VISTA M1 Support System

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1. ABSTRACT

The VISTA Telescope[1] is obtaining superb survey images. The M1 support system is essential to image quality and uses astatic pneumatic supports to balance the M1 against the varying effects of gravity and wind, with four axes being actively controlled via software and CANbus. The system also applies externally determined active optics force patterns. The mechanical, electronic, software and control design and as-built operation of the system are described, with the practical design points discussed.

Keywords: M1 Support, Pneumatic, CANbus.

2. VISTA TELESCOPE

VISTA, the Visible and Infrared Survey Telescope for Astronomy, is a 4.1-metre wide-field survey telescope installed at the ESO Paranal Observatory in Chile. It has a 1.65-degree field, 67-Mpixel near-infrared camera, for performing extensive surveys of the southern skies. The M1 support system is an essential part of its active optics capability.

3. M1 SUPPORT SYSTEM OVERVIEW

The M1 support system has four tasks :

- Supporting the axial weight of the M1[2] such that all actuators and hard supports carry equal forces.
- Overlaying onto these nominally equal axial forces a set of active forces, to produce the required wavefront corrections to obtain overall image quality in conjunction with the M2 Unit.
- Balancing the lateral weight of the M1 so that the lateral definer forces are zero.
- Balancing of the M1 around its x- and y-axes to compensate for out-of-balance and wind forces.

In this document, with the telescope horizon pointing, the M1 z-axis coincides with the optical axis so is horizontal and pointing forwards, the x-axis is also horizontal and at right angles to z, pointing to the right as seen from behind the M1, and the y-axis is pointing downwards forming an orthogonal set that is fixed to M1. The 'axial' support elements are aligned with the z-axis, and the 'lateral' support elements are aligned with the y-axis.

At horizon-pointing, the M1 weight is almost completely supported by lateral forces, and at zenith it is mostly supported by the axial forces. The gathering of force data and distribution of force commands is enabled by CANbus networks.

4. MECHANICAL DESIGN

The VISTA M1 support system consists of 81 axial supports with 3 axial definers arranged in 4 concentric rings. The position and density of the supports was optimized based on the available space with the 4m diameter envelope and the residual surface figure after application of the active optics system. The lateral support system consists of 24 lateral supports arranged perpendicular to the x axis and three lateral definers that are positioned tangentially to the M1 circumference and spaced at 120 degree intervals.
As the support system is pneumatic a passive restraint system was also required for when the system is offline or there was an interruption in the air supply. The passive restraint system consisted of a set 12 axial, 6 lateral and a maintenance restraint contacting in a continuous ring on the top surface outside the optical diameter. This passive system was positioned approximately 1mm beyond the actively supported and aligned M1 position. It was designed such that under the extreme seismic levels that can be experienced in Northern Chile the M1 substrate stress levels were within safe margins. The layout and actuator / definer performance requirements were specified by the VISTA project as the interface between contractors was at the support system to Mirror interface.
In the figure below the basic arrangement of the M1 support system is shown.

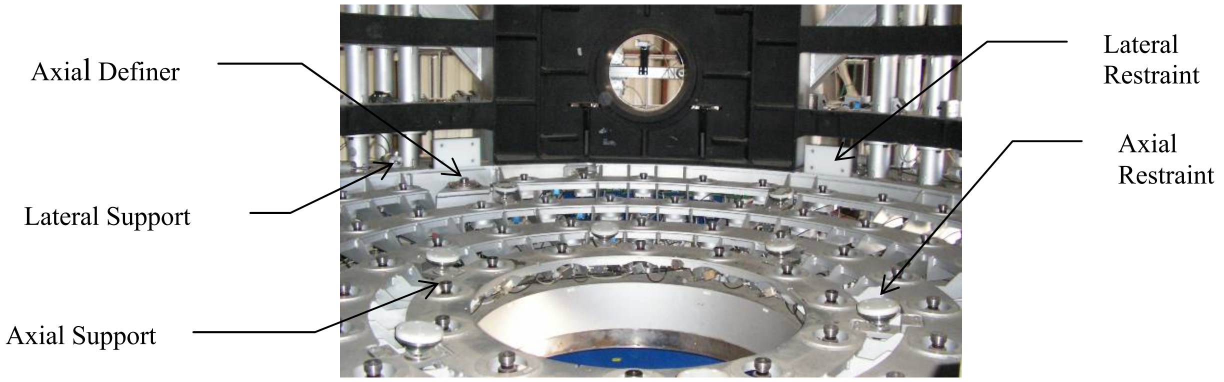

Figure 1. VISTA M1 Support System

4.1 Axial support

The axial supports are based around use of a Marsh Bellofram diaphragm to minimize stick slip effects in control. The actuators are astatic with localized force control based on feedback from a high precision load cell at the base of the assembly. The actuators were designed with a stroke range in excess of 4mm to allow for adjustment of the M1 position but also to account for tolerances in the machining of the mounting surfaces in the cell. The layout of the actuator is shown in Figure 2. The actuator contact assembly includes an axial thrust bearing and centering flexure to allow for lateral movement of M1 without inducing moment due to contact friction. The Load cell range was 0 to 1000N with adjustable zero point and span.

