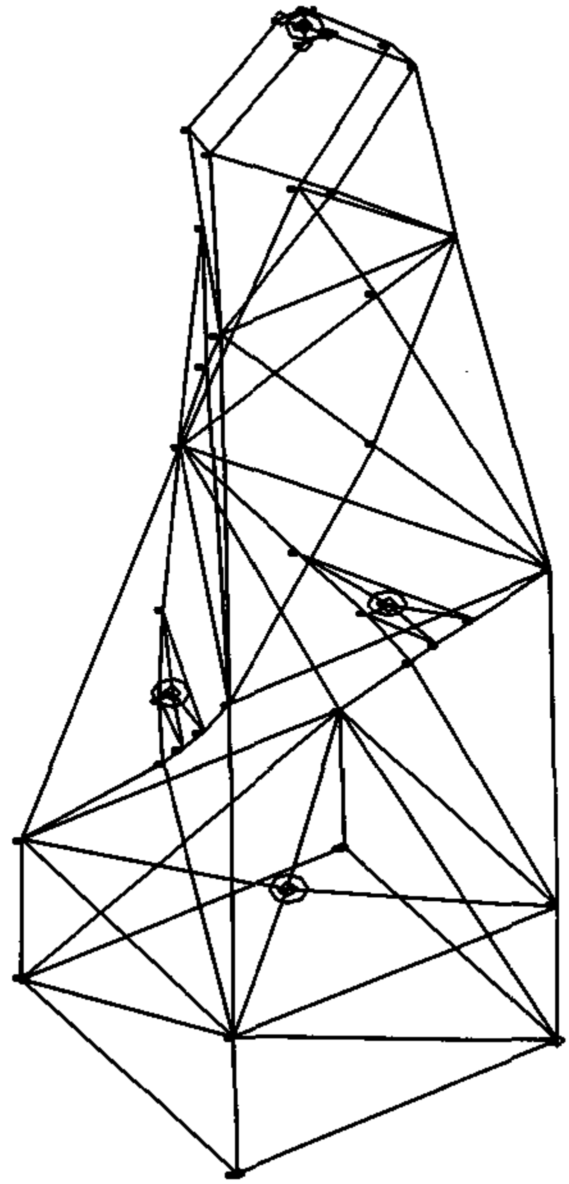

Fig. 4: Deformed shape of the gondola structure for the load case 4 (the deformations are shown larger than they actually are).

The weight of the structure was decreased by changing the values of the design variables without violating any of the considered constraints (yield stress, general bucking, local buckling and crippling). This process was able to reduce the mass in approximately 30% from the initial draft (Meijerink, 1995). The final design is approximately 6.5 meters tall and shall weight, when totally assembled, about 1,500 kg. The material adopted for the structure is an aeronautical grade aluminum 6061 T6. The final size satisfies the requirements for launching and transportation operations.

2.2 Attitude control system

The purpose of the attitude control system in this experiment is (1) to stabilize the telescope when pointing to a target and (2) track the target while acquiring the data (Pires, 1996). Both requirements are fundamental due to the long time required by the acquisition system to collect the data from each target (at least one hour). The diagram shown in Fig. 5 shows the main parts of this system including the sensors, actuators, on board computer and the software. All these parts are briefly described below.

