# Gemini primary mirror control system: design, implementation and experience

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**ABSTRACT**

The Gemini Primary Mirror Control System is a distributed control system responsible for definition, figure and temperature control of the 8.1meter diameter meniscus primary mirror of the Gemini telescopes. This paper describes the major design and implementation issues of the system and the experience to date of commissioning it.

**Keywords:** Active optics, Controller Area Network, Distributed Control, EPICS, Gemini Telescopes.

## 1. INTRODUCTION

The Gemini Primary Mirror Control System (PCS) is a distributed system, responsible for all aspects of primary mirror control. Development started at the Royal Greenwich Observatory (RGO) in the UK in 1996, alongside development of the mirror support system. The system was commissioned on the Gemini North telescope over the winter of 1998/99. Enhancements to the system are ongoing. The author was the 'Work Package Responsible' for the PCS at the RGO.

The PCS is responsible for mirror definition, figure correction via an active optics system, and active thermal control of the mirror. A brief description of the support system is given here to put the rest of the paper in to context, for a full description see L. Stepp, E. Huang and M. Cho[1].

### 1.1. Primary mirror support system

The support system comprises of five sub-systems.

- Passive Support System (PSS) - For mirror definition and support
- Air Pressure Support system (APSS) - For mirror support
- Active Optics System (aOS) - For figure control
- Thermal Control System (TMS) - Thermal management and control
- Cell Sensing System (CSS) - Environmental monitoring of mirror cell

#### 1.1.1. Passive support system

The primary mirror is mounted in a cell and faces upwards towards the zenith. This cell provides for axial and lateral support of the primary mirror (M1) in a changing gravity vector as the telescope tracks an object. The co-ordinate system for M1 is shown in Figure 1

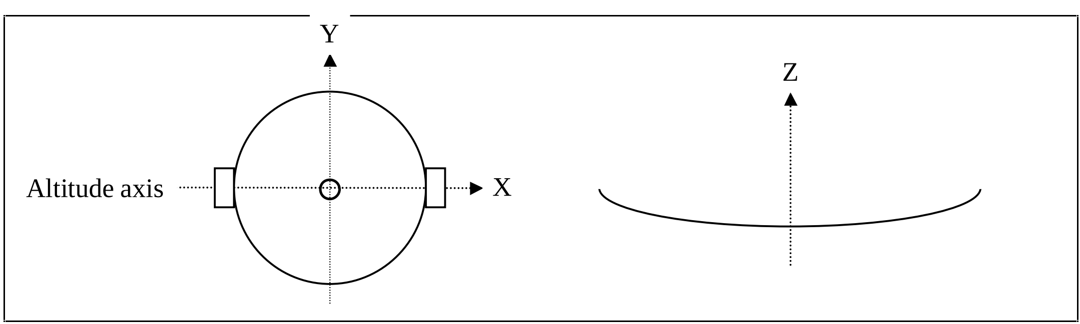


**Figure 1 Primary mirror co-ordinate system**

The M1 Passive Support System performs the following five tasks:

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- Axial support of M1
- Axial defining system for translation along the z axis (Tz), rotation about the x axis (Rx), and rotation about the y axis (Ry).
- Lateral support of M1
- Lateral defining system for translation along the y axis (Ty) and rotation about the z axis (Rz)
- Lateral defining system for translation along the x axis (Tx).

This passive support system is capable of aligning the primary mirror along the six axes: x, y, z, tip/tilt, and rotation about the optical axis to maintain the optical alignment to the required accuracy. X and Y axis alignment and rotation about the optical axis is provided by the passive lateral supports. Rotation about the optical axis is achieved by pushing on one set of lateral supports whilst pulling on the other. Z displacement, tip and tilt alignment is provided by the passive axial supports.

The axial system is capable of being divided into either 3 or 6 zones depending on the amount of wind buffeting which must be resisted. At present only 3 zone mode is in use. This division into zones is controlled by valves which subdivide the hydraulic actuators The overall height of a zone is controlled by a hydraulic actuator, referred to as a master cylinder unit, which can add or subtract small amounts of fluid from the zone. Each of the six axial zones has 20 actuators, giving a total of 120 axial actuators.

Lateral control is provided by similar master cylinder units. Y-definition is divided into 2 zones. X-definition is provided by one zone

**1.1.2. Air pressure support system**

The passive support system is augmented by the use of the Air Pressure Support System (APSS). The APSS bears 80% of the weight of the primary mirror at zenith and leaves the loading on the passive support system constant as the telescope tilts in elevation.

The air pressure support system employs the ‘air bag’ principle but is a fundamental departure from conventional air bag systems in that there is no physical bag. In this instance the ‘bag’ is formed by the rear face of the mirror and the upper face of the cell, with the gap between the two at the inner and outer diameters of the mirror being closed using inflatable sealing devices. These seals are also used to actively compensate the gravitational forces on the mirror peripheries.