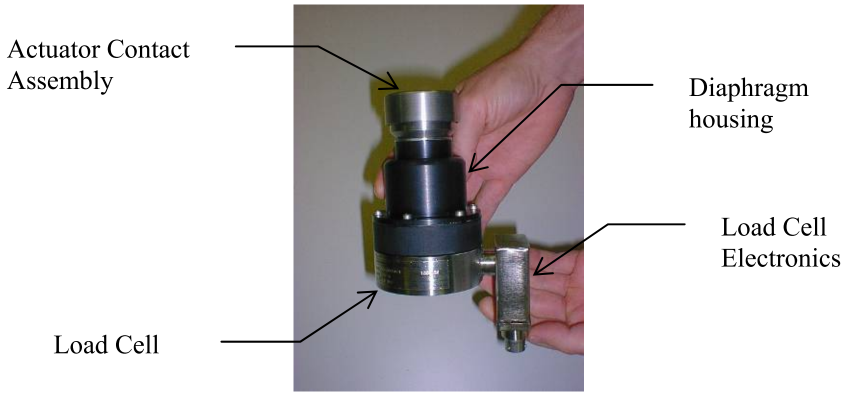

Figure 2. Axial Support

The mounting of the actuator to the cell and then the method of restraining was significant, as the zero point of the load cell is inherently affected by stress induced in the load cell due to the support. The initial fastener torque and the induced stress in the load cell through temperature induced expansion and contraction of the fasteners and interface caused the zero point to vary with temperature. The load cells were internally temperature compensated, so that if subjected to temperature changes in isolation the zero point was stable. However when attached to the cell and subject to its influence the drift effect was found to be about 0.6N per degree temperature variation.
The linearity and repeatability of the system was unaffected and therefore the zero point could be offset in the control system by recording the zero load voltage offset when the system was energized but before the actuators were commanded to lift the M1, so the actuators were supporting their own mass only. This offset is then used in all commands to the system until the next zero point calibration. For maximum effectiveness this process is conducted at the start of every night automatically.

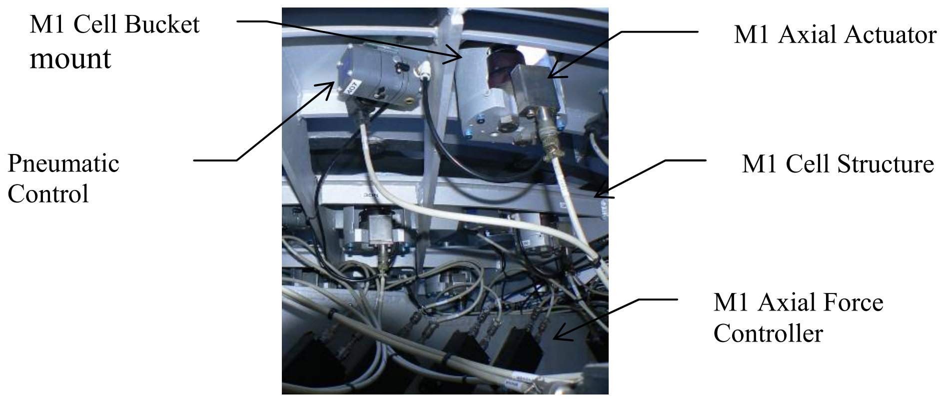

Figure 3. Axial Support Installed

In Figure 3 the arrangement of the axial actuators is shown. An axial support system consisted of an actuator including load cell, a pneumatic control valve located adjacently to minimise the length of pneumatic pipe, and thus the controlled air volume. Also located close by is the force controller which closes the force loop locally on the demanded force for that particular actuator.

The realized mechanical performance of the axial supports was as follows:

- Range of Travel ≥ ± 2.0 mm
- Actuator Force Range 5 to 900 N
- Absolute accuracy, individual support ≤ ± 2.0 N maximum error
- RMS error of all supports and definers < 0.6 N r.m.s.

- Load Cell Resolution ≤ 0.5 N
- Closed loop force control demand bandwidth (-3dB) ≥ 3 Hz
- Update rate for demanded forces ≤ 20 ms
- Non-repeatable lateral force at piston ≤ 0.35 N rms
- Repeatable lateral force at piston ≤ 4.5 N rms

4.2 Axial Definer

The axial definers which are located at 120 degree intervals in the outer ring of axial support positions are shown in Figure 4.

