Preliminary considerations for CFGT control system

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ABSTRACT

The Chinese ever-ambitious project of 30 meter-class telescope, Chinese Future Giant Telescope (CFGT), has brought about an extraordinary challenge for the control system's robustness. Various severe factors that we have never experienced before, will impact on our considerations for the control system. With the practice in our ongoing LAMOST project plus an investigation and a reasonable prediction the paper tries to deal with, at very preliminary stage, the control system configuration in general and a number of extreme difficulties in particular, such as the drive system and analysis of wind torque disturbance rejection, etc.

Keywords: giant telescope，control system, disturbance rejection, LAMOST, CFGT

1. INTRODUCTION

Currently the LAMOST team is working intensively on the 4-m class telescope; and the telescope site installation is due to begin soon. Still the team elite with far sight has had eyes for even large telescopes of next generation, which led to CFGT of 30-m optical telescope concept came into being a couple of years ago. In optics CFGT conception features a number of novel visions. However the requirements for control system are far from completed and conclusive. Yet we know that as astronomical telescopes concerned the project is largest ever put forward in China, which means enormous painstaking, long time endeavour but a final great reward. The detailed design for control system is out of the question at this stage; only the preliminary consideration is included in this paper. This paper has resulted from the experience accumulated throughout the R&D of LAMOST, as well as the investigation of current circulating literatures on giant ground optical telescopes.

2. ROAD MAP OF CONTROL SYSTEM REALIZATION

CFGT will be the most challenge and also fascinating project for Chinese astronomical community. Figure 1 shows, as we vision, the road map of progressively realizing the accommodable control system.

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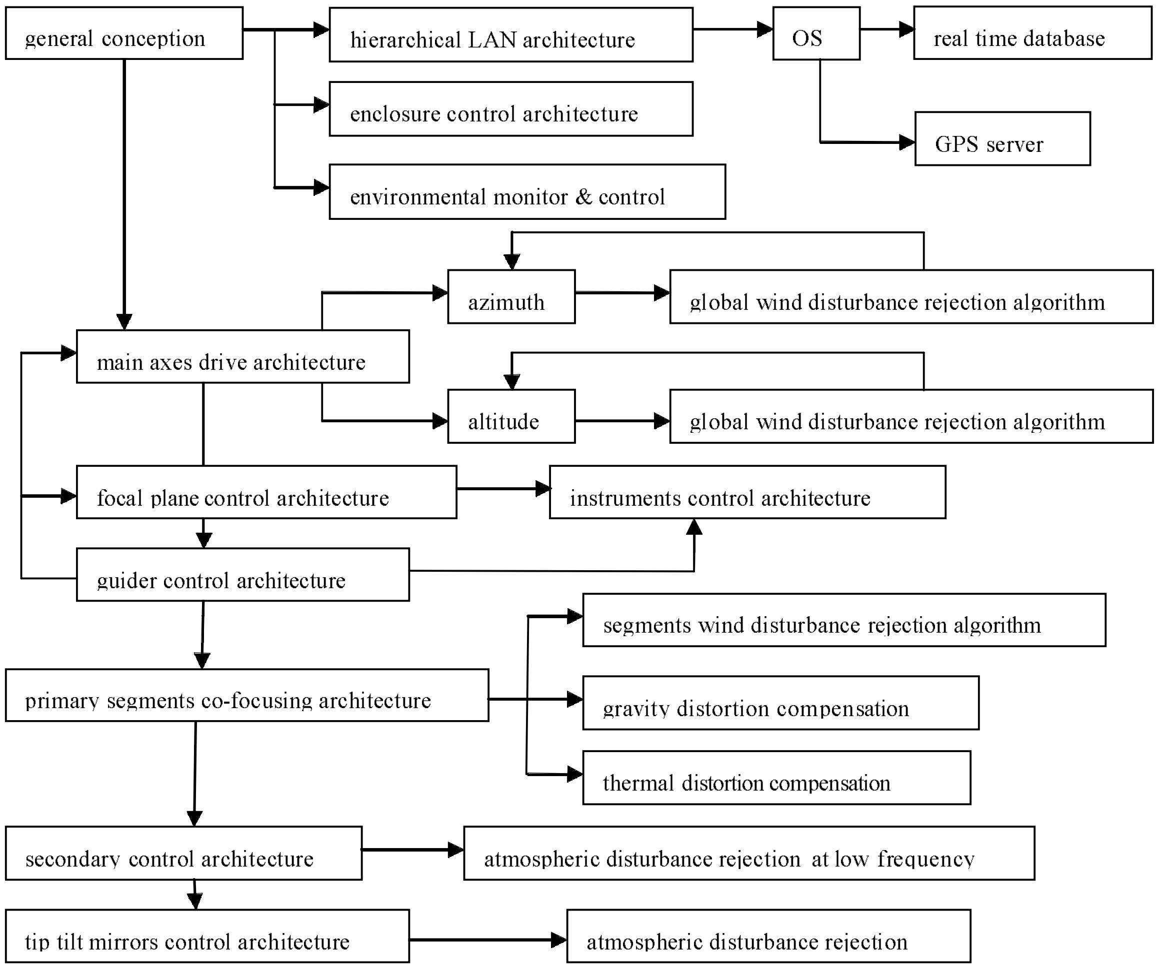

