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Preface

The 15th IMACS World Congress on Scientific Computation, Modelling and Applied Mathematics held in Berlin from August 24-29, 1997 is sponsored by IMACS (The International Association for Mathematics and Computers in Simulation), the German Research Foundation (DFG) and the Encyclopedia of Life Support Systems (EOLSS). It is being hosted by the Research Institute for Computer Architecture and Software Technology (GMD FIRST) of the German National Research Center for Information Technology (GMD) and the German Computer Society (GI). Co-sponsors of the Congress are GAMM (International Association of Applied Mathematics and Mechanics), IEEE (Institute of Electrical and Electronic Engineers), IFAC (International Federation for Automatic Control), IFIP (International Federation for Information Processing), IFORS (International Federation of Operational Research Societies) and IMEKO (International Measurement Confederation).

Over the last four decades it has become an established tradition for a broad international community of experts from various fields to gather at IMACS world congresses. This Congress stands firmly within the IMACS tradition. More than 1000 participants from all over the world are presenting and discussing new results in theory, software and applications in various fields of research and industry. Computer simulation is bringing transparency and insight into the actions of complex systems in many areas including natural and engineering sciences, environmental research, biotechnology, medical research, economics and managment. The Congress aims to provide a forum for interdisciplinary discussion; at the same time, we place a high value on maintaining the human touch.

The proceedings include both invited and submitted papers which reflect current state-of-the-art activities in their respective field. We are particularly pleased to be able to count amongst our speakers many scientists who have made significant contributions to recent developments. The proceedings are published in six volumes which collate papers on the following topics: 1. computational mathematics, 2. numerical mathematics, 3. computational physics, chemistry and biology, 4. artificial intelligence and computer science, 5. systems engineering, 6. application in modelling and simulation.

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Attitude Control System of the MASCO Balloon-Borne Gamma Ray Telescope

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ABSTRACT

We describe the attitude control system of the MASCO experiment. The MASCO project is a balloon-borne gamma ray telescope in final phase of 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 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 angular resolution 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. Several kinds of sensors (an electronic compass, an axis encoder, a two-axes solar sensor, two accelerometers, a gyroscope and two CCD cameras) are used by this system for redundancy and some of them achieve a precision better than 0.1 deg. The main actuators are: a reaction wheel for azimuth control, an azimuth motor located in the gondola-balloon decoupling mechanism for desaturation of the reaction wheel and a telescope elevation motor with a harmonic drive reduction. The control system software architecture consists basically of two main files, one with the main calculation routines and the other with the interface routines. 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.

INTRODUCTION

The MASCO (which stands for MÁscara COdificada - Portuguese for Coded Mask) project[1] is a balloon-borne gamma ray telescope in final phase of development at the National Institute for Space Research (INPE - Brazil) that is scheduled to fly at the end of 1997 or beginning of 1998. This experiment is a low energy gamma ray telescope that employs a Modified Uniformly Redundant Array (MURA[2]) coded mask. 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 parts: detector system and stabilized platform. The whole system is illustrated in figure 1 and represented in figure 2 by a block diagram.

Detector System

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.

Stabilized Platform

The stabilized platform consists in a tubular metallic structure (gondola) that contains the detector system, the control system for stabilization of the platform and pointing of the telescope (in azimuth and elevation), the navigation monitoring system (GPS), the power system, the ballast control and the interface with the parachute and balloon.