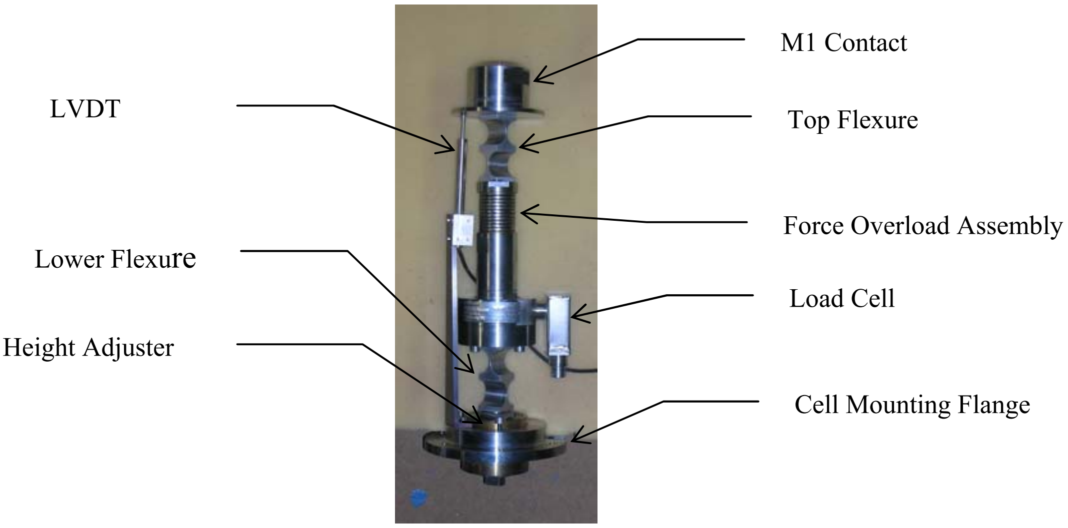

Figure 4. Axial Definer

The axial definer controls the M1 position in both tilt and focus. This required a highly stiff and repeatable axial load path with minimal stiffness in the the lateral direction, so during the design process flexures were found to be necessary to meet the performance requirements. The additional complication due to it being a pneumatic system was that a force overload device was necessary so that when the air supply was removed, the M1 was not supported on just the three definers. The overload device is an assembly of Bellevile washers which provide a 'breakaway' affect at approx 1500N but provide a stiff load path through the operational range of the definer. The load cell also was designed for high accuracy but with low deflection (ie high stiffness). These are conflicting requirements and the supplied item is a high range load cell with a specially modified amplifer package. The design of VISTA did not require the M1 position to be remotely adjustable therefore the height adjuster was a fine thread on a large diameter with a suitable preload system to remove backlash in the screw. The adjustment resolution was 25 microns. Feedback of the current M1 relative position is provided by the LVDT which was integral to the axial definer assembly.

The realized mechanical performance of the axial definers was as follows:

- range of Adjustment +/-3 mm
- Adjustment Step Size ≤25 µm
- Each axial definer shall incorporate a load cell.
- Accuracy of force measurement ≤ ± 2.0 N 1
- Range over which accuracy of force measurement required 5 to 900 N
- Limiting force of each axial definer 1700 N
- Minimum stiffness of each axial definer (wrt altitude axis) ≥ $30x10^6$ N/m

4.3 Lateral support

The initial layout of the lateral supports was a Schwesinger type similar to that used in the VLT, however after further sensitivity / tolerance analysis it was found that the benefit in support configuration versus the additional complexity of the set up and manufacture was not cost effective. The realized layout involved supports arranged to provide equal transverse forces acting through the centre of gravity of individual mirror slices.

The actuators utilized the same diaphragm technology for force application in off the shelf cylinders. These cylinders were combined with precision rose bearings and brackets to accurately control the actuator line of application. The lateral support system was divided into 4 segments each connected to a separate control valve that was commanded directly from the M1 control system.
In initial testing an issue with the control valve was identified that lead to an instability in the system when attempting to maintain M1 balance during full speed slewing of the altitude axis (2 deg/s^2). The problem was the quantity of air that had to be exhausted by the control valve and obviously as the altitude axis was closer to zenith the cylinder pressure was much reduced as the balance force supported by the lateral system tended to zero. To alleviate this a ‘booster’ valve was included in the system so that the control valve only controlled the booster valve which acted as a pneumatic amplifier.

The realized mechanical performance of lateral supports was as follows:

- Force range 10 to 2700 N
- Absolute accuracy, individual support +/-14 N maximum
- Absolute accuracy, all supports and definers at any instant ≤ 5.0 N r.m.s.
- Resolution ≤ 1.5 N
- Max frictional torque from linkage at mirror periphery Non-repeatable ≤ 0.15 Nm, Repeatable ≤ 1.5 Nm
- Closed loop bandwidth (-3dB) > 1 Hz

4.4 Lateral Definer

The lateral definers are positioned adjacent to the axial supports on the cell and control the M1 position in the lateral plane, and are arranged tangentially to the M1. The layout of a lateral definer is shown in Figure 5 Lateral Support. In the same manner as the axial definers, flexures were used to provide a high stiffness but repeatable position. These flexures also had to cope with the movement of the M1 from its actively supported and aligned position to its rest position which was approximately 1mm lower in z.