Figure 1: Road map of control system realization

3. CONTROL HIGHLIGHTS SEEN FROM TOP LEVEL

Compared with the technology in the areas of optics and mechanism, control technique is probably most active factor in terms of telescope automation as well as pushing its performance to the extremity. The quarter of last century and the new millennium have seen a great advance in the technology for astronomical telescope control. Some of striking novel techniques in this regard are PC based tiered distributed network, state of the art communication, large number of data storage and process architecture, real time database, embedded controller, thin mirror active force correction, segmented mirror co-focusing, interferometer array technique, large moment of inertia drive with high precision at low velocity, friction or direct drive, high accurate encoder measurement, various kinds of adaptive control algorithm, large size CCD, modern monitoring devices, infrared photography, large scale integrated circuits and nanometer measurement and control. Many techniques of those mentioned above are certainly incorporated in our preliminary consideration of CFGT. Figure 2 shows a possible control network for CFGT.

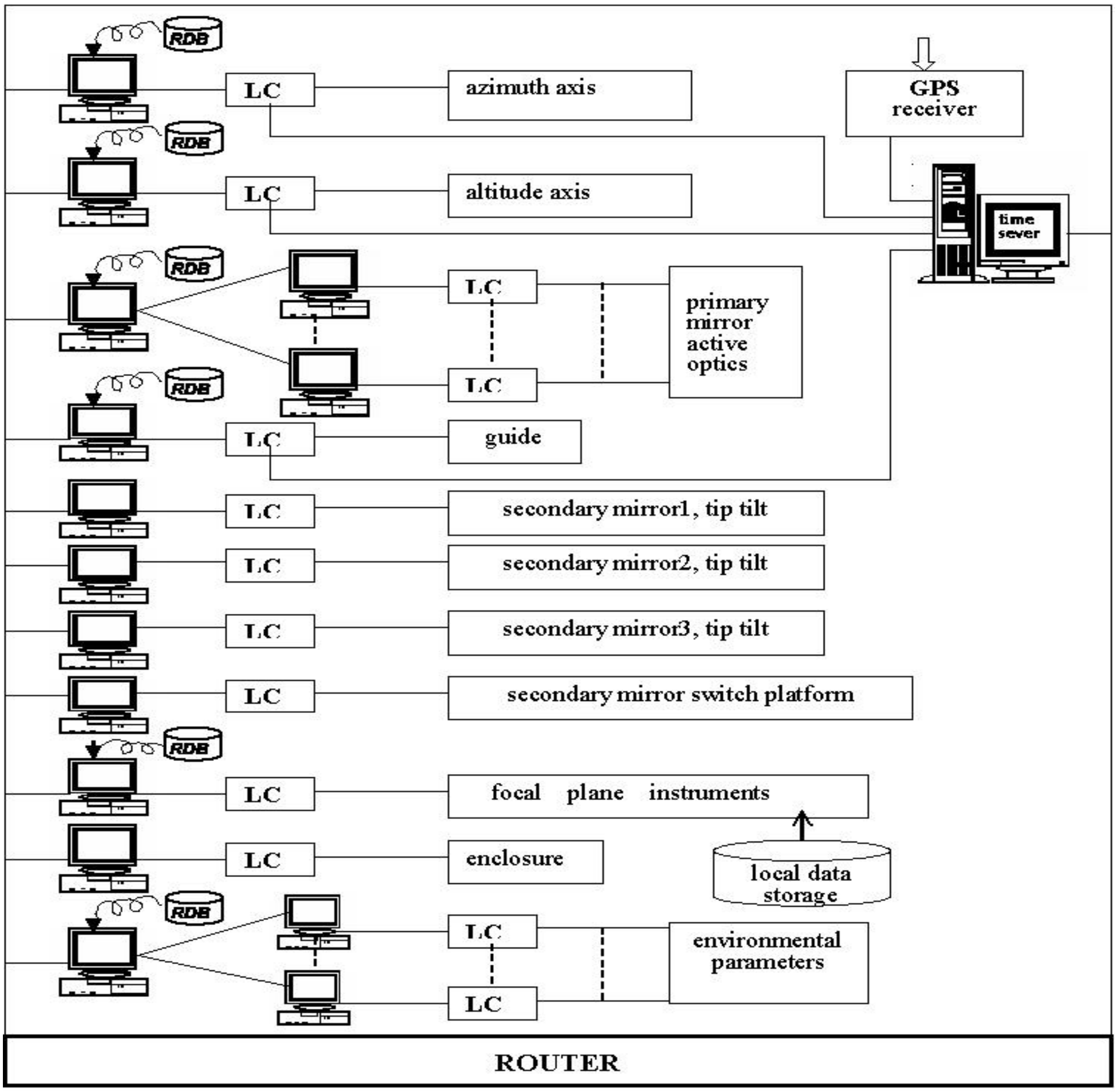

Figure2: CFGT control network

