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MACE Telescope : Servo Design Aspects

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Abstract : The design parameters of the servo system for the MACE imaging Cerenkov telescope, based on functional, performance, operational and safety requirements of the system are briefly discussed. The servo system is designed around electronically commutated motors using fully digital controllers, pc - compatible hardware and software and ethernet connectivity for remote monitoring and control.

1. Introduction

The MACE telescope is a 17 meter dia., 150 ton structure consisting of 240 number of mirror panels and 1.5 tons of focal plane instrumentation.The main servo system is required to steer the telescope in Azimuth (240) and Elevation (0 - 110) and support positioning of the telescope and tracking of celestial sources to 1 arcminute accuracy at 30 kmph wind speeds.The drive system must support quick repositioning of the telescope to any position within a minute. Other requirements for the servo system include stowing under heavy wind, hardware / software travel limits, protection of the camera against pointing towards sun and the moon, a local mode user interface and support for remote controlled operations etc.

This paper attempts to establish servo system design parameters, options and trade offs based on the functional, performance, operation and safety requirements of the project. Firstly, the various random and systematic error sources are identified with a view to apportioning of errors. A dynamic model is evolved and factors which affect structural resonance, bandwidth and response times are outlined. Towards establishing motor torque budget and sizing of motors and amplifiers, various torque loads are identified. The servo system is proposed to be designed around electronically commutated motors using fully digital controllers, pc-compatible hardware/software platform and VDU - based HMI and ethernet / TCP / IP connectivity for remote monitoring and control. In addition to the main servo system presented here, the MACE telescope will require active mirror alignment wherein each of the 240 mirror panels are driven by two stepper motors so as to dynamically correct for alignment errors due to gravity deflections. The alignment error is sensed by processing the image of a mirror - mounted laser pointer on the focal plane, alongwith three reference LED's. Due to the large numbers involved, the design of this control system must accommodate constraints of cost and size. The design should also promote minimum cable runs, low power and power - down modes and low maintenance requirements. These can be realised using state-of-art low power micro controllers and data networks.

2. Performance Specifications

Table I shows the salient performance figures for the MACE telescope servo system.

Table I

Parameter	Value
Coverage	Azimuth: $\pm 240^0$; Elevation : $0 - 110^0$
Slew Speed	180^0 per minute
Tracking Speed	30^0/minute for tracking upto maximum zenith angle of 24 arcmin
Tracking Acceleration	0.004^0 / sec for 24 arcmin zenith angle
Pointing Accuracy	1 arcmin RMS
Tracking Accuracy	1 arcmin RMS @ 30 kmph wind, 5 kmph gust
Angle Measurement Resolution	10 arc sec (17 bit)

3. System Description

The servo system of the MACE telescope shown in Fig. 1 is required to support Slew, Position and Track modes of operation. Typically slew mode is used for quick re-positioning of the telescope to a desired direction while switching between sources. In the position mode, precision resolvers are used as feedback sensors for accurate positioning at the designated angle. The telescope is held at the commanded position continuously correcting for wind induced disturbances. The track mode is the normal operational mode where in the demand angles are continuously updated from an external host computer.

The servo system uses AC induction motors during slewing. Two numbers of permanent magnet brushless servo motors with resolver based rotor position sensors for sinusoidal commutation, are used during fine positioning . The servo motors are powered by 4 quadrant amplifiers with regenerative braking. Amplifiers will employ IGBT/MOSFET based drives with fully digital control using state-of-the-art motor control DSPs. The two motors are in a counter-torque arrangement such that with a small torque bias, the effect of backlash is eliminated. The motors are coupled to the drive chain using clutches and gear reducers.

Motors are equipped with fail-safe brakes and tacho generators. The telescope can be stowed in a safe position under heavy wind conditions. Hardware position limits mounted near either end position cut-off the drive in case of over travel. This is in addition to software implemented pre-limits.

The controller is implemented on PC compatible hardware platform with VDU based HMI. The system provides TCP/IP connectivity to external computer for remote access and control. The software will be modelled and designed using modern object oriented modelling and design methods (e.g. OMT,UML).

4. Torque budgeting

The following table identifies various torque components adding up to the motor torque budget.

Wind torque	Largest % torque. Proportional to (wind speed)^2
Acceleration torque	(Inertia x Acceleration)
Viscous friction torque	B*w where B=2 $\xi \sqrt{JK}$; ξ = 0.03 to 0.07 W is the speed in rad/sec B is the viscous friction coefficient in Nm/Rad/sec J = Inertia and K = stiffness
Bias torque	5% to 10% of total torque.
Unbalance torque	Should be kept minimum by using balancing mass
Gear box inefficiency	>70%
Stiction + Coulomb friction	To be specified by the manufacturer.