The air pressures in the ‘air bag’, inner seal and outer seal are controlled by the PCS via proportional pneumatic valves.

**1.1.3. Active optics control system**

The figure of the primary mirror is adjusted by the active optics support system. This is capable of maintaining the figure of the primary mirror to the required accuracy by correcting for deformations in the mirror figure caused by changing gravity vector as well as dynamic effects due to thermal expansion stresses and wind loading.

The active system is implemented as 120 actuators, each consisting of a pneumatic actuator with a load cell mounted on top. An actuator is astatic and adds or subtracts a force from the passive hydraulic support under which it is mounted. The air pressure in the active actuator is controlled by a proportional pneumatic valve that maintains constant pressure in response to a demanded pressure command. The force applied to the back of the mirror by the pneumatic actuator is commanded by a demand signal originating from the PCS and is maintained by a control loop around the load cell and proportional pneumatic valve.

In operation there is an open loop model, developed during commissioning, which continually generates a vector of forces to apply to the mirror and a closed loop model, which uses Wavefront Sensor (WFS) information to generate corrections to the forces.

**1.1.4. Thermal management system**

In order to cool and heat the primary mirror a radiation plate system is used. This system will be active during the day as well as during the evening and consists of a cooled or heated water-glycol mixture circulation system. Heat can be added or removed from the coolant by a modular chiller, which is mounted in the plant room, remote from the telescope.

The thermal management system monitors M1 temperatures and controls the temperature of individual radiation plates via heaters, which heat the coolant flowing into individual panels.

Thermal sensors are located at 42 locations on and around the primary mirror and cell structure and are monitored by the PCS. These sensors are monitored at a 1 Hz rate and are used to indicate the current temperature distribution on the upper and lower surfaces of the primary mirror, in the air around the primary mirror and of the radiator panels.

#### 1.1.5. Cell sensing system

The M1 cell sensing system consists of sensors and associated electronics for monitoring conditions in the M1 cell assembly. The data gathered by these sensors is primarily for engineering purposes.

The sensors monitored are 3 accelerometers, 23 temperature transducers and 24 strain gauges.

## 2. DESIGN

### 2.1. Requirements

The International Gemini Project Office (IGPO) awarded the PCS work package to the RGO. Once the work package was awarded, the first task was to fully define the formal list of requirements.

Some requirements were easily defined. The controls group at IGPO had already decided that EPICS[2] would be used on all the Gemini real-time systems and that a Gemini Standard Controller[3] be used. The Gemini Standard Controller consists of a VME chassis housing a Motorola MVME167 processor card. It was also mandated that wherever possible only hardware supported by EPICS should be used.

Other requirements were more difficult to define. At the time that work commenced on the PCS, the design of the mirror support system was not finalized. This meant that many requirements had to remain fluid for some time. For example, it was not for some months after system design had started that it was determined that the resolution required from the axial load cells required 14-bit rather than 12-bit ADCs. Both the quantity and performance of the I/O was not fully specified until well into the system design phase. Therefore the system design of the PCS had to remain flexible in its capabilities.

Other major requirements for the system included a very limited amount of heat that could be dissipated into the mirror cell and restricted space available within the confines of the mirror cell.

What was clear was that the PCS would have to handle a large number of I/O signals and have a large number of mechanisms to control.

### 2.2. Control hierarchy

The software control of the Gemini telescopes is split into a hierarchical arrangement of distinct systems. There are 3 principal systems, these being the Observatory Control System, Telescope Control System (TCS), and Data Handling System. Beneath the TCS are a number of real-time systems of which the PCS is one.

The job of the PCS is to provide the interface between the TCS and the primary mirror support and thermal management hardware. The relationship between the PCS and other components of the Gemini Control System is shown in Figure 2.

During operations, the PCS receives commands from the TCS. However, for calibration and diagnostic purposes, an engineering screen system is provided so that commands can be sent directly to the PCS without going through the TCS. Thus it is possible to use the PCS as a standalone system. It is not possible for the PCS to issue a command to a higher level system such as the TCS.

### 2.3. Inputs and outputs

The number of inputs eventually handled by the PCS totals 1236, as shown in Table 1.

The number of signals and their locations, dispersed around the mirror cell, clearly had implications for the system design. A system architecture was required that would bring all these signals to the PCS VME chassis. It was apparent early on that some form of distributed system was desirable. The sheer number of signals militated against running all signal cabling back to the VME system. The space constraints and heat dissipation requirements pointed to the need for small rather than large nodes in a distributed system.