3.1 Hierarchical distributed network

Hierarchical distributed network is easy to expand for more PC as well as varieties of new networking devices to hook up. A few years ago some computer experts predicted that PC fashion would gradually fade and the era of post PS would come. Yet this never happens and, as we see, will not happen even for the epoch of giant astronomical ground telescopes. The

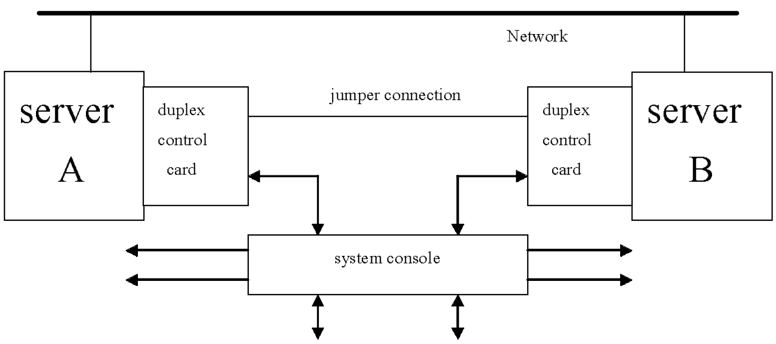

Figure3: Fault tolerance scheme

visible evolution of PC and its associated devices witness that they have become smarter, faster, smaller and overall more sophisticated. The implication of this trend is that the network control architecture for CFGT with distributed function will basically inherit current distributed tiered control architecture like in the control framework of LAMOST, employing a group of PCs and LCs (Local Controllers). The LC is built on embedded QNX or Linux.

On each node we proposed an on line dual backup or multi-server redundancy, which is not shown in figure 1 for fear of appearing too much crowded. A little bit more detailed schematic for the fault tolerance scheme is shown in figure 3 with functions of dual-processor status monitor, automatic or manual switch and the data communication between the two.