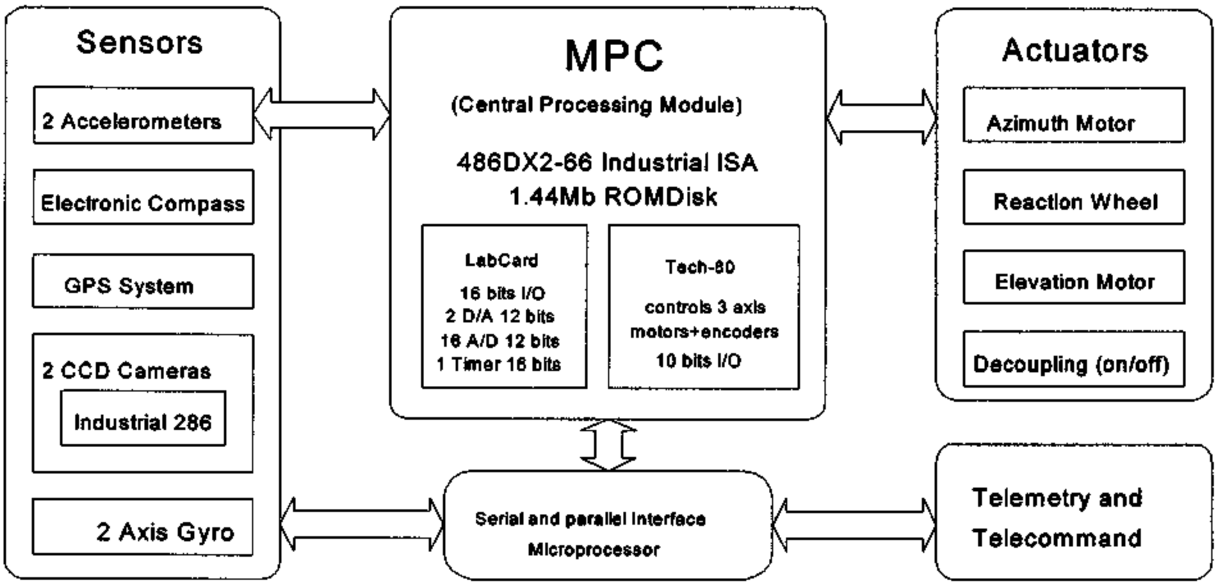

Fig. 5: Attitude control system hardware of the MASCO experiment.

2.2.1 Software architecture

The control system software architecture consists basically of two main files, one with the main calculation routines and the other with the interface routines. Other files, specific for each sensor, actuator or interface cards are included. The main program starts with the initialization routines and enters a loop of sequential execution of tasks. For each operation mode there is a different sequence of routines. A new sequence can even be sent by command from the ground. The task sequence begins with acquisition of sensor data, calibration and signal validation done by the interface routines. After that, the actual and expected gondola and telescope states are calculated considering each sensor in the main routines. A hierarchy of measurement validity is used for each operation mode in defining the actual orientation. Plant and control parameters can be identified or changed on-line in real time. The commands are calculated and the interface routines take place again in calibrating and sending them to the actuators through converters and drivers. Finally, the communication with ground is done with partial data transmission at each cycle. Fig. 6 shows the block diagram of the software architecture.

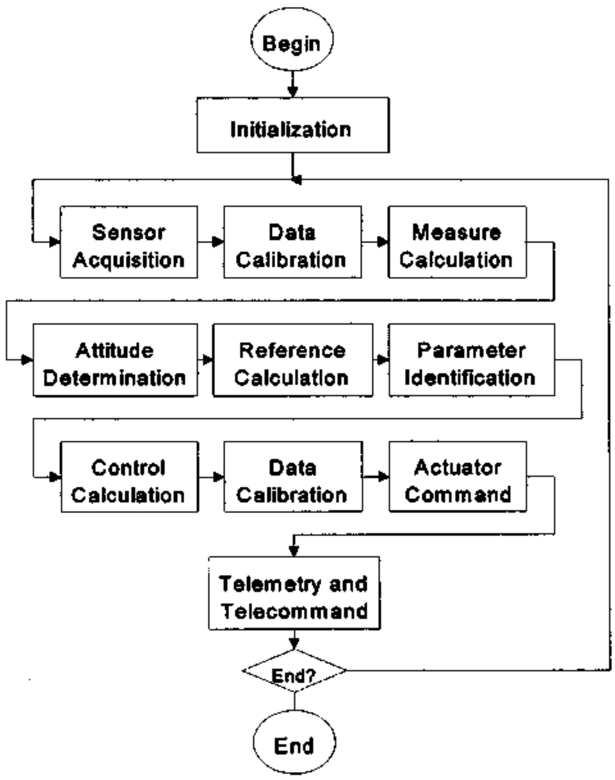

Fig. 6: Attitude control system software architecture of the MASCO telescope.

