DESIGN OF ONE METER CLASS TELESCOPE MOUNT FOR SPACE SURVEILLANCE

Fabio Santoni(1), Fabrizio Piergentili(2)

(1) DIAEE, University of Rome "La Sapienza", Via Eudossiana 18, 00184 – Rome (Italy), Fabio.santoni@uniroma1.it
(2) DIMA, University of Rome "La Sapienza", Via Eudossiana 18, 00184 – Rome (Italy), Fabrizio.piergentili@uniroma1.it

ABSTRACT

The design of a one meter class telescope mount is addressed, specifically developed for space object tracking, including orbiting objects, in any orbital regime, as well as objects re-entering in the Earth atmosphere. .

The telescope mount design is completed and a first prototype is at the moment under manufacturing, thanks to the collaboration between the Space Systems Laboratory of University of Rome "La Sapienza" and the University spin-off Roboptics srl, in the framework of a program funded by the Lazio Region.

The requirements of the core parts of the mount deriving from its utilization for LEO fast moving objects are pointed out in the paper, highlighting control system specifics and structural static and dynamic analysis.

1 INTRODUCTION

The Space Surveillance of high Earth orbital regimes has been accomplished using optical instruments [1-6]. The slow angular motion of objects orbiting in these regions permits to achieve high sensitivity, measuring objects with sizes down to ten centimetres in Geosynchronous region.

The recent developments in telescope and CCD technologies make them suitable also to detect and measure fast moving low Earth and even re-entering space objects [7-11]. In particular, recently developed systems allow obtaining at the same time large field of views and high sensitivity.

Optical systems are characterized by their high accuracy in angular measurements [12- 14], whereas radar by range and range rate. Combining these information a very accurate orbit determination is possible. The knowledge of orbital parameters, together with their covariance, is of great importance in the assessment of collision risk between orbiting objects [15] as well as in the identification of the impact region on the Earth for re-entering massive objects since the unknown atmospheric parameters (i.e. density) produce fast varying and very difficult to determine trajectory [16-17].

Moreover, the capability to track LEO fast moving objects is essential when photometric measurements of these objects are required, in order to determine their attitude motion, [7-11].

Therefore, it is highly desirable for a space surveillance system to deploy optical instruments capable to observe fast moving space objects. These kinds of systems require a robust and precise high-speed tracking mount, in addition to the technological advanced solutions for optical instrumentation and sensors. In particular the combination of high pointing accuracy and fast angular movement requires a high level of automation and extremely accurate synchronization of the mount rotation axes, both in the equatorial and in Alt-Azimuthal configurations.

As a result of a trade-off analysis, including considerations on the system modularity and suitability for future developments, and Alt-Az configuration was selected for the first realization, preferring a fork mount with respect to a German mount because of its better adaptability to large telescope One of the main features of the design developed, according to a specific requirement of space surveillance systems, is the ability to be operated remotely, in extreme temperature and wind conditions, not common for astronomic observations. In particular a very low operational limit was set for the minimum operation and storage temperature, as low as -20°C.

A discussion about the mount motion requirements for LEO tracking ground-based optical system is given in section 2.

, Finite element models have been used for the static and dynamical analysis of the fork structure leading to an optimized structure based on a trade off between mount weight and stiffness in terms of deflections and vibration frequencies.

The mount tracking system design has been validated through numerical simulation, to test the control laws and the effectiveness of the actuators and sensors chosen. To this purpose a number of trajectories of different orbiting objects have been simulated in order to evaluate the mount tracking errors.

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

2 THE LEO TRACKING MOUNT REQUIREMENTS

Tracking of LEO objects through optical devices is a very demanding task: the relative motion of these objects is very fast, their trajectories are not well defined since large uncertainties subsist, mainly due to unknown atmospheric parameters, space debris ballistic coefficient and attitude motion .

In particular, a system suitable for these kinds of objects should be capable to track simultaneously on two independent axes, contrarily to the usual astronomic equatorial mounts that, in standard sidereal tracking mode, could track celestial objects moving only around one axis (right ascension).