3.2 Real time database architecture

Along with the augment of telescope aperture from sub-meter to several tens of meters inevitably it calls for more sophisticated and comprehensive control system. We have noted that contemporary telescopes have put forward stringent requirements for on line diagnosis and on line data process; and it is predictable that it will be more so for CFGT. A variety of information flow such as command, status, warning and observation data etc. goes on in the system all the time with each time tick. Systematic and harmonious way of dealing with all these pieces of information requires, among other things, a real time database, which is only available by means of one of modern IT eminent achievements. The real time database features real time as its name implies. Our LAMOST experience could shed some light on its application for CFGT. Figure 4 shows the real time database built on QNX real time OS. The purpose of the database is multi-fold, one of which could be for on line diagnosis. For example in the tracking process of LAMOST the main axes' encoder readings would be recorded in the real time database with each servo tracking tick. A diagnosis routine would check the encoders' readings in real time against the object tracking data to decide if it is necessary to modify the PID algorithm in the servo at the time of tracking. Having said that above we have no in the least any intention to deny the necessity for non-real time database that is still most important tool for off line process of large volume of image data even for CFGT. However if modern technique provides a way to do it in real time or to do it more and more in real time, then why not give it a try for the sake of productivity. Figure 4 shows the architecture of LAMOST real time database. For CFGT we proposed that the architecture shown in figure 4 could be taken as a unit, and there will be several real time databases so that any data could be stored in a corresponding local database to reduce data traffic and gain more real time convenience.

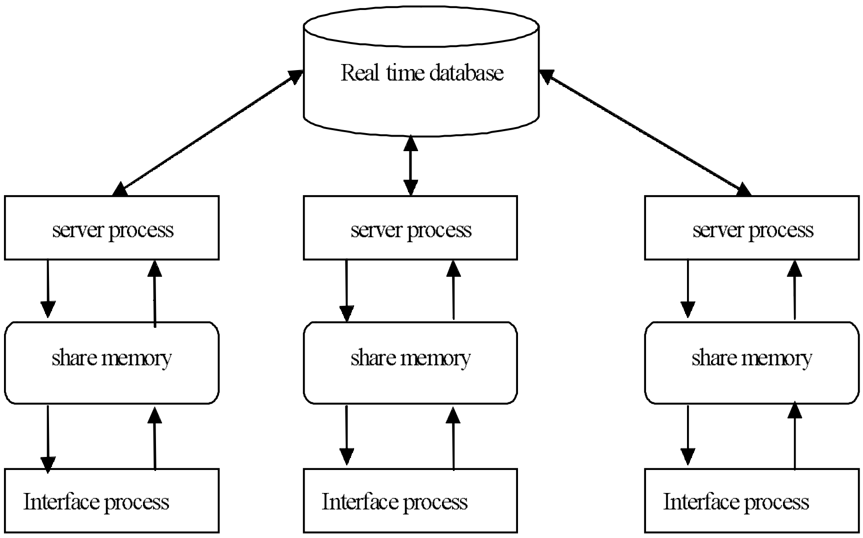

Figure 4: Real time database architecture

3.3 Some other software platform consideration

Common **O**bject **R**equest **B**roker **A**rchitecture **(CORBA)** is Object Management Group's (OMG) open, vendor-independent architecture and infrastructure that computer applications use to work together over networks. Using the standard protocol Internet Inter-ORB Protocol (IIOP), a CORBA-based program from any vendor, on almost any computer, operating system, programming language, and network, can interoperate with a CORBA-based program from the same or another vendor, on almost any other computer, operating system, programming language, and network. We have seen the CORBA technique has been successfully applied in a number of telescopes control software architecture, and it is very much at our heart for CFGT's application.

3.4 GPS-based timing system

The control system of CFGT telescope is highly distributed real time system, and the time base is crucial. For the past a few years LAMOST control team has developed a GPS based timing system, which can provide a time tick across the QNX4.25 OS based network with precision of 1 millisecond. We supposed the same philosophy can be applied in CFGT, but referring to the following table the precision of the tick needs to be improved to 0.1millisecond, which, we think, is not very much an issue with modern timing technology at hand.