2.2.2 Operating modes

Besides the robust and the fine pointing modes there are several other operational modes like "manual" (from ground) pointing mode, pre-flight (tests) mode, ascending and descending mode, adaptive control mode and special modes for the case of failure of any equipment. These modes can be changed on-line automatically or by sending its number through a command. The equations of motion together with the proposed PID and P controllers were developed in Souza (1990) and Chingcuanco (1989), but the pendulation and the decoupling actuator had to be added. The controller gains are designed off-line with a more optimized method Fonseca *et al.* (1995, 1996) that was developed for elastic space manipulators and servomechanisms. When operating in adaptive control mode, the controller gains can be adjusted on-line, because the method uses an optimized pole allocation in a classical approach with solution by analytical equations. In the case of the elevation axis, a PI controller for motor velocity enclosed by a P for telescope position feedback is an option. This is ideal for elastic servomechanism because it suppress the static friction steady state error (integral part in the velocity feedback) without overshooting in the position feedback that is measured after the elastic effect of the harmonic drive reduction. Besides that, a feedforward compensation for the movement based on the equations of motion minimizes the error to be corrected by the feedback part. In the case of the azimuth axis, the PID controller for azimuth error has an output for the reaction wheel, whose velocity is controlled indirectly by the azimuth motor with a slow P controller. The design method was changed to consider this crossed aspect.

2.2.3 Sensors and actuators

Several kinds of sensors (an electronic compass, an axis encoder, a two-axes solar sensor, two accelerometers, two CCD cameras and a gyroscope) are used in the attitude control system for redundancy and some of them achieve a precision better than 0.1 deg. Only the CCD cameras can function independently of the others, since they observe directly the absolute reference system. The other sensors need the computation of the signal of a GPS system to establish a local horizontal reference system from which azimuth and elevation (angle from local vertical) are defined. The cross-elevation angle of the gondola is not directly controlled, but it is monitored and has some coupling with azimuth. The attitudes calculated from the several sensors are ordered according to a hierarchy, so that the most accurate sensors have priority.

An electronic compass has the worst precision (0.5 deg) and is used for a first robust azimuth approximation together with a telescope transversal axis encoder for the elevation correction. In this robust control the pendulation in elevation is not necessarily damped. It is expected that the angular amplitude remains below 2 deg because of the great length of the suspension cables from the balloon to the gondola. The robust correction trajectories would be components of a trapezoidal velocity profile, but less jerkily trajectories are investigated even for this robust mode. In case of fine pointing modes, the encoder remains used for transforming the gondola coordinates into telescope coordinates and the compass confirms the calculated azimuth.

When the telescope enters a range of less than a certain value of deviation (aproximately 5 deg), a fine pointing mode is automatically started. In this mode, a solar sensor developed at INPE, with precision of 0.15 deg in two axes, working together with two accelerometers with sensitivity of 244 μg, and a gyroscope, take the priority in measuring the actual angular position of the gondola and the telescope. A difficult task is the cancellation of the amount of the actual linear acceleration due to the linear and pendular motions of the gondola, since the desired measurements are those of the gravity components (with knowledge of the Earth and Sun positions, the gondola attitude is determined). The objective is to use the gyroscope in this context to measure the gondola angular velocities allowing compensation of the centripetal accelerations and the GPS for compensation of the gondola linear accelerations from the measurements of the accelerometers. Only two of them are available at the moment (three would be ideal), but since the expected pendulation is small the vertical axis accelerometer may be omitted. However, the possibility of locating them in the vertical plane fixed to the elevation axis of the telescope has been considered. There is still the possibility of using the gyroscope fixed in the telescope with an off-set to the axis of view for measuring increments of elevation and azimuth angles relative to a known initial attitude during the fine pointing. The gyroscope should have its drift corrected periodically using the initial attitude determined by other sensors. In these cases, the elevation would be directly that of the telescope and not of the gondola.