To illustrate the angular tracking velocity required to the mount it has been considered a study case considering an observatory located in Italy and a general LEO object at 650km height and 65° inclination.

In Fig. 1 the ground track is shown. The red parts are the trajectory position in which the orbiting debris is visible from the observatory. In this kind of analysis the solar illumination on the debris has not been considered as a requirement since the same mount could host a laser ranging systems which not requires direct solar illumination..

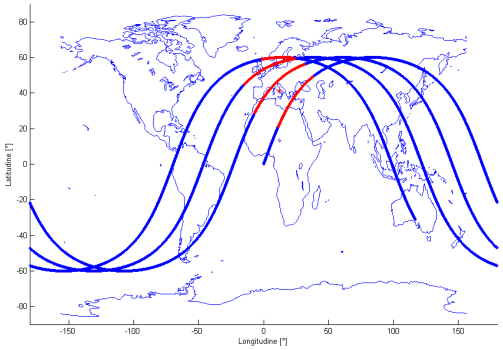

Figure 1. – Ground track of a LEO Space Debris

On the basis of relative motion between ground station and space debris it is possible to evaluate the right ascension and declination angles and their associated angular rates. Due to the definition of these angles, a singularity appears when the declination is +90° or -90°, since in this condition the right ascension is undefined. Close to this position short trajectory arcs of the space objects could imply large angle variations. In Fig. 2, the angular velocities for the tracking of the space debris considered in Fig. 1, are shown. Peaks happen when the telescope is pointing in direction of the celestial pole.

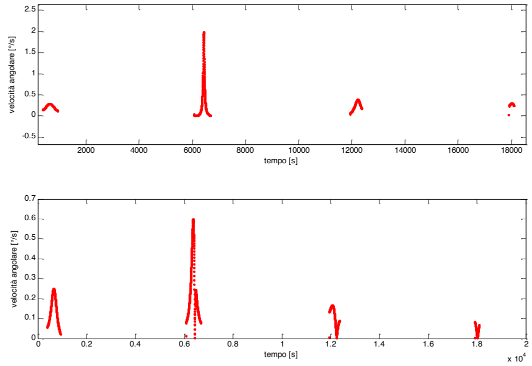

Figure 2. – Right Ascension rate (up) and Declination rate (down) for tracking of LEO 650km x65° space debris.

An Alt-azimut mount has similar problems when the elevation is near 90°.

In order to evaluate the mount requirements the maximum global angular rate was considered (considering the angle between the local vertical and the satellite direction), as a function of the satellite height; considering this angle the singularities are avoided and the real mount required angular speed are achieved.

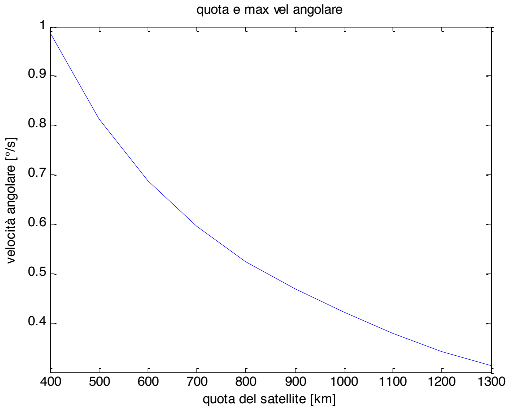

Figure 3. – Maximum angular rate for a tracking system suitable for LEO space objects.

The maximum angular rates, sketched in Fig.3, diminish when the height increase, and are lower than 1 deg/s. This implies that a mount capable to accurate tracking should move at an angular rate greater of at least one order of magnitude, thus the minimum angular tracking rate of the mount will be set to 10deg/s.