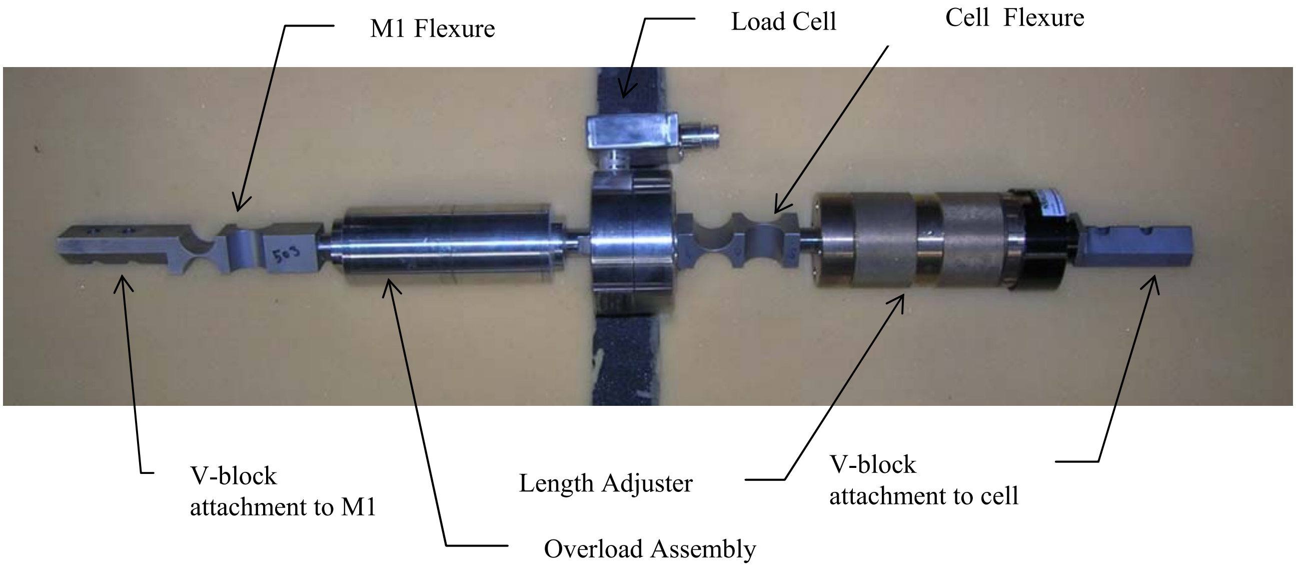

Figure 5 Lateral Support

The realized mechanical performance of lateral definers was as follows:

- Range in the lateral plane +/-1 mm
- Resolution of Adjustment ≤ 0.020 mm
- Total stiffness in Y direction ≥ 8.7×10^7 N/m
- Accuracy of force measurement ≤ ± 10.0 N
- Range over which accuracy of force measurement required - 100N to +100N
- Maximum force limiter setting per definer 5000 N
- Max frictional torque in linkage Non-repeatable ≤ 0.15 Nm, Repeatable ≤ 1.5 Nm

Due to the significant structural requirements on the cell structure access was difficult for the different parts of the M1 system but especially for the lateral definers. The connection of the definer to the M1 end of the definer in most cases had to be carried out blind mainly due to the M1 connection being adjacent to the axial definer structure.

5. ELECTRONICS DESIGN

Electrically, the CANbus data transfer system worked well, with the A-D accuracy being within specification, though there were some sampling rate issues. The performance-critical area of the electronics design was at the analogue loops that were closed around the precision load cells and pressure valves, and in fact the load cells themselves, so great care was taken in the design and the selection of suitable parts. However, even with a lot of design effort, the successful grounding and earthing of the whole collection of loops took some time, due to the millivolt-level accuracy required to cover the 1000:1 dynamic range. The final design included a single ground reference for the 4 Beckhoff nodes, floating the individual force control loop metal cases, and single-ended termination of cable screens at the centralised control CANbus cabinet end.

Figure 6, General Force Control Block Diagram shows the general layout in block diagram form of the force control network, including the analogue force control loop board. The block named 'Beckhoff Modules' represents the CANbus network, and the LCU block (Local Control Unit) is the host computer containing two CANbus interface cards.

Figure 7, Analogue Force Control Loop shows the analogue loop closing circuit in schematic form – every actuator had one of these circuits built into a screened box placed as near as possible to it to minimize noise and earthing differentials. The signals 'Valve CMD' (valve command) and 'Load Cell FB' (load cell feedback) went to the actuator pressure valve and load cell respectively, and the other signals went to and from the CANbus network.
Note that if the difference between the commanded force and the load-cell force is too great, a diagnostic error is produced.