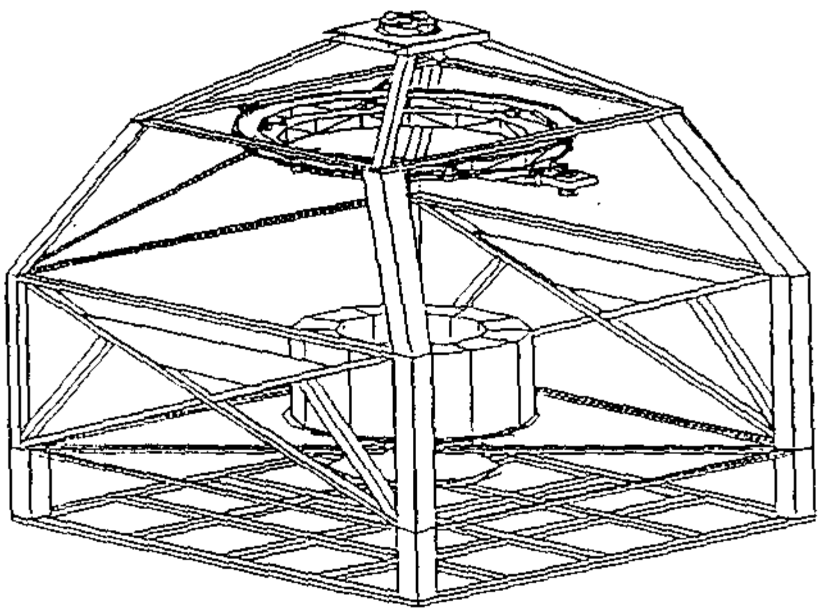

Fig. 1 - The MASCO telescope in its gondola.

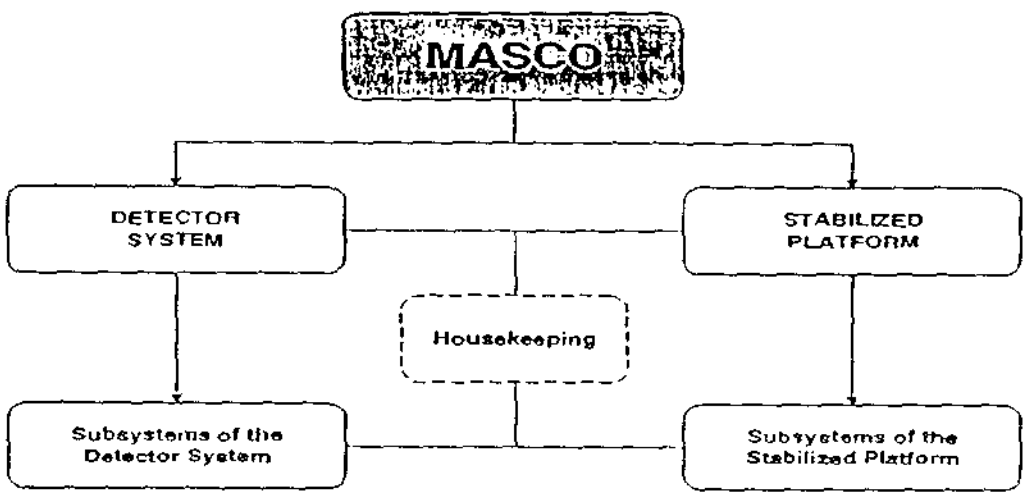

Fig. 2 - Block diagram of the MASCO project.

SENSORS

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.

Compass and Axis Encoder

An electronic compass (C100 from KVW Industries, Inc.) has the worst precision (0.5 deg.) and is used for a first robust azimuth approximation together with a telescope transversal axis encoder (ROD 426.001A from Heidenhain) 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 jerky 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.

Accelerometers, Gyroscope and Solar Sensor

When the telescope enters a range of less than a certain value of deviation (for example, 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 (Q-Flex QA 2000 from Sundstrand Data Control, Inc.) with sensitivity of 244 μg, and a gyroscope (GAM-1 DG-2A from SFIM), 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 measured 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 (amplitude of the order of one deg) 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 other sensors and that initial attitude must be determined by them. In these cases, the elevation would be directly that of the telescope and not of the gondola.

Stellar Sensors

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 absorption. 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.