Mount tracking:	The position servo rate could reach 200 Hz.
Focal plane adjustment:	The servo rate for image rotation compensation comes around 100 Hz.
Primary mirror co-focusing active optics:	This normally takes place before observation.
Primary segments tip tilting wind disturbing rejection:	10 Hz.
Possible secondary mirrors tip tilting for atmosphere disturbing rejection:	100Hz-1KHz.
CCD star guide:	1Hz.
Dome control:	There is no real time requirement.
Environment monitor & control:	Normally sense once every several minutes and respond accordingly.
Spectrographs:	There are dedicated clock drives for CCDs' readout.
Fiber positioning system:	The positioning normally is implemented before the observation.

3.5 Segmented primary co-focusing concept

CFGT's primary consists of 1095 segments, which requires for co-focusing to improve the image quality. The principle has been used in our current project of LAMOST. On the back of each segment of Schmidt plate are installed a group of 3 displacement actuators to provide tip, tilt and piston motion of the segment. Together with Shack-Hartmann apparatus it is achievable to stack all segments focus alignment within the specification. On each edge where two adjacent segments meet assembled are two pairs of edges sensors to monitor the relative movements of the two edges. The displacement actuators and edge sensors are so networked in LAN based on a field bus architecture working harmoniously to maintain the image stacking. It is reasonable predictable that this kind of stacking maintainability could keep several tens of minutes to several hours depending on different positions of the mirror as well as the thermal conditions.

Varieties of displacement actuators and edge sensors using different techniques are within the scope of our investigation for CFGT's application. For the past a few years we have seen some of these devices have been successfully applied for contemporary telescopes.

4. DRIVE CONSIDERATION

For large contemporary alt-azimuth telescopes the general approach of main axes' drive is friction drive or direct drive. The latter is becoming more and more promising as the size of the telescopes are getting larger and larger. For CFGT we do not foresee any other options than the above two at this point. We proposed to employ a direct drive for CFGT's altitude axis, and either direct drive or friction drive for its azimuth axis.

Direct drive for large telescopes applications were reported for VLT, Subaru and GTC telescopes. We have to make a through investigation to learn. Direct drive systems, as their name imply, employ motors mounted directly on the telescope axes, which makes the structure simple, requires little maintenance, has intrinsic insensitivity to mechanical misalignment and zero stick coefficient. Particularly different from friction drive direct drive distributes the thrust force along the structure, thus minimizing localized deformation and maximizing structural stiffness. The limiting factor depends on the structural stiffness of the telescope and the interface rigidity between the motor and structure. The disadvantages of direct drive are probably high cost, slight torque ripple, heat generation and the presence of strong magnetic fields. These issues are necessary to properly cope with. Last but not least the amplifier must be carefully designed.

For such direct drive motors mentioned above custom fabrication is required. The motors can be viewed as lightly curved linear motors. They are segmented motors with a "sandwich-like" design of the windings around the rare-earth permanent magnets. The magnetic race (rotor), generally manufactured in small segments (around 1 m in length), is bolted to the main bearing journal, and a number of small motors (winding pads, stators) are installed facing the magnetic race at strategically stiff. The drive tachometers could use one winding segment per motor.

Friction drives, on the other hand, are more mature technique and widely used in main axes' drive for modern astronomical telescopes, which are usually cheaper than direct drives. Inherently friction drives are smoother and more accurate than gear drives. The current ongoing project of LAMOST employs a friction drive for both azimuth and altitude axes. Figure 5 shows the schematic for mechanical part of azimuth drive for LAMOST. Co-axially assemble on the motor axis is the drive wheel, which is pushed against a cylindrical journal of azimuth axis by load machine. Drive wheels are fine devices but rely on high-quality surface. The material and magnitude of the push force must be decided carefully. The velocity reduction ratio between motors and journals is another issue, which in LAMOST's case is around 50. Based on our experience the range of reduction ratio from 20 to 150 is proper. If the reduction ratio is too small it makes difficulty for the axis's load inertia transferred to motors' axes to scale down match