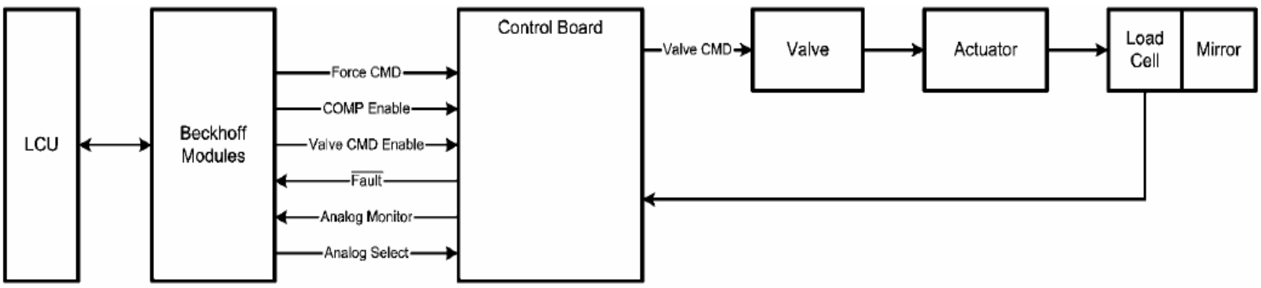

Figure 6, General Force Control Block Diagram

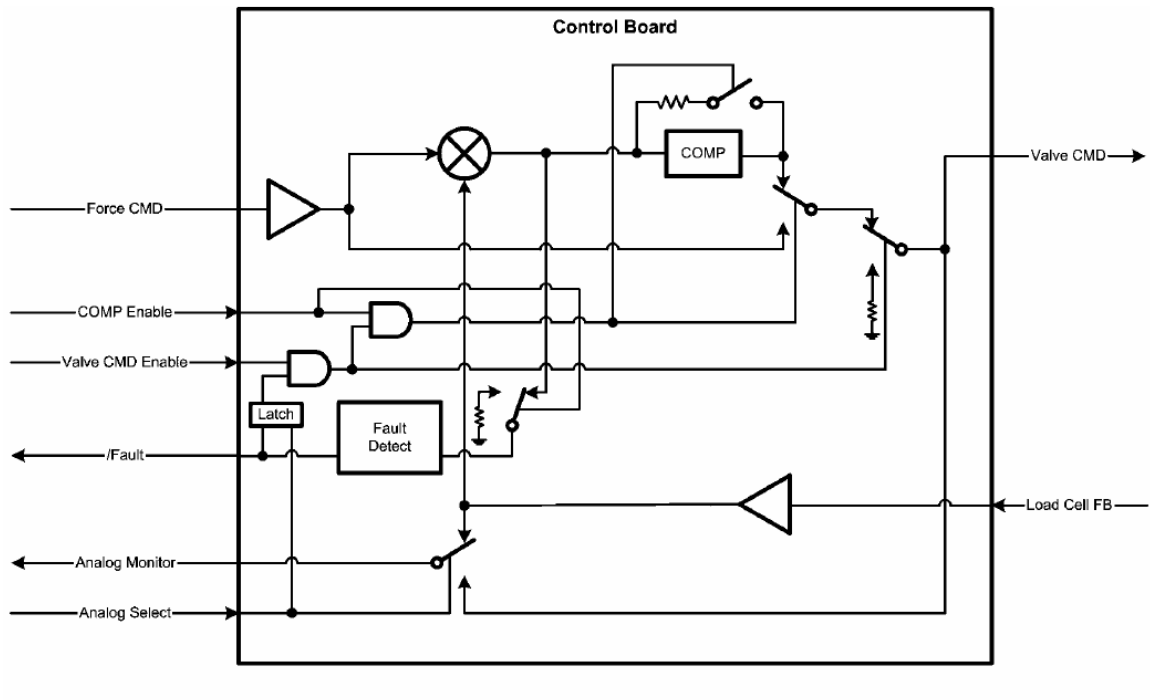

Figure 7, Analogue Force Control Loop

6. SOFTWARE

6.1 Functions

The main functions required of the software are:

(a) Read the forces on the three axial definers and use these to apply a new force pattern to the 81 axial actuators (20 Hz)

(b) Apply new active optics forces on the 81 axial actuators (updates approximately every 30s)

(c) Automatically reconfigure the forces in the event that an axial actuator fails

(d) Read the forces on the three lateral definers and use these to apply a new pressure to the lateral supports (10 Hz)

(e) Ensure that M1 is not subjected to sudden changes and that definers are not overloaded

(f) Monitor the forces achieved and generate alarms if they fall outside tolerance

(g) Monitor various sensors (anemometers, temperature, LVDTs, etc.)

The algorithm used to balance the axial forces is described more fully later, but it basically comprises fitting a flat plane to the 3 axial definer forces and applying this plane to the 81 axial actuators via a servo controller. Doing so ensures that wind and other effects do not distort the shape of the M1 surface. This algorithm therefore requires 3 read operations and 81 write operations every 50 ms. The algorithm also needs to account for the active optic force pattern, which is supplied to the M1 LCU by the higher level active optics software using data from the wavefront sensors and from look up tables. The active optics forces are subtracted from the 3 definer readings before fitting the tilted plane and are then added back into the calculated 81 actuator forces.