Generally, for a large structure such as MACE, the wind-torque contributes up to 80% of the total torque requirement Since the motor inertia reflected at the load axis is proportional to the square of the total gear ratio, the motor inertia dominates the load inertia, in a system with large reduction ratio. This is desirable from servo point of view since the back-lash effect is lesser in this case.

5. Error budgeting

Early in the design it is important to identify all sources of error which limit the pointing and tracking accuracy of the system. This is followed by apportioning of error to each term. The various factors to be considered while apportioning errors are tabulated below :

Wind ___Steady -- -- gusty	Steady wind results in steady deflection. Depending on the location of the angle sensor, major part of this deflection will be outside the position servo loop and will be uncontrolled. Normally the stiffness of the mechanical members are designed so that the pointing error due to this is less that 10% of the allowed pointing error. Gusty wind causes random pointing error. Position loop band width must be adequate to attenuate gust effects.
Gravity deflection	This error is repeatable and correctable in principle.
Wheel + track errors (Wheel concentricity, track errors, foundation)	These are accounted by design.
Initial alignment, axis orthogonality.	Accounted during design and correctable in principle.
Angle sensor accuracy	The servo pointing accuracy is limited by the accuracy of the angle sensor. A 17 bit encoder can provide measurement resolution of 10 arc seconds.
Acceleration error	This is due to finite Ka of Type 2 servo. The demand acceleration is highest for AZ near 90 deg EL, thus causing key-hole effect typical of this mount. The contribution is insignificant for a telescope required to track celestial objects.
Bearing non-repeatability	Causes random error.
Position update rate	Typically the servo computer will perform linear interpolation of demand angles send by external computer. The error due to this approximation assuming a parabolic input is governed by the equation : E = A/8D^2 where E = error in degrees, A is the acceleration in degrees / sec^2 and D is the update rate in Hz.
Latency, synchronisation	While tracking as per demand angles sent by an external computer