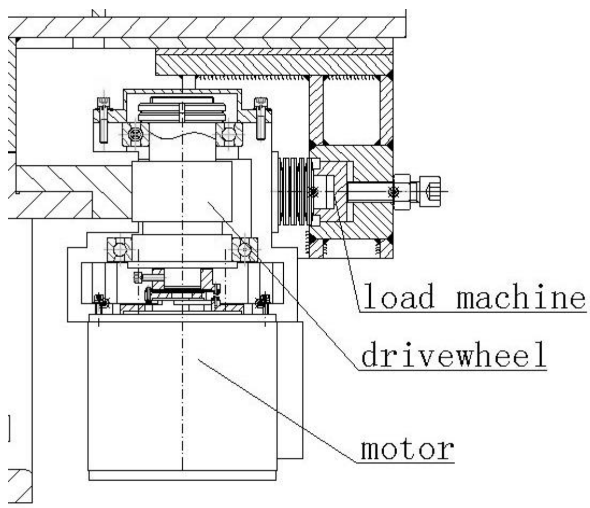

Figure 5: Mechanical part of LAMOST azimuth

the motors' inertia; and it requires large torque of the motors, On the other hand, it increases the disturbance sensitivity if the reduction ratio is too large. Further investigation is needed for CFGT; however the LAMOST's case could be as a start point to study.

5. ENCODER SYSTEM FOR MAIN AXES

The encoder system for main axes is one of important issues for successful drive servo of CFGT. Based on our lesson and experience learned from tracking test of LAMOST model mount the conclusion is that it is better to install the encoders co-axially on the main axes to avoid problem of non-monotonic readings due to the mechanical slip usually present in a friction coupled encoder. The reason is self-evident because of fewer intermediate joints for the direct couple, hence better measuring accuracy. The precondition for such a configuration is that the encoder itself must have adequate resolution and measuring accuracy. Modern tape encoder technology with high resolution and sophisticated multi-reading-unit system plus advanced data processing algorithm will come to play in these applications. We predict that our LAMOST project in this aspect will certainly provide some useful experience for CFGT.

In LAMOST the rotation angle of either axis is measured by a tape encoder, which is engaged in coaxial way on the end of each axis. The two encoder's brand is ERA 780C from HEIDENHAIN with 1146.1mm in diameter and 90000 lines in one full circle. Please note that the letter of "C" in the brand denotes the tape has distance-coded references. According to HEIDENHAIN the accuracy of 0.08" RMS is reachable if the star-measurement correction is adopted with 8 reading heads. Another product of HEIDENHAIN, an IK320V VME-Bus counter card with interpolation 4096-fold can provide interface for two reading heads, and 8 such cards are needed in total for azimuth and altitude axes. For CFGT we need more accurate tape encoder. However we foresee that by the years to come for CFGT in reality the supplier could make considerable progress with this type of encoder and especially in the way of mounting the scale tape on a mount ring without strain to the scale, i.e. without introducing errors into the readings.

6. TORQUE DISTURBANCE COMPENSATION CONCEPT

As the size from medium to giant the result is massive telescopes with low resonant frequencies, which again makes the telescopes susceptible to wind-buffeting among other torque disturbances. A number of literatures have addressed the problem with many formulae plus wind tunnel testing. Many data pertain to CFGT's case are not available yet at this stage. Here we describe the torque disturbance compensation concept pertain to CFGT. Our basic idea of approach to protect the telescope from wind blowing is cascaded layers of protection. To the bottom line the wind will causes a number of effects. Firstly the wind pushing against the main axes introduces the mount vibration, and wind pushing against on the segmented primary mirror as a whole further deteriorates the mount vibration. Secondly wind effect on each individual segment of primary introduces individual segment vibration. Thirdly wind effect on components such as the secondary mirrors or any other elements under the wind force also causes image blur. The frequency characteristics of each kind of wind disturbance must be carefully studied associated with the wind characteristics on the future CFGT's site. And the control system should be configured as cascaded servo loops with different bandwidths and different physical elements to deal with each effect. General approaches of vibration control are tuning the telescope structure so that resonances fall outside of the excitation spectrum, compensation of the disturbance at the source by moving a mass in the opposite direction to cancel the effect and damping of the motion created by the disturbance. In this paper we illustrate the torque disturbance rejection on the mount. The general effects of wind given by formulae are shown in the following table.