Together with the fast angular rate, the mount should assure high pointing accuracy to respond to the demanding performances of Space Surveillance

Table 1 – Mount specifications

Motion Control Specifics	
Maximum angular speed (AZ and ALT)	20 deg/sec
Angular measurement resolution	0.01 arcsec
Motor Torque (AZ / ALT)	300 Nm/180 Nm
Dimensions	
Overall height	2000 mm
Overall width	2000 mm
Base diameter	1000 mm
Maximum distance between mounting plates	1300 mm
Temperature	
Operative	---20° ÷ 40 °C
Storage	---40° ÷ 60 °C

Systems.

The recent, state-of-the-art astronomy imaging technologies coupled with large field of view optical instruments permit to reach pixel accuracies on the order of the arc-sec, thus leading to space debris centre of mass position accuracy on the order of tenth of degree [7-13]. Thus, for feedback sensor, an order of magnitude of 10^{-2} arcsec is required. This pointing accuracy is obtained using direct drive motors, eliminating transmission hardware between the motor and telescope axes. High accuracy angular measurements are obtained by exploiting state of the art absolute optical encoders, capable to measure angles with extremely high precision, down to 0.01 arcsec directly on the axes.

Another important requirement in the development of such a kind of system is the environmental compatibility, with particular regard to operative temperature. As a matter of fact the fast tracking of the mount could be not compatible with the utilization of a protective dome, thus the system could be exposed to very rigid temperature. The mount has an extended operative and storage temperature ranges: (-20÷40 °C operative, -40÷50°C storage). This makes it suitable for remotely controlled observations in severe climatic conditions. The Mount specifics are depicted in Tab. 1.

The design requirement of the mount, to be compatible with a one meter class telescope are:

- Maximum telescope weight: 500kg.
- Distance between support plates 1300mm.
- Free distance of the mounting axis from the centre of the base 1600mm.

According to these requirements the final mount dimensions are sketched in Fig. 4. The mount design make it also Nasmyth--Focus telescope compatible.

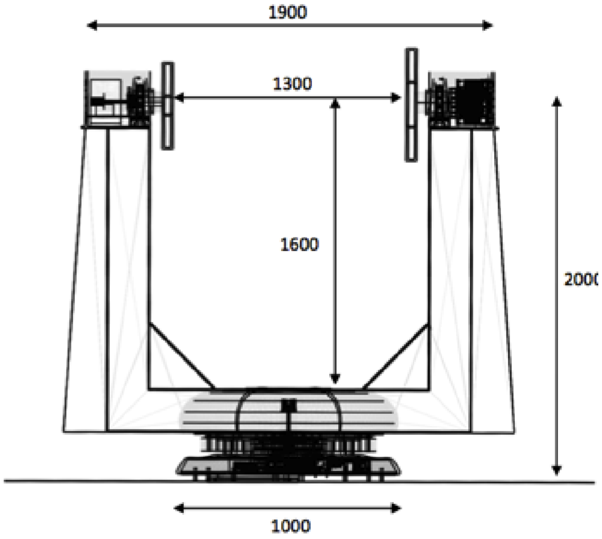

Figure 4. – Mount size

The mount wiring include 24 user selectable lines (user selectable serial RS232 or USB digital connection for command and data exchange and power lines) connecting focal plane instruments to the mount base. These connections are realised through wire free systems, permitting complete and continuous rotations of the system.

3 MOUNT DESIGN

The design of the mount is based on two main parallel subsystem design: Control and structure.

Control system design is inherent to all requirements concerning electronic hardware and wiring, and software for motion control, including feedback sensors, actuators and guidance algorithms.

Structural design concern the mount structure design, including analysis of displacement under static loads and vibration frequencies achieved from numerical analysis of dynamic behaviour.

3.1 Control system

The control system is based on the use of high performance motion control and robotics automation equipment.

The control algorithm has been analysed by implementing the whole electromechanical system in a Simulink diagram.

The overview of the control system scheme is given in Fig 5.

The three main blocks are :

- the controller
- the Motor model
- the sensor

The controller implements the tracking logic, in this phase a continuous Proportional, Derivative and Integral control have been implemented.