ACTUATORS AND CONTROL SYSTEM

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 $kg.m^2$ of inertia) for azimuth control driven by a DC-motor (Inland QT-5404C) 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 (Inland T-7203) with 30 Nm of torque and a harmonic drive reduction system (HDC-065-100-2A) 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 (IPC-610) are converted and sent by a Tech-80 board (model 5638) to power drivers (model 215A from Copley Controls, Corp.) 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 a LabCard (PCL-812 from Advantech) board through an interface card designed at INPE to manage several serial and parallel signals. Figure 3 shows the block diagram of the control system hardware[3].

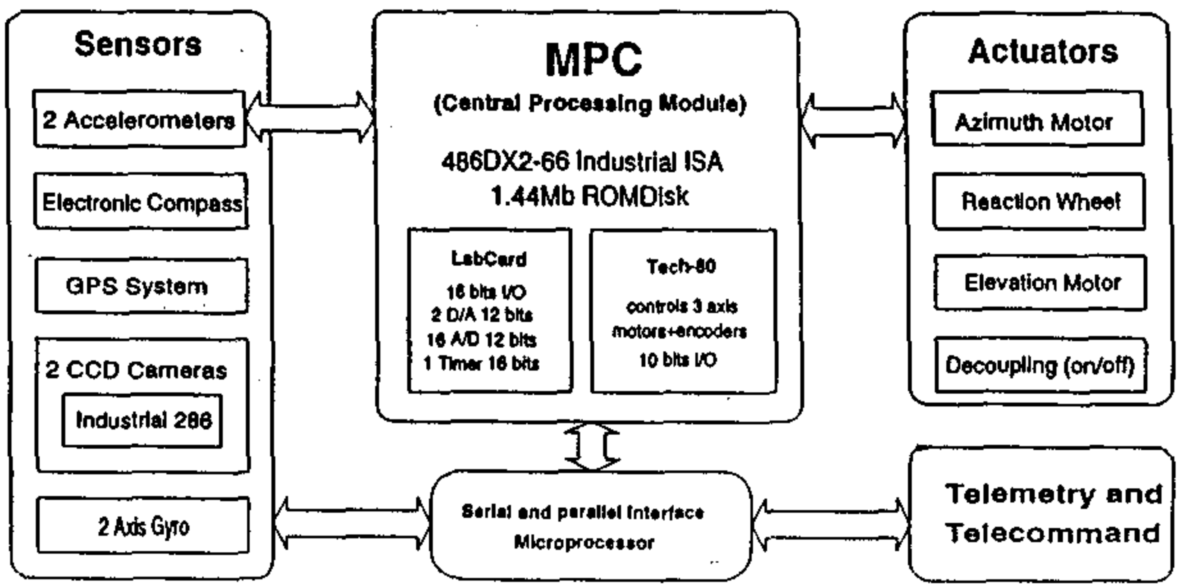

Fig. 3 - Control system hardware of the MASCO telescope.