Wind static effects	$F = C_D \rho \frac{V^2}{2} A$	C_D : Drag coefficient ρ : Density of air V : Velocity of air A : Cross-sectional area normal to wind direction
Dynamic wind effects: Vortex shedding	$f = \frac{SV}{L} = \frac{0.2V}{L}$	V : Wind speed S : Dimensionless quantity, typically 0.2 L : Characteristic transverse dimension
Effects of wind vertex shedding on telescope structure	$F = C_L \frac{\rho V^2}{2} A \sin(2\pi f t)$	F: Transversal force C_L : Lift coefficient A : Cross-sectional area normal to wind direction ρ : Density of air V : Wind speed f : Vertex shedding frequency

If the relative data for the telescope's structure plus the site wind information are available we will be able to estimate the wind effects for the servo compensation. In principle the wind disturbance on the mount as a whole can be viewed as a variable disturbance torque applied on the mount drive motors' axes. Figure 6 shows a generic disturbance block diagram. Suppose input $r(t) = 0$, use PID control $D(s) = K_P + K_I / s + K_D s$, let $G(s) = (1/Js^2)$ and $\beta = 1$. J is the moment of inertia of a torque motor, and $y(t)$ becomes the output rotation angle of the motor. Computation of transfer function in figure 7 gives $T_w(s) = s/(K_P s + K_I + K_D s^2 + Js^3)$. For step disturbance $W(s) = 1/s$ we

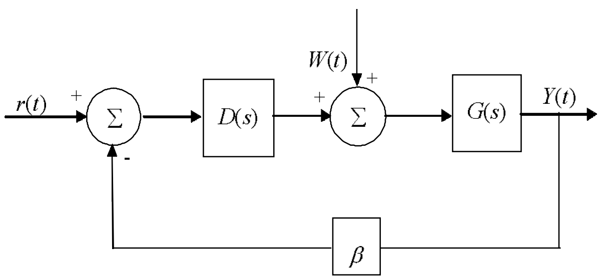

Figure 6: Generic disturbance block diagram

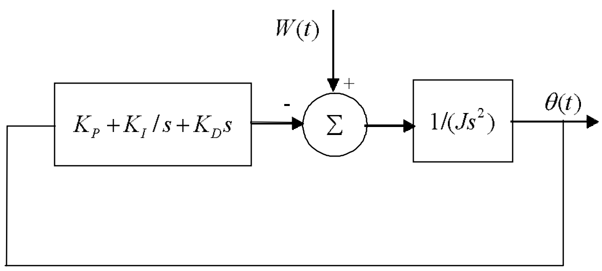

Figure 7: Motor PID control with input zero

have $\theta(s) = T_W(s).W(s)$. The steady state of $\theta(t) = \lim_{t\to\infty}\theta(t) = \lim_{s\to 0} s.\theta(s) = \lim_{s\to 0} s.T_W(s)W(s) = \lim_{s\to 0} s/(K_P s + K_I + K_D s^2 + Js^3) = 0$. The result shows classical PID control can effectively reject step disturbance in this application. However for ramp disturbance, in which case the $W(s) = 1/s^2$, the steady state becomes $\theta(t) = 1/K_I$. This expression clearly shows the PID control can not reject the ramp disturbance in this case. Generally speaking whether the PID control can reject the disturbance depends on the characteristics of the disturbance and the system type. Again the result assured us of the importance to make through investigation of the wind characteristics around the year to effectively dealing with the disturbance.

The above derivation utilizes the classical PID and transfer functions based on analogue physical parameters. As the computer and modern control technology evolving many advanced topics involved in the design and analysis of control systems are coming into being. In particular, the subjects of discrete-time estimation (both state-space and information space), optimal stochastic control and robust control, etc. are more and more utilized in high-tech areas. And the control system for astronomical telescopes is no exception. Here we briefly introduce the conception of online estimation and compensation of torque disturbance. Figure 8 shows a transfer-function block diagram for a torque motor drive. The idea is that in order to keep the motor rotation with high precision in the presence of unknown torque disturbance that might be caused by wind gusts it is important to estimate the disturbance magnitude online fast adequately (enough bandwidth) so as to change the input voltage accordingly and compensate the disturbance torque.