The motor model is based on a DC/DC motor scheme adapted to simulate the behaviour of a Torque direct drive motor, the system is controlled by a Pulse Width Modulation on the input voltage. The stall torques has been set to 300Nm for the azimuth motor and to 180 Nm for the Elevation motor.

The sensor is simulated as an angular absolute discrete encoder with an accuracy equal to the half of the minimum discretization angle. In this case the accuracy has been set to about 0.01 arcsec.

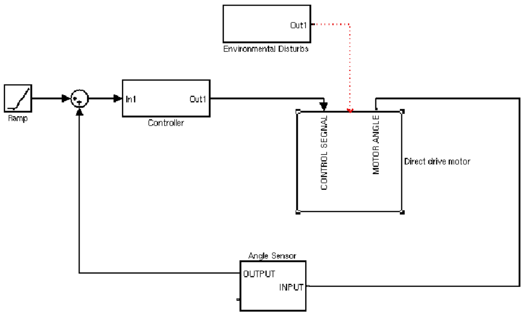

Figure 5. – Mount Control System scheme

The input trajectory is a ramp of 10°/sec. Disturbance torques have been considered, including friction (static and viscous), and wind gusts potentially acting on the telescope The system noise has been considered through disturbance torques, essentially due to wind gusts that invest the telescope.

The PID controller tuning has been refined through the analysis of BODE diagrams, in Fig.6 are presented the final diagrams, in magnitude and phase for the azimuth axis.

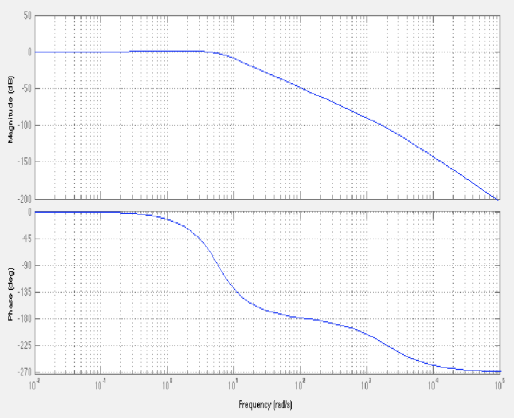

Figure 6. – Bode Diagram – Azimuth axis

From the Bode Diagram it is possible to notice the cut-off frequency set at about 10°/s for the Azimuth axis.

The answer to the ramp is presented in Fig.7 for the Azimuth axis.

From the error angle between real azimuth and nominal trajectory graph, it is possible to evaluate a rise time of about 0.32 s and a settling time of 4.3 s.

The error at regime is shown in Fig. 8 and it is lower than 10^{-3} arcsec.