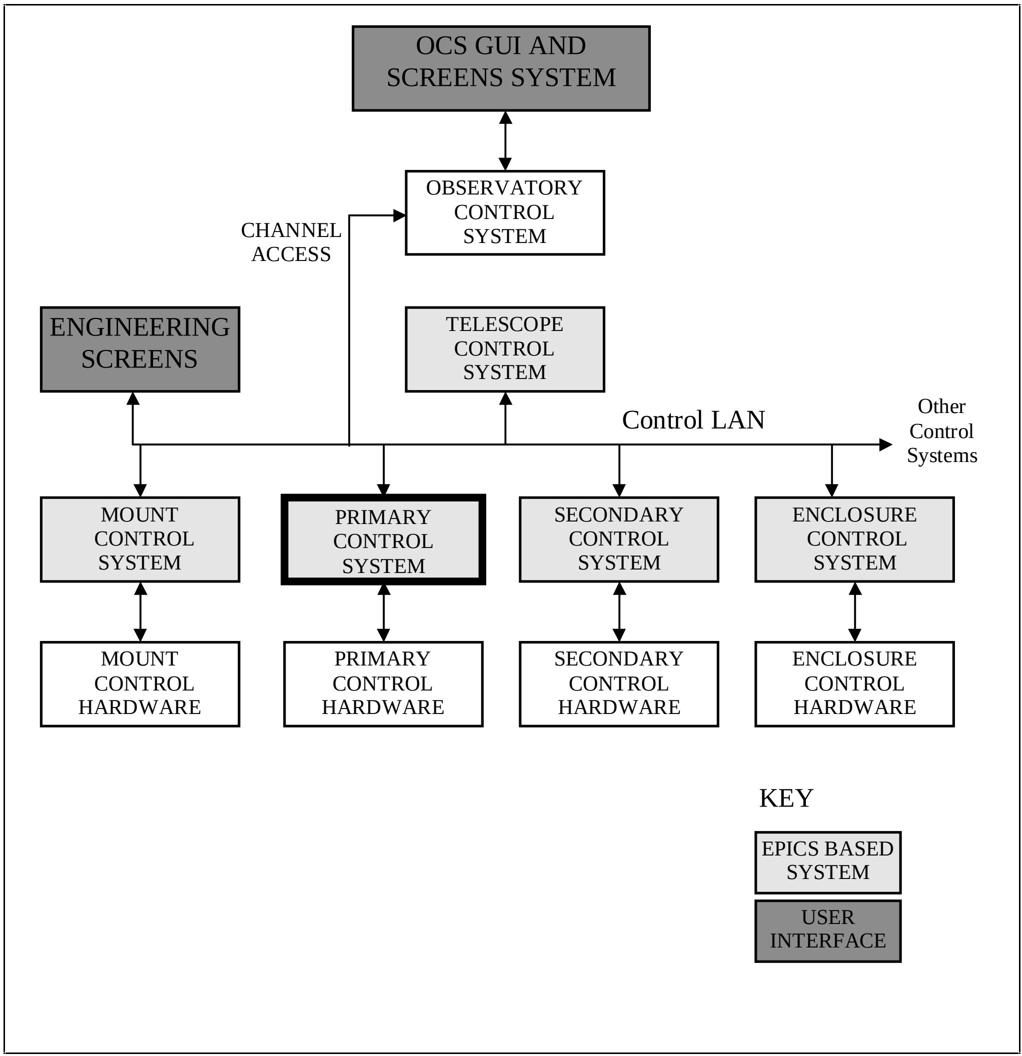


**Figure 2 Relative position of PCS in Gemini Control system**

An extensive trade study was undertaken to determine the best solution. Amongst the options evaluated were

- A PLC based system
- A Profibus system
- A Bitbus system
- A CAN[4 5 6] system

The PLC solution offered the advantage of 'off-the-shelf' hardware and a proven EPICS interface. This option was rejected on a cost basis. The hardware cost alone exceeded the entire PCS budget.

The Bitbus system was evaluated because an EPICS interface existed and other EPICS sites were already using it. It became apparent that many sites found Bitbus unreliable. When it was discovered that Intel, the inventors and main backers of the standard, were withdrawing support for it, it was rejected for the PCS.

A Profibus system, with hardware coming from PEP modular computers, was considered very seriously. It offered advantages of 'off-the-shelf' hardware and an extensive range of modular components being available. This solution was eventually rejected due to the complexity of Profibus and its cost. Profibus provides a wealth of features, but many of them were not required for the PCS and it was felt that the resulting system would be more complex than necessary. The Profibus solution was only suitable if large nodes were to be employed. This meant having 6 or more active optics actuators controlled per node.