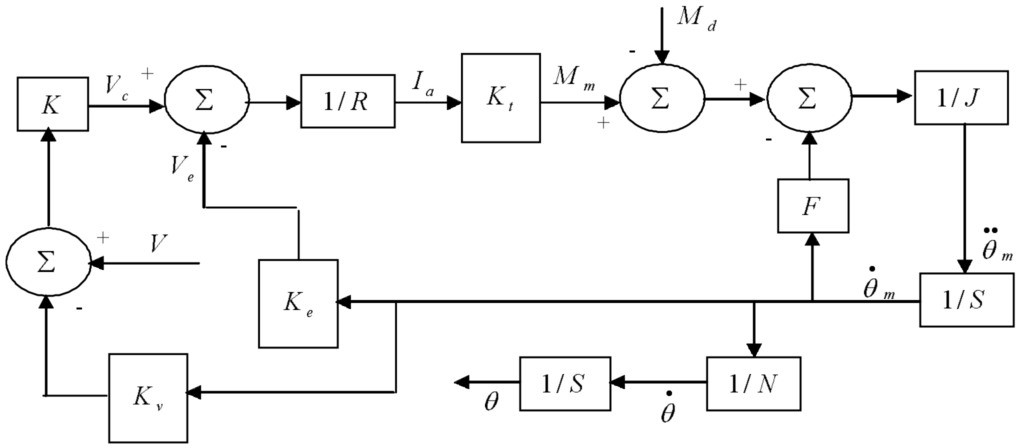

Figure 8: Motor drive block diagram

In figure 8 V is input voltage, K is voltage amplification, V_c is control voltage, R is motor armature resistance, I_a is motor armature current, K_t is motor torque constant, M_m is control torque, M_d is torque disturbance, J is motor moment of inertia, $\ddot{\theta}_m$ is motor angle acceleration, S is Laplace operator, $\dot{\theta}_m$ is motor angle velocity, F is hysteresis coefficient, N is velocity reduction ratio, $\dot{\theta}$ is angle velocity of load axis, θ is angle of load axis, K_e is reverse emf constant, V_e is reverse emf, K_v is tachometer transfer coefficient.

We further have

$$\begin{bmatrix} \ddot{\theta}_m(t) \\ \dot{M}_d(t) \end{bmatrix} = \begin{bmatrix} -a & -1/J \\ 0 & 0 \end{bmatrix} . \begin{bmatrix} \dot{\theta}_m(t) \\ M_d(t) \end{bmatrix} + \begin{bmatrix} K_t K/(RJ) \\ 0 \end{bmatrix} . V(t) \tag{1}$$

$$V_c(t) - KV(t) = \begin{bmatrix} -KK_v & 0 \end{bmatrix} . \begin{bmatrix} \dot{\theta}_m(t) \\ M_d(t) \end{bmatrix} \tag{2}$$

$$a = [K_t(KK_v + K_e) + FR]/(RJ) \tag{3}$$

The dynamics in (1) and (2) can further be expressed by matrices

$$\dot{X}(t) = AX(t) + BU(t) \tag{4}$$

$$Y(t) = CX(t) \tag{5}$$

In expression (4) $X(t) = \begin{bmatrix} \dot{\theta}_m(t) \\ M_d(t) \end{bmatrix}$ is state vector and $U(t) = V(t)$ is control vector and $A = \begin{bmatrix} -a & -1/J \\ 0 & 0 \end{bmatrix}$ is state-transition matrix. In expression (5) $Y(t) = V_c(t) - KV(t)$ is output vector and $C = \begin{bmatrix} -KK_v & 0 \end{bmatrix}$ is output matrix. Once the value of M_d is determined let $V(t) = [R/KK_t]M_d(t)$. From figure 8 we have $M_m = [KK_t/R]V(t) = [KK_t/R][R/KK_t]M_d = M_d$. This equation means that at least theoretically it is possible to compensate the torque disturbance. Considering $V(t)$ is sampled time-discretely the above equations should be resolved by means Z transition and iteration in computer.

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