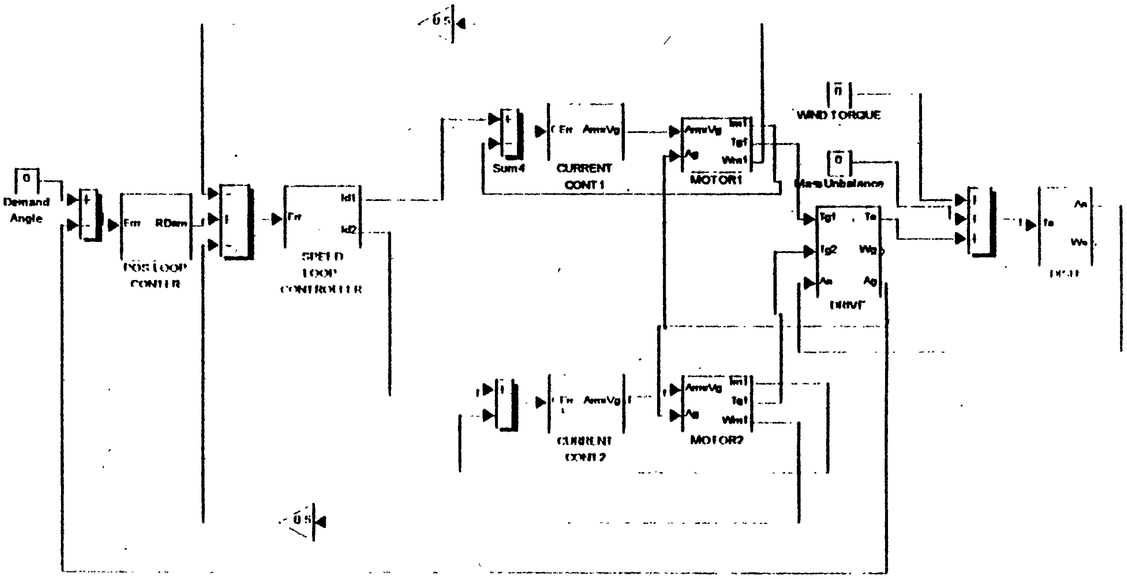

Fig. 1

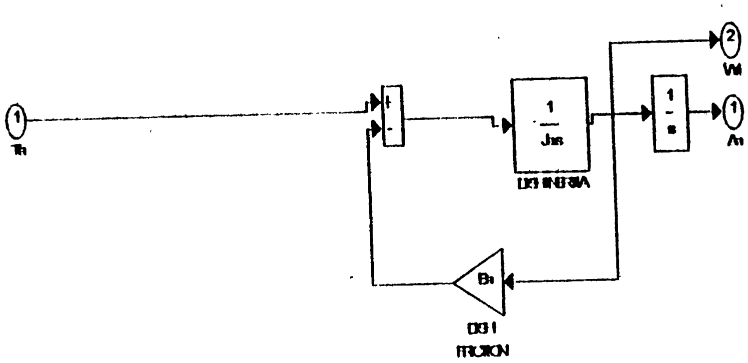

Fig 2(a)

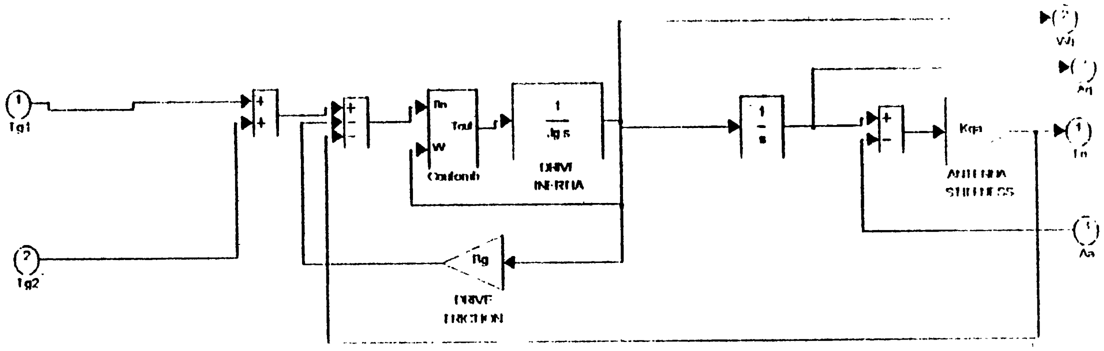

Fig. 2(b)

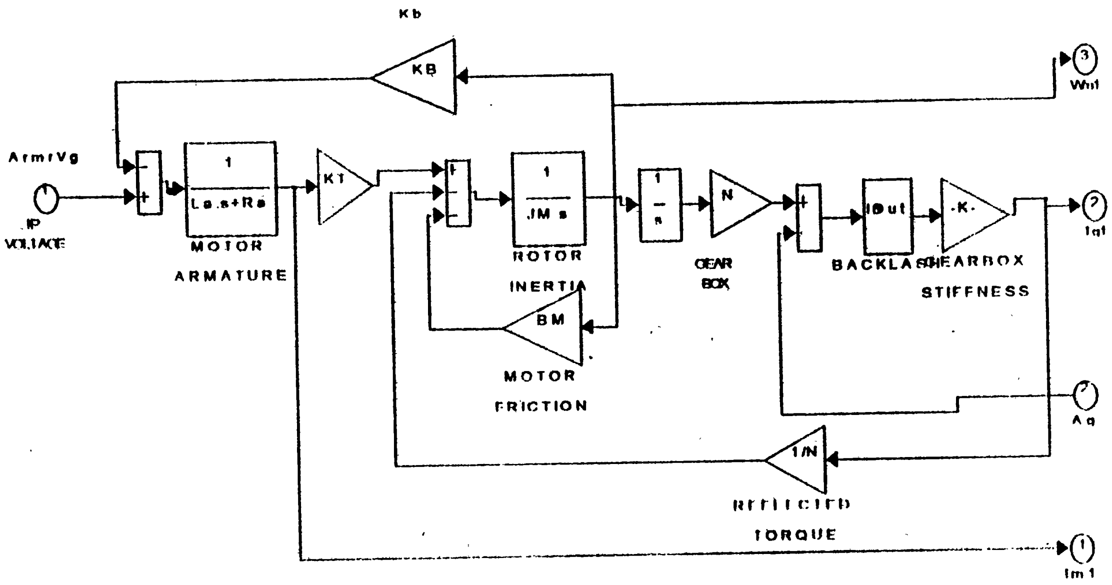
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Fig 2(c)