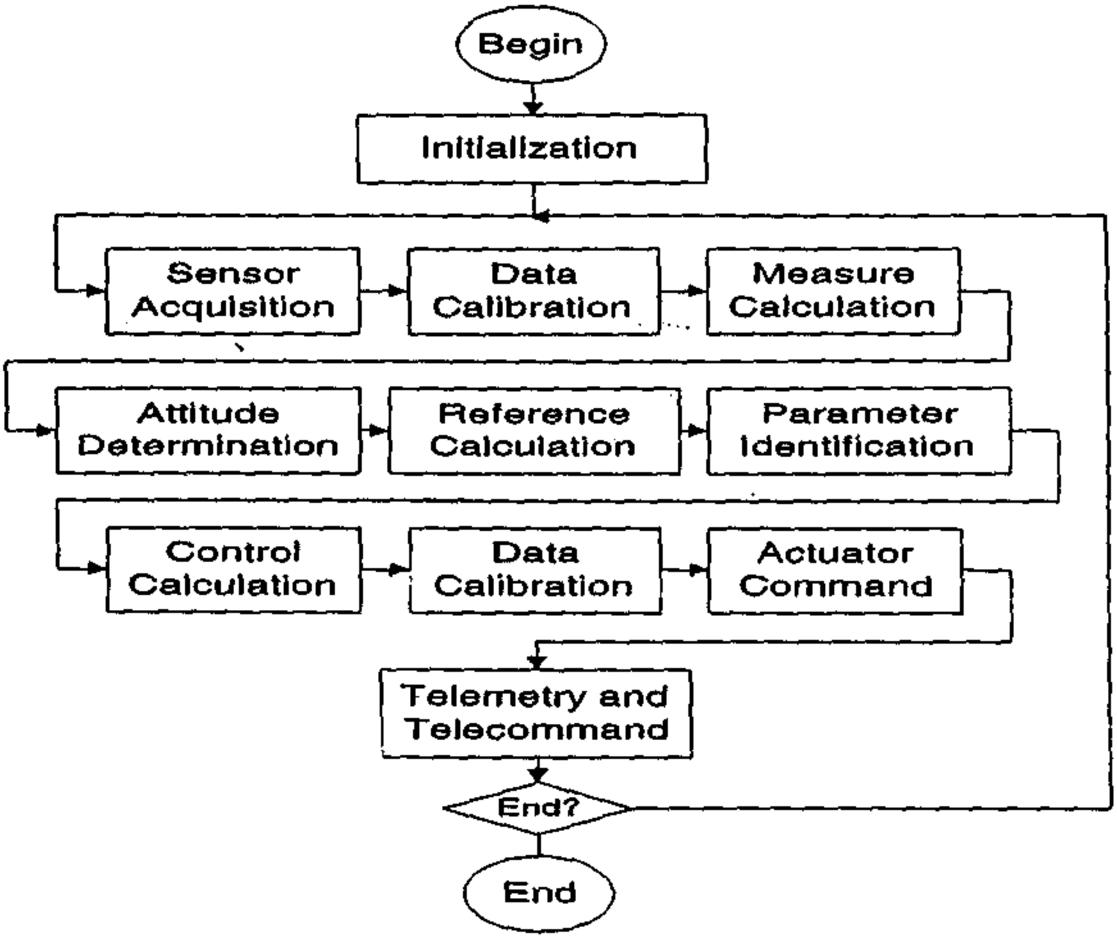

Fig. 4 - Control system software of the MASCO telescope.

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. There is a small group responsible for the development of this software. 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. Figure 4 shows the block diagram of the software architecture.

OPERATION 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 especial 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 basically developed in previous works[4,5], but the pendulation and the decoupling actuator had to be added. The controller gains have been designed off-line with a more optimized method[6,7] that was developed for elastic space manipulators and servomechanisms. When operating in adaptive control mode, the controller gains can be adapted 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, suppressing static friction steady state error (integral part in the velocity feedback) without overshoot in the position feedback, measured after the elastic effect of the harmonic drive reduction. Besides that, a feedforward compensation for the movement based on the equations of motion tries to minimize the error to be corrected by the feedback part. In the case of the azimuth axis, the PID controller for azimuth error has output for the reaction wheel, whose velocity is controlled indirectly by the azimuth motor with a slow P controller. The design method had to be changed to consider this crossed aspect.

CONCLUSION

The MASCO project is a balloon-borne gamma ray telescope of the National Institute for Space Research (INPE - Brazil) with an angular accuracy requirement of less than 14'. Several kinds of sensors (an electronic compass, an axis encoder, a two-axes solar sensor, two accelerometers, a gyroscope and one or two CCD cameras) are used for redundancy with some of them achieving a precision better than 0.1 degrees. The main actuators are: a reaction wheel developed at the institute for azimuth control, another azimuth motor located in the gondola-balloon decoupling mechanism for desaturation of the reaction wheel and a telescope elevation actuator with a harmonic drive reduction. The control system software architecture consists basically of two main files, one with the main calculation routines and the other with the interface routines. Optimized pole-allocation control is used in the design.

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