The CAN based solution offered several advantages. CAN had a number of features that made it ideally suited to this application. It is very good at transferring small packages of data in a deterministic manner. It has high error and noise resistance and is rugged. Another major advantage is that much of the message protocol handling is done in the silicon of the CAN controller IC, simplifying the task of software. Commercial manufacturers offered small processor boards with CAN interfaces. It also offered the possibility of having one node per active optics actuator. This offered advantages in terms of the space required for the node and allowed greater modularity in the system design. It also meant that the cable length for cables carrying analogue signals from the load cells to 14bit ADCs in the node boxes could be kept to a minimum, reducing their susceptibility to EMI.

The main disadvantage with a CAN solution was that there was no EPICS driver software for CAN hardware. At the same time as the trade study was going on we became aware that an EPICS/CAN solution had been selected for a project to upgrade the UKIRT primary mirror support system. Once the decision to use CAN for the PCS had been made we were able to share development costs of the EPICS software interface for CAN hardware in the VME system. This proved to be a very fruitful collaboration and this software is now available to the entire EPICS community.

| SOURCE | QTY |
|---|---|
| Active Optics | |
| Pneumatic Load Cell | 120 |
| Hydraulic Load Cell | 120 |
| Valve demand | 120 |
| Valve pressure | 120 |
| Preload Valve demand | 6 |
| Preload Valve pressure | 6 |
| Node temp | 372 |
| APSS | |
| APSS Valve demand | 6 |
| APSS Valve pressure | 6 |
| APSS Pressure sensors | 6 |
| Seal Valve demand | 2 |
| Seal Valve pressure | 2 |
| Node temperature | 24 |
| PSS | |
| Master Cylinder Position | 15 |
| Master Cylinder Demand | 15 |
| Master Cylinder limit Switches | 30 |
| Lateral Load Cell | 64 |
| Position sensors | 8 |
| Node temperature | 9 |
| Pressure sensors | 25 |
| Fill Valves | 44 |
| Cell Sensing | |
| Strain Gauges | 32 |
| Temperature sensors | 23 |
| Thermal Management | |
| Heater control | 24 |
| Temperature sensors | 42 |
| **Total** | 1236 |

**Table 1 PCS I/O signals**

The solution eventually decided upon at was to use CAN as the bus linking a number of node boxes to the VME system. One node box would be allocated to each actuator. In order to improve maintainability, by reducing parts count and increasing commonality, we wanted to keep the number of different types of node to a minimum. It was determined that the minimum number of types of require was four. These are described in Table 2.

| NODE TYPE | DESCRIPTION |
|---|---|
| Axial/Pneumatic | Control aO actuators by closing a PID loop around proportional pneumatic valve, actuator and load cell. Used for any node using a pneumatic valve, e.g. APSS valves |
| Master Cylinder | Controls stepper motors used for driving master cylinders. Two channel. |
| Lateral Load Cell | Reads eight load cells. |
| Strain Gauge | Reads six strain gauge channels. |

**Table 2 Node box types**

Each node box contains a motherboard, which is specific to the type of box. The motherboard contains specific circuitry for the job it has to do. For example, the Master Cylinder motherboard contains circuitry for driving stepper motors. A common type of processor board is used across all variants of node box. This plugs into the motherboard. Each node box has its own program, which is held in FLASH PROM. All types of box software contain a common boot block. Using this it is possible to download code, over CAN, to program the box. There is one software program for each type of box. New code is only downloaded when code is modified.

The hierarchy of the PCS once a CAN solution had been chosen is shown in Figure 3. It can be seen that eight CAN buses are used. With a total of 157 node boxes, approximately 20 boxes are attached to each bus. The number of CAN buses required was calculated by estimating the bus loading for various configurations using a method described by Tindell and Burns[7].