For the lateral supports, the same pressure is applied to all four groups of actuators. This pressure is controlled through a servo controller to null the sum of the forces on two of the three lateral definers. This control allows M1 in effect to be moved up or down but not side to side. After nulling, the magnitude of the three lateral definer forces serves as a diagnostic that there are no excessive unrelieved forces in the system.

It is important that M1 is not subjected to sudden changes, e.g. by suddenly removing the axial support. The hardware design is such that damage cannot be caused by such events, but if they were to happen frequently then definers or other components could be stressed and fail to meet their tolerance or reliability requirements. In addition, sudden changes or overloading of definers could cause M1 to move slightly necessitating the start of night calibration procedure to be executed again. The software employs several methods to protect the hardware from such occurrences:

(a) the rate of change of each force is limited to a maximum value

(b) a programmed procedure is used to activate M1 at the start of the night, raising and lowering it a few times to relieve forces

(c) a programmed procedure is used to deactivate M1 at the end of the night, gradually decreasing the axial forces and lateral pressures

(d) prevent axial forces being applied that would lift M1 off its axial definers so losing calibration

6.2 Hardware Configuration

Like other VLT-type applications that control hardware, the VISTA M1 control software runs on a Local Control Unit (LCU) comprising a VME-based Motorola diskless computer running the VxWorks operating system and the VLT's LCU Common Software.

Digital controllers at each support were considered but this approach did not conform to ESO standards and so a design was chosen with CANbus interfaces controlled directly by the LCU. Axial forces and lateral pressures are applied via A-D converters. Forces and pressures are similarly read back using D-A converters and control /status signals and using digital I/O modules. Industry standard modules are used for all these interfaces in the form of Beckhoff CANbus terminals, distributed across six CANbuses connected to two ESD CAN4 VME interfaces in the LCU. The CANbus terminals and other electronics were all housed in a Force Control Cabinet on the backend of the telescope with analogue and digital lines going to the individual supports. These lines are of order 4m in length and carry DC signals with 10 mV resolution and so care was needed with grounding, shielding and cable termination.