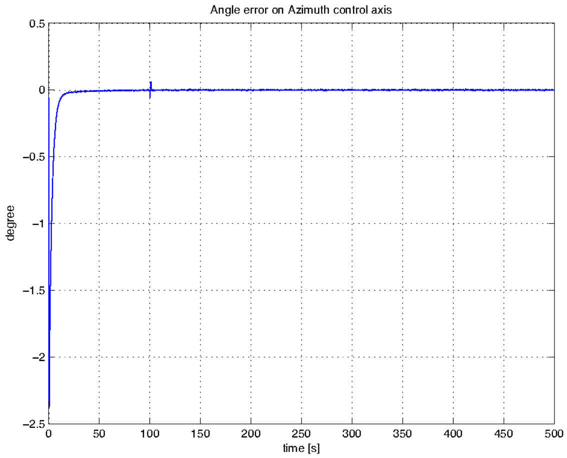

Figure 7. – Error angle – Azimuth axis

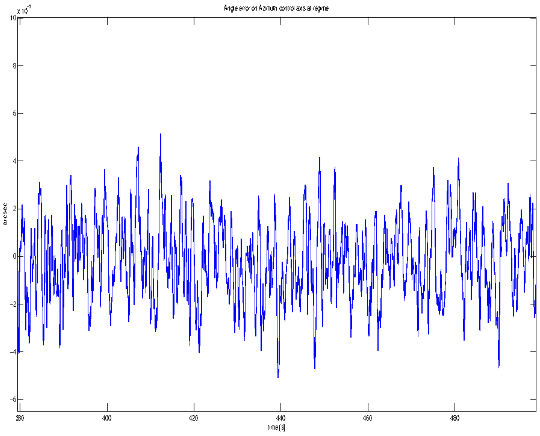

Figure 8. – Error angle at regime – Azimuth axis

Last considered situation is the presence of environmental disturbance. This disturbance has been modelled as a step on the trajectory of 200 arcsec in one direction and in the opposite direction after 1 sec. The system answer is sketched in Fig. 9. It is possible to appreciate the fastness of the control system in stabilising the disturb error.

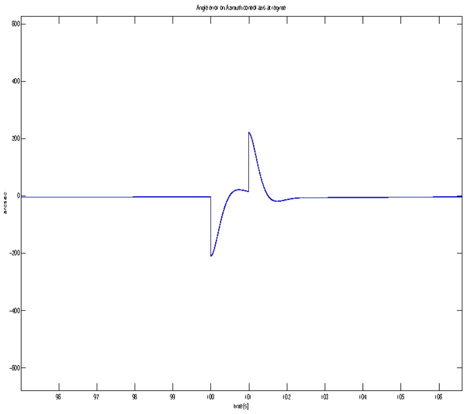

Figure 9. – Error angle due to external disturbance– Azimuth axis

The elevation axis control system is similar to the azimuth one.

The control software is based on open source operation protocol for compatibility with commercial astronomical equipment software control (e.g. ASCOM platform) and for enabling the development of user specific command sequences, different from sidereal tracking.

3.2 Structure design

The mount structure has been designed using Finite Element Model simulation. The structural frequency with a 700kg load is above 20Hz. This performance is reached with no loads for the optical system, which is not included as a structural element in the system. The mount overall weight is about 600kg; its extremely compact size has been achieved by mean of the utilization of high precision crossed rolling cylinder 800mm. circular bearing at the azimuth axis.

In Fig.10 and Fig.11 the displacements and stresses distribution respectively are sketched under static 700 kg load. It is possible to notice that the maximum displacement at the telescope-mount coupling part is lower than 0.1 mm.

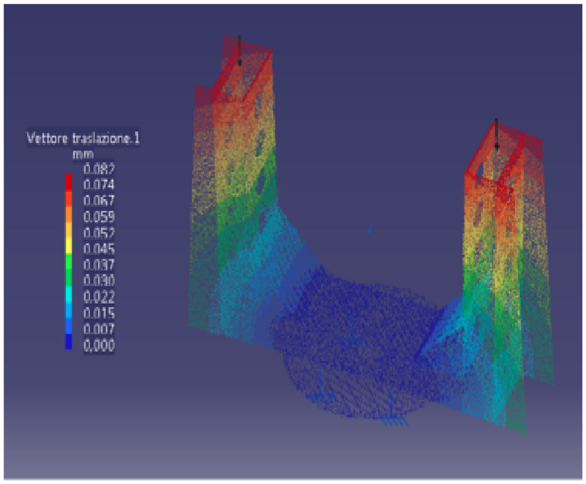

Figure 10. – Mount static displacements (load 500 kg)

Principal stresses, concentrated where mount arms are connected to base are orders of magnitude lower than steel maximum acceptable stress.

It should be noticed that such performances were reached without considering the telescope as structural part.

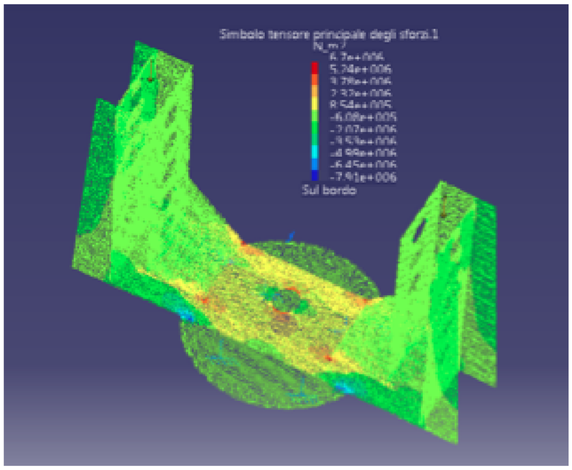

Figure 11. – Mount static stresses (load 500 kg)

The structural analysis was carried out also for the dynamical part in order to identify the vibration frequencies.