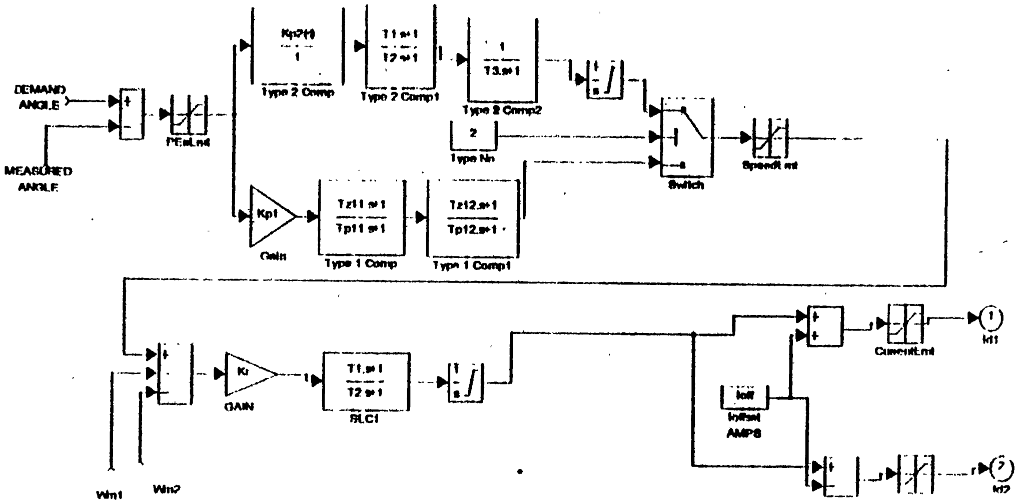
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Fig.3

	the transport lag may cause significant error unless accounted for during design. This can be achieved by synchronising the clocks and locally caching the command angles.
Limit cycles	Limit cycle oscillations may be caused by various system non-linearity such as residual back-lash, quantization in ADC and DACs, stiction and coulomb friction in mechanical elements etc.

These can be classified in to random and systematic error sources and total peak error can be computed as below.

$$\text{TOTAL ERROR} = \Sigma\ (\text{Sytematic error}_i) + 3\ \sqrt{(\ \Sigma\ (\text{RMS RANDOM ERR}_i)^2)}$$

6. Modelling and simulation

It is planned to develop a detailed dynamic model of the MACE telescope with the control system and carry-out simulation experiments which will help us to obtain apriori estimates on accuracy and dynamic performance. The actual values of various mechanical parameters will only be available at the end of the structure design. A typical dynamic model applicable to large telescope is based on a 3 mass 2 spring model of the mechanical system consisting of the dish, gearbox and motor whose models are depicted in Fig 2a, 2b and 2c respectively. The model incorporates various non-linearity such as back-lash, stiction, friction, saturation, transport lags and quantizations. With the model frequency response, dynamic performance, effects of mass unbalance, wind disturbance can be studied and controllers can be designed. Effects of digital (time discrete) implementation of compensators can be also quantified.

7. Control Loops

The controller configuration follows the classical three loop cascade, viz., current loop , speed loop and position loop as depicted in Fig 3. The innermost current loop (torque loop) is a high bandwidth PI controller typically implemented in hardware and integrated with the motor power amplifier. However , current advances in motor controller DSP make it possible to implement 1 kHz current loops and BLAC motor control functions in DSP firmware. The speed loop encloses the current loop and provides improved system damping using motor mounted tacho for feed back.There is common speed loop for both motors of each axis. High DC gain is required to minimise steady state speed error. Closed loop bandwidth should be at least 5 times higher than the desired position loop bandwidth to guarantee spectral separation with enclosing position loop.The speed loop compensator is a lag/lead filter and may be implemented in software. Typical functions include speed and acceleration limiting, deceleration control during braking etc.

The position loop design is most important in realising the required servo performance. The achievable bandwidth is limited to < 1/5 of Locked Rotor Frequency (LRF). The LRF is essentially dictated by the structure and can be estimated by knowing structure inertia and stiffness. High position loop bandwidth is desirable to reduce wind errors as well as to meet required rise times and settling times. It is typically implemented as Type II servo - lag / lead compensator. A type II servo results in zero position error for velocity inputs and a constant position error for accelerating inputs. The acceleration lag = $\alpha / K_a \sim \alpha / W_n{}^2$ where α is the acceleration, K_a is the acceleration constant and W_n is the bandwidth. Position loop compensator is realised in the software.

8. Conclusions

The design and development of servo system for a large telescope is being carried out indigenously. While using state-of-the-art components and techniques, the concerns of economy, obsolescence, maintainability and availability are kept in mind. By carrying out extensive simulation studies, the development risks can be minimised and the design can be optimised.