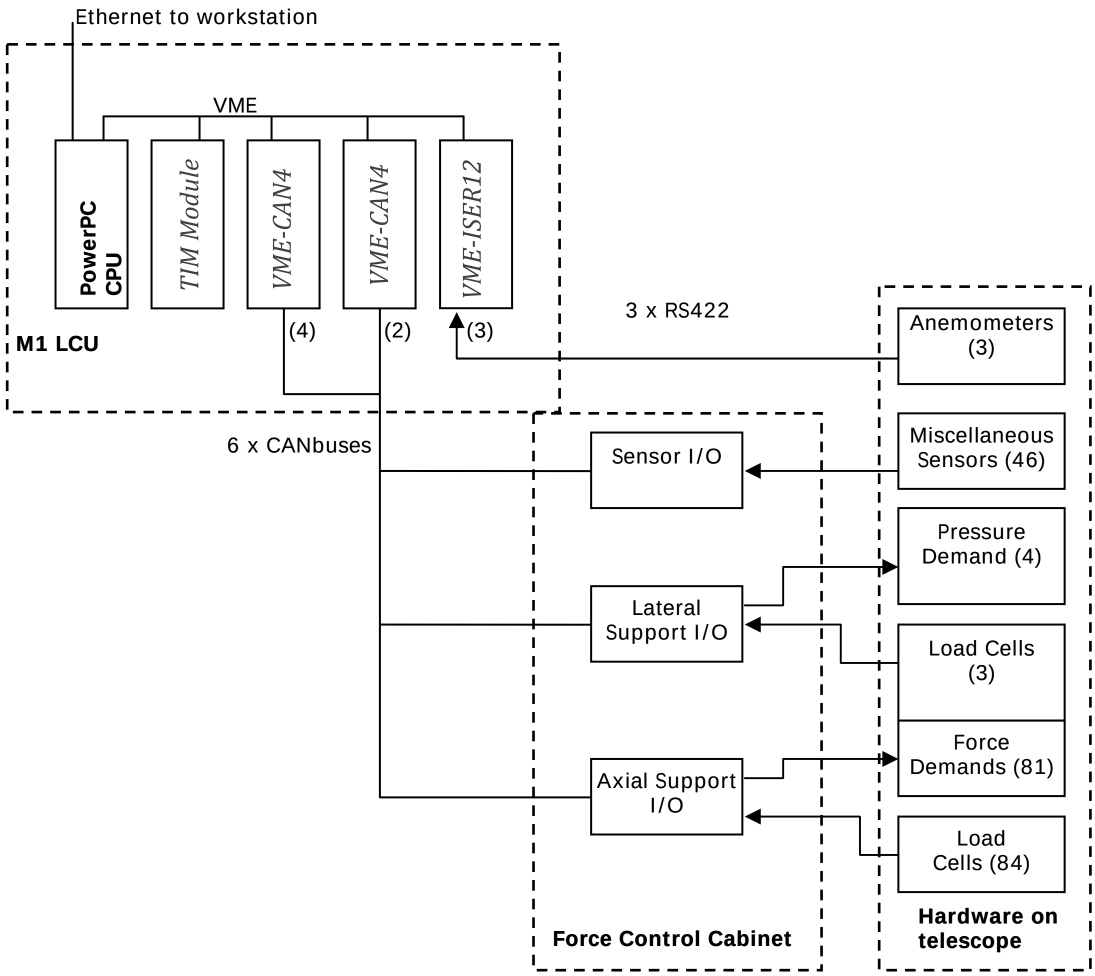

Figure 8, CANbus Electronics Distribution

6.3 Software Implementation

The software was written under contract by Observatory Sciences Ltd. and integrated with the hardware at VRSI's factory in Texas and at the telescope at Cerro Paranal. The software is written in C as a standard LCU application using the VLT LCU Common Software, which includes the *canio* and *canstack* modules for CANbus. Separate tasks were written for each of axial control, axial monitoring, lateral control and lateral monitoring, but it was found that some subtle resource contention issues caused performance and reliability problems. This was circumvented by combining these four tasks into one, whilst still retaining the basic modularity of the code (monitoring of anemometers over RS422 remains in a separate task). This meant there was never any contention for CANbus hardware or software resources.

The SYNC method was used for CANbus I/O. Every 50 ms the CPU sends a SYNC signal on each CANbus and in response all the configured terminals transmit their data, so avoiding the overheads of polling terminals for their data. In fact two SYNC signals were sent, the first to staticise the data in the A-Ds and the second to cause this data to be transmitted to the LCU. The original goal to perform axial control at 50 Hz was not met due to the software overheads being underestimated, but 20 Hz has proved adequate to meet the overall requirements and reliable operation is achieved.

7. CONTROL ALGORITHMS

The four main tasks of the support system are implemented by the following control loops :

7.1 Axial balancing in z

The control system has to ensure that all forces in the 3 definers and the 81 actuators are equal at any telescope azimuth angle. If the axial definer forces are Da1,Da2 and Da3, then this is accomplished by sending a force command equal to the average definer force to all 83 actuators, as long as there is no net moment around the x-and y-axes.

$$axial\_force(n) = [(Da1 + Da2 + Da3)/3] * axial\_compensation$$

Where n = 1 to 81

$$Da1 + Da2 + Da3 = axial\_weight * 3/84$$

$$axial\_compensation = (1 + 0.025s)/(1 + 15s)$$

The axial compensation increases the effective stiffness between 0.01 and 1.0 Hz. Compensators are given here in continuous form but in practice are discretised at the system sample rate.

7.2 Axial Moment Balancing

By summing the 3 definer forces and their distances from the x-and y-axes, the x and y torques can be calculated and therefore the derivation of the necessary balancing forces to be added to the axial forces to equalize the 3 definer forces. Note that this equalization happens in parallel with the axial balancing in z, as the axial balancing itself uses the average and cannot compensate for the differences.

The applied torque compensation forces are scaled by actuator distance to ensure smooth force differentials around the axis lines.

$$axial\_torque\_x(n) = Sx(n) * [Da1 * Sx1 + Da2 * Sx2 + Da3 * Sx3] * axial\_torque\_compensator$$

$$axial\_torque\_y(n) = Sy(n) * [Da1 * Sy1 + Da2 * Sy2 + Da3 * Sy3] * axial\_torque\_compensator$$

Where n = 1 to24

Sx(n) = distance of actuator (n) from x-axis, Sy(n) = distance of actuator (n) from y-axis

Sx1 = distance of definer Da1 from x-axis, Sy1 = distance of definer Da1 from y-axis, and so on.

The compensator is the same for both axes :

$$axial\_torque\_compensator = G * \frac{1 + 0.1s}{(1 + 0.01s) * (1 + 7.5s)}$$

Where G = (negative) system gain

7.3 Axial Active Forces Overlay

This function involves adding the calculated active forces to the 81 axial forces, as the pattern of computed active forces is always symmetrical such that their net moment around the x- and y-axes is zero. This action forms part of the VISTA active optics control loop.

7.4 Lateral Balancing

The control system has to null the forces in the lateral definers, so a negative feedback loop using an integrator and lead-lag compensator for maximum low-frequency gain is closed around the sum of the definers. The geometry of the lateral definers causes only two to carry the y-axis forces, say La1 and La2 including geometric constants.

$$lateral\_force(n) = \int (La1 + La2) * lateral\_compensator$$

where n = 1 to 24

$$La1 + La2 = lateral\_weight - \sum_{1}^{n} lateral\_force(n)$$

$$lateral\_compensator = G * (1 + 0.016s) * (1 + 0.08s)/(1 + 0.008s)$$

Where G = (negative) controller gain

7.5 Algorithm Design and Test

Matlab-Simulink was used extensively for simulation and control algorithm design during the system design and integration, and was also interfaced to dSPACE hardware to test some of the control software before the system was fully built, by creating a hardware-in-the-loop model of the support system dynamic load as seen by the software. In passing, some of the telescope axis software was also verified in this manner, so this was a useful risk-reduction process[3].