The list of the first ten vibration frequencies is sketched in Tab. 2.

Mode number	Frequency [Hz]
1	24.4
2	24.9
3	26.5
4	30.0
5	46.1
6	46.7
7	55.9
8	56.0
9	70.1
10	71.5

Table 2 – Mount vibration frequencies

The first frequency is greater than 20 Hz assuring structural rigidity suitable for the required high precision tracking.

The representations of the first four modes are given in Fig 12, 13,14 and 15.

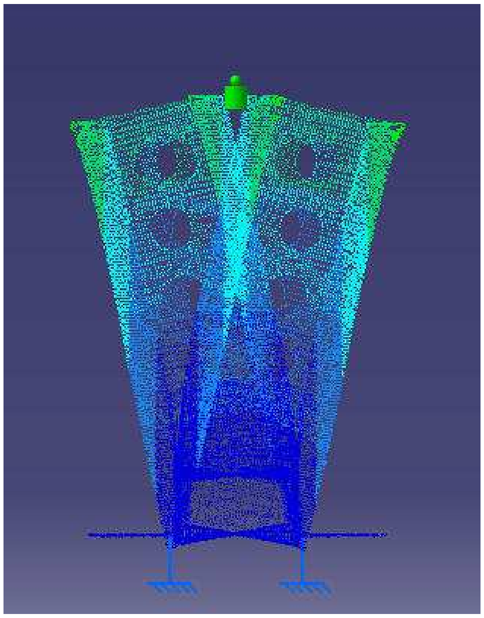

Figure 12. – First vibration mode

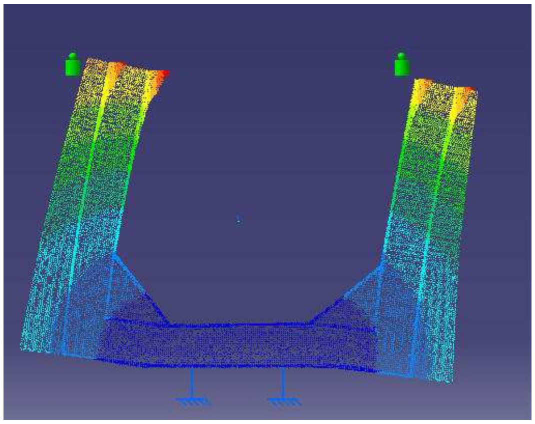

Figure 13. – second vibration modes

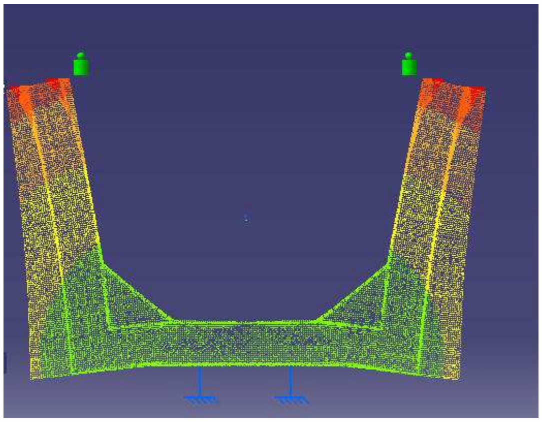

Figure 14. –third vibration modes

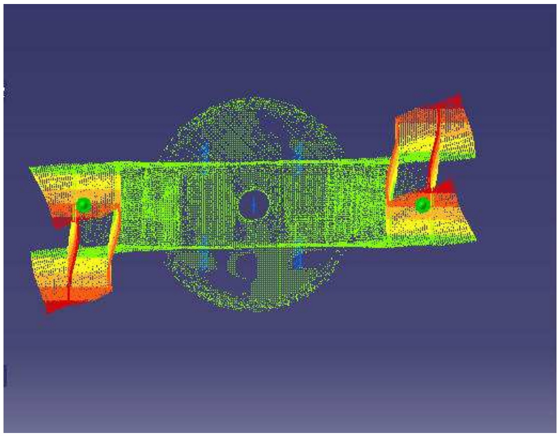

Figure 15. – Fourth vibration mode

It is possible to see that the first mode with principal component rotational, which could be coupled with the motion control system, is the fourth one, with a frequency of 30 Hz. This frequency is higher than the control system cut off frequency, thus the effect of structure vibration is decoupled from the control system.

The rendering of the final design of the mount is presented in Fig. 16.

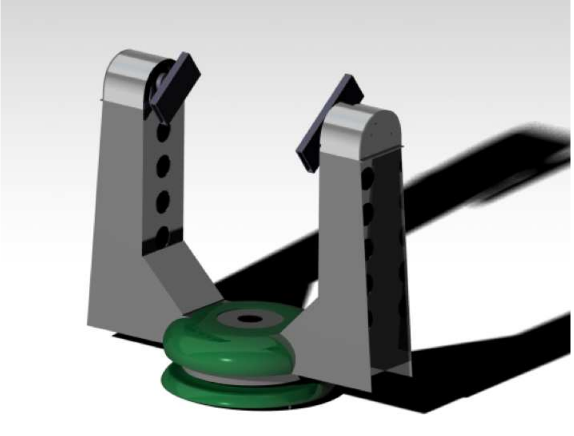

Figure 16. – Rendering of the mount for 1 meter class telescope