Two CCD cameras are used for the night phase of the flight. They are fixed in the telescope, but not necessarily aligned with it, since during a significant period of the mission the field-of-view will be intercepted by the balloon (which is transparent to gamma rays). At the planned flight altitude (40 km) the telescope should be pointed at least 30 degrees above the horizon, but the ideal is above 60 degrees in order to minimize atmospheric effects. It is possible that some first magnitude stars are visible by the cameras even during the day, but two or three celestial bodies are necessary for obtaining the angular orientation. A computer program that recognizes groups of stars in a fraction of a second was developed at INPE. The point pattern matching algorithm is based on geometrical criterion. The distances between stars from the camera image, as well as the relative angles and brightness are calculated and compared with a reference catalogue. The subgroup of stars used as references is within an area four times greater than the field-of-view of the camera and contains stars down to magnitude six.

There are five main actuators in the system although one of them is only for driving a decoupling mechanism between the balloon and the gondola with constant velocity (to avoid static friction or twisting) and another is only responsible for driving the mask with constant velocity or bringing it to a 90 degree crossed antimask position. The other three are: a reaction wheel developed at INPE (with 1 kgm^2 of inertia) for azimuth control driven by a DC-motor with peak torque of 6.8 Nm and saturation at 300 rpm, another azimuth motor of the same type and size located in the gondola-balloon decoupling mechanism for desaturation of the reaction wheel and a telescope elevation actuator with 30 Nm of torque and a harmonic drive reduction system with 1:100 rate. The telescope mass is about 900 kg and possible elastic effects due to the harmonic drive have to be considered. The command digital signals of an industrial PC are converted and sent through a dedicated board to the power drivers connected to the motors. The same board receives the encoder signals of the reaction wheel and of the elevation axis, but the other sensors and the telemetry are received by another board through an interface card designed at INPE to manage several serial and parallel signals.

3. CLOSING

This paper gives an overview of the MASCO project highlighting the main aspects of the mechanical structure of its gondola and the attitude control system. An initial design of the structure was defined so that it fulfilled all the geometrical and operational requirements. This initial design was optimized in order to reduce its weight. The attitude control system is a two axis PC based architecture of high complexity due to the type of mission, number of sensors and actuators and pointing requirements.

4. REFERENCES

Villela, T., Braga, J., D'Amico, F. & Jayanthi, U.B. *A MURA-based coded mask telescope*, Advances in Space Research, 15(5), 95 - 98, 1995.

Gottesman, S.R. & Femimore, E.E. *New family of binary arrays for coded aperture imaging*, Applied Optics, 28(20), 4344-4352, 1989.

Meijerink, G.G.T. *Optimization MASCO Structure*, Internal Report DMC/ INPE, 1995.

Pires, C. *Anteprojeto Sistema Apontamento e Referência de Atitude - SARA*, Internal Report DMC/ INPE, 1996.

Souza, A.P. *Projeto mecânico de um telescópio de raios gama a bordo de balão estratosférico*, Master Degree Dissertation, ITA, São José dos Campos, 1990.

Chingcuanco, A.O. *Modeling and control of a balloon-borne stabilized platform*, PhD Dissertation, University of California, Berkeley, 1989.

Fonseca, R.A. *Analytical determination of controller parameters for elastic servomechanism -PID (load position case)*, 1995 IFAC Conference on Intelligent Autonomous Control in Aerospace (Pre-print volume), Beijing, China, 1995.

Fonseca, R.A., De Moraes, R.V., & Schäfer, B. *Adaptive control and simulation of an elastic space manipulator replica*, 13th IFAC Triennial World Congress, International Federation of Automatic Control, San Francisco, USA, 1996.

XIV CONGRESSO BRASILEIRO DE ENGENHARIA MECÂNICA

14th BRASILIAN CONGRESS OF MECHANICAL ENGINEERING

08 a 12 de Dezembro de 1997 - December 8-12th 1997

Para acessar a home-page do Cobem97 conecte-se à Internet e clique sobre o endereço:

www.dem.feis.unesp.br/cobem97

ORGANIZAÇÃO

unesp

Ação conjunta: FEG - Guaratinguetá, FEIS - Ilha Solteira, FET - Bauru, IGCE- Rio Claro

PROMOÇÃO

ABCM

Associação Brasileira de Ciências Mecânicas