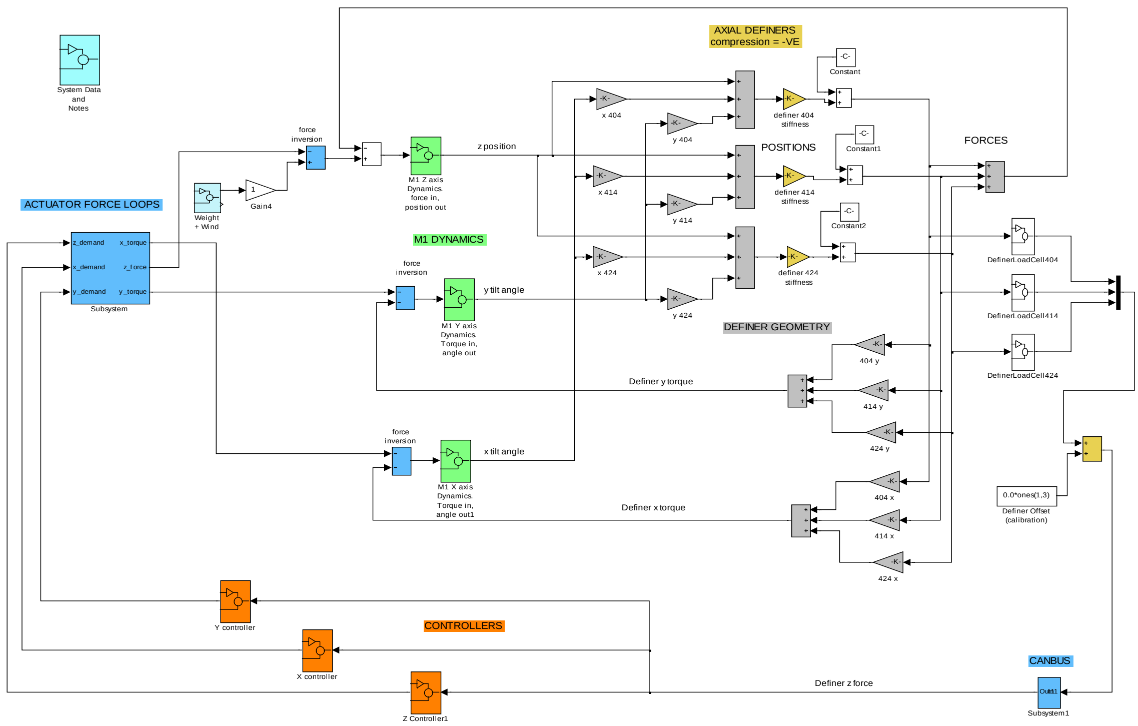

Figure 9 Axial control loops Modelled in Simulink

8. LESSONS LEARNED

8.1 Control Algorithms

The dSPACE hardware-in-the-loop system proved extremely useful for conforming system and software operation when the telescope hardware was not ready or convenient to access (noting that most software development occurred in the UK and the telescope hardware was either in Chile or the USA).

8.2 Mechanical

During the design process balancing the structural requirements with the access/maintenance requirements could have provided a more accessible system.

Testing of the systems individually did not highlight the zero drift load cell problem – whole system testing is essential.

Testing in actual operational configuration is big advantage e.g. being able to slew the cell during factory testing to check performance under real operational conditions.

Complexity in design does not always mean a better solution if considered in isolation from manufacture, e.g. reduction in complexity of the lateral support system arrangement did not reduce the overall system performance.

8.3 Electrical

Considerable effort was spent in optimizing the grounding and earthing of the distributed analogue system used to close the load cell / pressure valve loops. A digital design with A-D's at the load cell amplifiers would not have been so sensitive to local variations in earth voltages, however loop closing would have required local processor units and custom software design, which was not a customer-favoured option for maintainability reasons.

8.4 Pneumatic System Implementation Advantages

Compared to (e.g.) hydraulic oil and motor-leadscrew technologies, the pneumatic solution is clean and cool during operation, and applies moment-free forces that are free from limit cycles. There has never been any failure of a pneumatic actuator assembly over years of telescope test, integration and operation.

The pneumatic control design obtained the design bandwidth (3Hz) for bipolar force actions to resist wind forces, and also had the required high dynamic range.

8.5 Software

The software was developed separately from the hardware using a representative set of CANbus hardware rather than a full configuration; this masked some performance and reliability issues that had to be addressed during integration. Providing the software developer with a full set of CANbus hardware would have been preferable, from the viewpoints of both cost and risk.

9. REFERENCES

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