The same control system and the same main hardware and structural components can be exploited for a configuration of double fork mount. In this configuration the mount can host 2 telescope, 60 centimetres diameter (250 kg) each. The sketch of this second possible configuration is given in Fig. 17

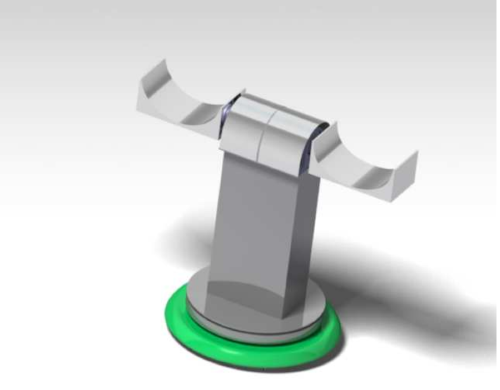

Figure 17. – Rendering of the mount in double fork configuration.

4 CONCLUSIONS

The design of a one meter class telescope mount, suitable for space debris tracking has been presented.

Both the control system and the structure have been simulated through numerical model and have been sized in order to satisfy requirements of the fast and accurate tracking of LEO and re-entering fast moving objects.

5 ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial contribution of FILAS (Finanziaria Laziale di Sviluppo), in the framework of the program “Sostegno agli Spin-off di Ricerca” (FILAS-SO-2011-1042), and the contributions of all the partners, including the University of Rome “La Sapienza”, the Consortium Sapienza Innovazione and Sator Astronomia Srl, which led to the establishment of the University spin-off Roboptics Srl, as a result of the research presented in this paper.