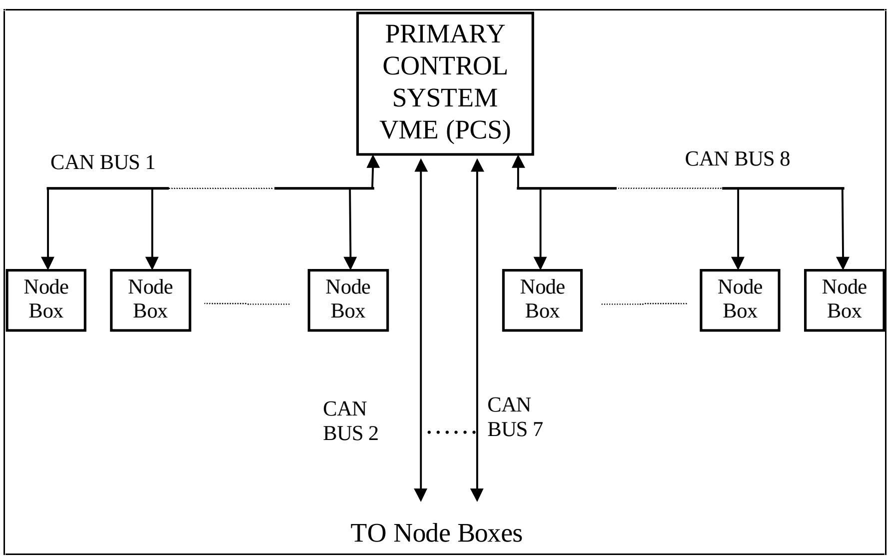


**Figure 3 Block diagram of PCS hiearchy**

Figure 4 shows the implementation scheme for control of one hydraulic zone. Demanded changes in M1 definition are sent from the TCS to the PCS at a rate of 0.2Hz. Using values of elevation (usually obtained from the Mount Control System) and temperature (obtained from the PCS's own sensors), the PCS converts the demands to changes in master cylinder position. The new master cylinder position is sent via CAN bus to the relevant node box. The node box closes a local proportional loop around the stepper motor and encoder to position the master cylinder piston. Once in position the motor power is reduced in order to reduce power dissipation. Other node boxes are used to read pressure and position sensors. The node boxes filter the signal (both hardware and software filters are used) to improve the signal to noise ratio before passing the filtered values to the PCS. The PCS uses the position sensor data to close a slow proportional loop around the master cylinder.

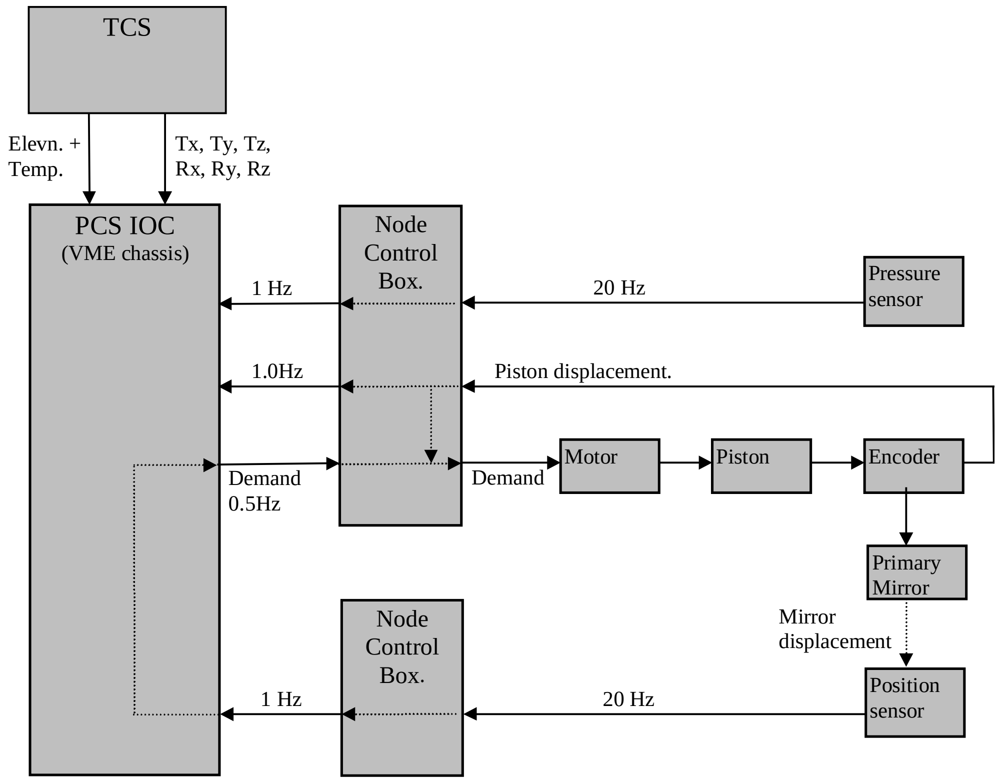


**Figure 4 Passive support control block diagram**

Figure 5 shows how the aO system is implemented for one actuator. Command information in the form of Zernikies, plus elevation information are fed to the PCS VME from the TCS. The Zernikies are fed at the rate of approximately once per minute, depending on the integration time of the wave front sensor. The Elevation is read at 1Hz from the Mount Control System.