REFERENCES

1. D. Hall, J. Africano, D. Archambeault, B. Birge, D. Witte, P. Kervin, “AMOS Observations of NASA's IMAGE Satellite”, The 2006 AMOS Technical Conference Proceedings, 10-14 September 2006, Maui, HI, 2006.
2. M. Porfilio, F.Piergentili, F. Graziani. ‘First optical space debris detection campaign in Italy’, Advances In Space Research. vol. 34, pp. 921 – 926; doi: 10.1016/j.asr.2003.02.035
3. Schildknecht, T., R. Musci, W. Flury, J. Kuusela, J. de Leon Cruz, and L. de Fatima Dominguez Palmero, “Optical Observations of Space Debris in High-Altitude Orbits – Discovery of a new Population”, 2004 AMOS Technical Conference, September 13-17 2004, Maui, Hawaii, USA.
4. M. Porfilio, Piergentili F., F. Graziani.’ Two-site orbit determination: The 2003 GEO observation campaign from Collepardo and Mallorca’ Advances In Space Research. vol. 38, pp. 2084 – 2092, doi:10.1016/j.asr.2006.06.004,
5. M. Porfilio, F. Piergentili, F. Graziani, "The 2002 italian optical observations of the geosynchronous region", Spaceflight Mechanics 2003, Advances In The Astronautical Sciences, vol. 114, American Astronautical Society, San Diego, USA, 2003 AAS paper n. AAS 03-186, ISBN:0-87703-504-0.
6. F.Santoni, R. Ravaglia, F. Piergentili, “Analysis Of Close Approach In Geo Using Optical Measurements”, paper IAC-12,A6,5,22.p1,x14304, 63rd International Astronautical Congress, Naples, Italy, 1-5 October 2012..
7. F. Santoni, E. Cordelli, F.Piergentili, “Determination of Disposed-Upper-Stage Attitude Motion by Ground-Based Optical Observations”, Journal of Spacecraft and Rockets, (2013), doi:10.2514/1.A32372
8. C. Fruh and T. Schildknecht, “Combination of light

curve measurements and orbit determination for space debris identification", *62nd International Astronautical Congress*, Cape Town, South Africa, 3-7 October 2011.

9. R. Linares, M. K. Jah, J. L. Crassidis, F. A. Leve and T. Kelecy, "Astrometric and photometric data fusion for inactive space object feature estimation",, *62nd International Astronautical Congress*, Cape Town, South Africa, 3-7 October 2011.
10. M. Jah, R. A. Madler, "Satellite Characterization: Angles and Light Curve Data Fusion for Spacecraft State and Parameter Estimation", The 2007 AMOS Technical Conference Proceedings, 12-15 September 2007, Maui, HI, 2007.
11. C. Wetterer; M. Jah, "Attitude Determination from Light Curves", Journal of Guidance, Control, and Dynamics, Vol.32, NO.5, 2009, pp. 1648-1651., doi: 10.2514/1.44254
12. Hogg, D. W., Blanton, M., Lang, D., Mierle, K., & Roweis, S., 2008, Automated Astrometry, Astronomical Data Analysis Software and Systems XVII, R. W. Argyle, P. S. Bunclark, and J. R. Lewis, eds., ASP Conference Series 394, 27–34.
13. Lang, D., Hogg, D. W.; Mierle, K., Blanton, M., & Roweis, S., 2010, 17 Astrometry.net: Blind astrometric calibration of arbitrary 18 astronomical images, Astronomical Journal 139, 1782-1800.)
14. N. Zacharias, et al., "The Third US Naval Observatory CCD Astrograph Catalog (UCAC3)", The Astronomical Journal, Volume 139, Issue 6, pp. 2184-2199 (2010), doi: 10.1088/0004-6256/139/6/2184
15. Santoni, F., Piergentili,F., Ravaglia, R., "Nanosatellite Cluster Launch Collision Analysis", in print in Journal of Aerospace Engineering, (July 2013), doi: 10.1061/(ASCE)AS.1943-5525.0000175.
16. F. Santoni, F. Piergentili, F. Graziani, "Broglio Drag Balance for neutral thermosphere density measurement on UNICubeSAT", Advances in Space Research, vol. 45; March 2010, p. 651-660, ISSN: 0273-1177, doi: 10.1016/j.asr.2009.10.001.
17. F. Piergentili, F. Graziani, "SIRDARIA: A low-cost autonomous deorbiting system for microsatellites", 57th IAC, International Astronautical Congress 2006, V alencia, Spagna, 2-6 Ottobre 2006, IAC-06-B6.4.