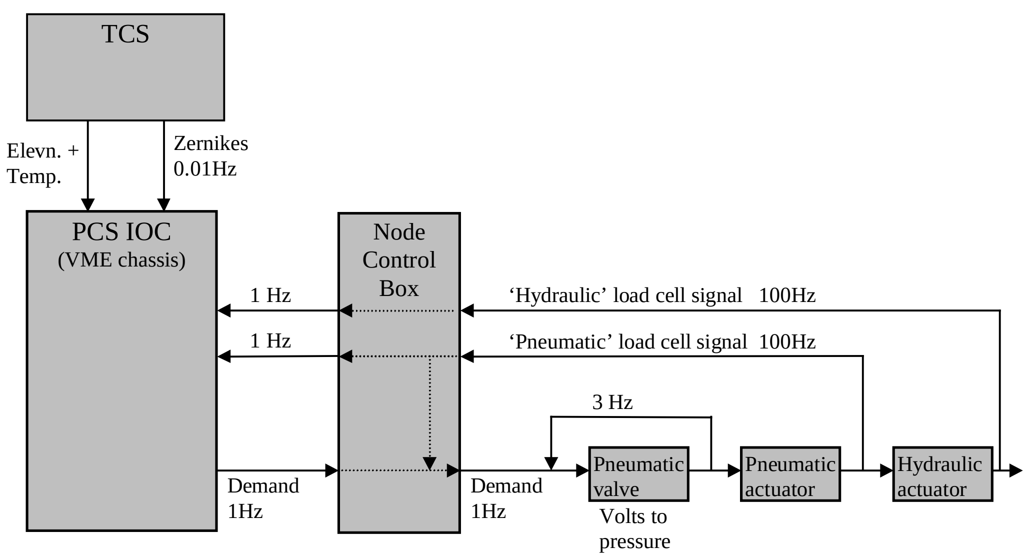


**Figure 5 Active Optics control block diagram**

The PCS calculates the required demand for each of the 120 axial pneumatic actuators at a rate of 1 Hz.

The Demand is fed to each node box from the PCS at 1Hz. The node box uses this demand as an input to a PID loop it is closing round the Pneumatic Valve and actuator with feedback from the 'pneumatic' load cell. The PID loop is closed digitally and runs at more than 60 Hz, i.e. more than 20 times the nominal bandwidth of the actuator.

The node box reads both load cells at a rate of 100Hz. These values are filtered (in both hardware and software) and fed back to the PCS at 1Hz. This ensures the PCS only ever uses load cell data with a maximum temporal spread of 1000 ms.

## 3. IMPLEMENTATION

Software design was undertaken using the Ward Mellor (with the addition of real time extensions) structured design technique. This process was greatly aided by the use of the Teamwork CASE tool from Cadré. The main outputs of the Teamwork model were data flow diagrams, a data dictionary and state transition diagrams.

The Teamwork model provided its main benefits during the architectural phase of the software design. During detailed design it was often the case that it was simpler to implement the design than model it first. The exception to this was when designing state transition programs to run on the EPICS sequencer. Here the state transition diagrams produced by Teamwork were of great help, not only in writing the code but in giving the software engineers a way of showing and discussing the design with engineers of other disciplines.

The documentation provided by the CASE tool also proved invaluable for design reviews. Again, it was possible for the PCS team to communicate their designs in a clear fashion to engineers from other disciplines. Figure 6 shows an example of the output from the Teamwork tool.

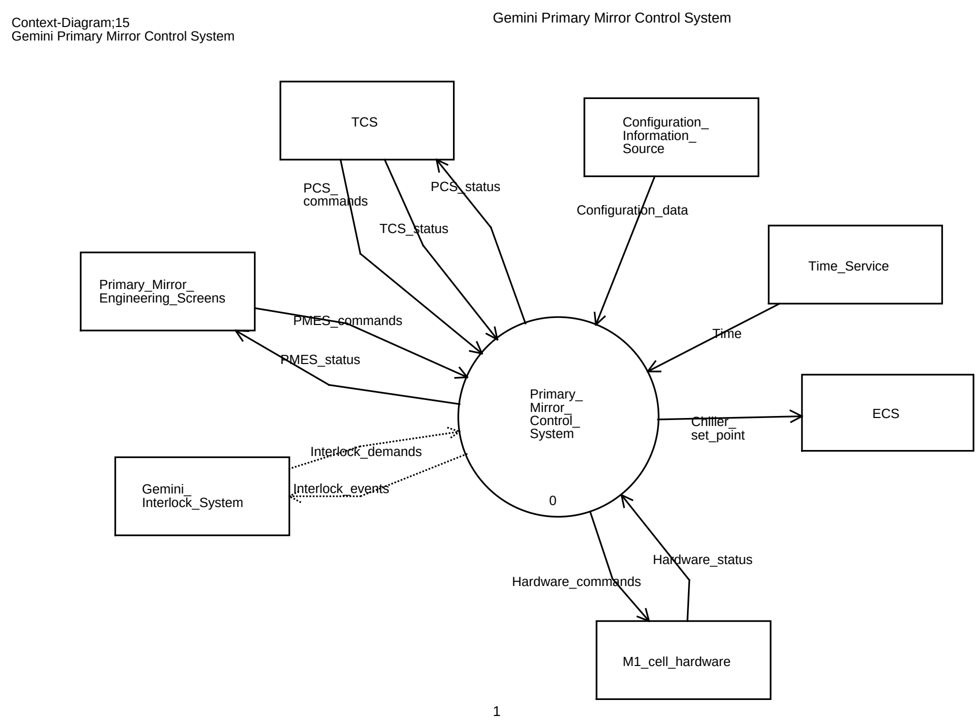


**Figure 6 PCS context diagram produced with CASE tools**

A pragmatic approach was taken to the use of EPICS in developing this application. The preferred method was to use records in an EPICS database. There are currently over 7500 records in the PCS database. However, use was also made of 'C' subroutines and 'Sequencer' programs. 'C' subroutines were used where computationally intensive components were required, such as in implementation of the aO algorithms. ‘Sequencer’ programs, written using the EPICS State Notation Language[8] are used for higher, supervisory level, tasks within the PCS, such as parking and un-parking the mirror.

The simulation facility provided by EPICS input and output records is used extensively to provide simulation of the mirror support hardware. This has proved useful in de-bugging code both, before the system was coupled to the hardware and subsequently for testing modifications without endangering any hardware.

The PCS project was also responsible for providing and programming the processor boards used to control the node boxes. Initially it was intended that commercial boards using a variant of the 8-bit Intel 8051 micro-controllers be used. However, following a trade-study it was determined that developing our own boards, based on the 16-bit Siemens C167CR micro-controller[9] would be a better solution.

There were many reasons for this choice; the main benefit of this option was the price/performance benefit. For approximately $15 more per board a gain of 5 times the processing power and 256 fold increase in addressable memory space was obtained. In addition the C167CR comes with many integrated peripherals, such as a CAN controller, 10-bit ADCs, timers, serial channels, and a watchdog timer, which helped to keep the system cost down.

Another requirement that favored the 16-bit solution was the decision to implement the PID loop controlling the aO actuators digitally within the processor, rather than externally with analogue electronic components. The 16-bit solution gave us much greater ‘head room’ in terms of processor resources to meet this new requirement. Given the relatively large number of boards required (for a telescope project at least) of more than three hundred, the development cost could be justified.

Development of the processor board was carried out by CoEfficient Design Ltd., a company with extensive experience of developing CAN products, who are located in Cambridge (UK), a short distance away from the then RGO. This proved to be a very effective arrangement. It reduced the load on project staff and the C167 processor board has proved to be very successful.

Software for the C167 boards was written in ‘C’. No operating system was used. The software is relatively simple and no operating system was required. An In Circuit Emulator (ICE) was procured to aid software development. Although it is hard to quantify, this saved a lot of time in code debugging and made code development relatively simple.

A CANAlyser[10], CAN bus analysis tool, was also procured for the project. This again proved to be invaluable, particularly for tasks such as debugging software drivers and analyzing bus problems during factory installation.

Since CAN was an unknown technology to the project team the approach to hardware design a cautions one. Initial experiments were done using the EPICS system, CANAlyser and a C167 evaluation board. These proved that the concept of reading signals with the C167 and transferring them to the EPICS database was a sound one. The design process then progressed through stages of a prototype of the C167 control board, marrying this with prototype node box motherboards and finally connecting 12 node boxes and the VME system together on a test rig attached to real mirror support hardware.

## 4. EXPERIENCE

Both mirror cells were fabricated at the factory of Neyrpic Framatome Mécanique Technologies (NFM) in Le Creusot, France. Teams from the RGO installed and commissioned the mirror support system in both mirror cells (for Gemini North and Gemini South) and the PCS at NFM over a period of approximately 12 months, beginning in the summer of 1997.

Once enough node boxes were installed in the cell, the team attempted to establish communications with them via CAN. First attempts ran in to problems and it was discovered that filter capacitors, that had been placed on the CAN lines in the node box to ensure that it met FCC EMC regulations, were placing too big a load on the CAN driver circuitry. Fortunately, the system design had allowed for a lot of spare bus capacity. Provision had also been made in the software design of the node box for the bus speed to be jumper selectable. It was therefore possible to reduce the bus speed, hence increase the bit length relatively easily. A speed of 50 Kbits/second was found to be reliable and still left the bus loading at less than 50%.

This was a fairly typical experience of setting up a CAN system, one that we had come across before in the laboratory environment. It sometimes took a little work, (usually involving an oscilloscope), to get the CAN nodes communicating but once the system was running it was very reliable.

The fact that the PCS team was able to run the PCS during installation of the mirror supports hardware proved invaluable for both groups. Support system installation problems were often picked up very quickly, enabling them to be rectified at an early stage. Software problems were also revealed much sooner than would have otherwise been the case, again, allowing the team to correct problems in a timely fashion.

Interface problems between the control system and the support system were also revealed at this time. The fact that both teams were on site, working towards the same goal, meant that these problems too were dealt with quickly and efficiently.

With installation of the components complete a dummy mirror was fitted to the cell. Functional tests then took place, which allowed many bugs to be ironed out and proved that the support system and the control system were fundamentally sound. We were thus able to gain a significant amount of confidence in the system before it got to the telescope.

During installation and factory commissioning, the PCS team was able to watch and assist as engineers and technicians from the mirror supports team used the PCS as a tool to test and fault find the mechanical parts of the support system. They did this through the engineering screens, created with the EPICS Display Manager[11]. The fact that people from non-software disciplines were able to use the PCS as a tool was an indication to the PCS team that at least some of our design work had been correct! Feedback from the mechanical engineers was useful in enabling us to make many of the engineering screens more useful to them.

Following factory testing the first mirror cell was shipped to the Gemini North telescope, on Mauna Kea, Hawaii. After initial check-out on arrival at the summit in September 1998, the cell was installed in the telescope with a dummy mirror fitted. This was the first ever opportunity to test the PCS/mirror cell with the cell pointing away from zenith. It was confirmed that the Passive Support System and the Air Pressure Support System were able to function correctly, although the stability of the APSS remained outside of specification at that time.

Following these tests, the real mirror was fitted to the telescope. One of the first things that became obvious was that the functioning of the APSS was much improved. Although care had been taken during assembly of the dummy mirror, it had still leaked air at its segment joints. After some tuning of its PID parameters the performance of the APSS was brought within specification.

The installation of the real mirror afforded the first opportunity to test the aOS at the system level. Tests conducted in December 1998 with the Prime focus Wave Front Sensor (PFWFS)[12] showed that the aOS was working, although it was in need of calibration.

Tests and calibration continued, until first light in June of 1999. Images were obtained with Hokupa'a, an adaptive optics instrument from the University of Hawaii, for first light. Hokupa'a requires the surface error of the primary to be less than approximately 500nm, a figure that is now routinely achieved in open loop mode at all elevation angles.

## 5. CONCLUSION

This paper has tried to give an overview of the purpose of the PCS, the design issues that were faced, how they were overcome and the experience with the system to date.

The PCS has proven to be one of the most reliable on the telescope. In the authors opinion, one of the reasons for this is the length of time that was available for testing the software with the real hardware. Control system and support system were first married together at the NFM factory in France, just over a year before the mirror cell got to the telescope. This allowed many of the problems in the system to be corrected at a relatively early stage. Furthermore, a high confidence level with the system had been achieved which gave a firm foundation to build upon when integrating these systems with the rest of the telescope.

The fact that both the PCS and mirror supports project were both undertaken by the RGO and therefore that these project teams were located in the same building was also a big contributor to the success of the project. Even so, the good communication between the teams required effort from the people involved. The close physical location was certainly a big factor, but it still required the people involved to have a professional attitude and a genuine desire to see the projects succeed.

The choice of system architecture, in our opinion, has been proved correct. The distributed system, using CAN for communications, has proved able to meet specification, has proved reliable, has been flexible enough to meet evolving requirements and was completed within budget.

Another important decision that has also worked out well was the selection of the micro-controller and its development system for use in the distributed nodes. The C167 processor together with an in circuit emulator proved to be a good solution. The emulator made debugging problems much quicker than other techniques such as 'crash and burn'. It has resulted in reliable and robust code. This is shown by the fact that the last firmware upgrade to the node boxes was carried out in April of 1998, nearly two years ago.

The ability to download firmware upgrades over CAN to be blown into FLASH memory remotely proved to be a real boon, and were the project to be undertaken again, this would be put at the top of the requirements priority list. It saved many man hours of precious factory commissioning time, although it has not been required at the telescope as yet. The alternative of crawling through the mirror cell and replacing 157 FLASH memory ICs at an altitude of 14,000 feet is not appealing. According to our development tool vendors, who are heavily involved with CAN, to their knowledge, the project was the first in the United Kingdom to implement such a feature.

Just over halfway through the project the parent body of the RGO, the United Kingdoms Particle Physics and Astronomy Research Council (PPARC) announced, after a protracted decision process, that the RGO was to be closed and that most staff would be made redundant. This was not conducive to motivating staff or producing high morale. That the PCS and mirror support projects were not only completed but were completed to high standard at such a difficult time is a credit to all of the RGO staff involved.

## 6. ACKNOWLEDGEMENTS

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