Software and Control for the Magdalena Ridge Observatory Interferometer Delay Lines

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ABSTRACT

The delay lines for the Magdalena Ridge Observatory Interferometer (MROI) will provide remote control of optical delays of up to 380m with sub-wavelength precision in vacuum. The delay-line prototype is now fully functional, all features having been demonstrated in a 20m long evacuated test rig. We describe the architecture, design and performance of the delay line software: this features distributed real-time control and flexible remote logging of diagnostic data from the delay line hardware components at up to 5 kHz.

Keywords: optical interferometry, delay line, real-time control, software

1. INTRODUCTION

The Cavendish Laboratory of the University of Cambridge is designing and prototyping single-stroke vacuum delay lines for the Magdalena Ridge Observatory Interferometer[1] (MROI).

The Cavendish Laboratory is contracted to undertake the design of all components of the delay line system as well as delivery of the first production trolley and its associated control electronics. Subsequent delay line trolleys will be supplied by Cambridge as required, under separate contract. New Mexico Tech (NMT) will be responsible for fabrication/procurement of the delay lines pipes and supports and metrology system hardware.

The delay lines are required to introduce vacuum optical paths between zero and 380 m using a single stroke, with an absolute precision of 10 μm and jitter below 15 nm over 10 ms intervals.

In order meet these requirements, the design for the MROI delay lines has several novel features, including use of the inner surface of a vacuum pipe to guide the delay line trolley, active roll and shear correction, and contactless power and control. To mitigate the risks associated with these, a prototype trolley has been built and tested both in an open test track and in a 20m-long vacuum test rig at Cambridge. Results from these tests demonstrate that the performance requirements for the delay line have been met — for more details refer to Ref. 2.

These novel features imply that the control system must differ from those of other optical delay lines in several respects:

- There is a need to manage additional servo loops, for control of beam shear and trolley roll.
- The metrology (OPD) loop must be closed wirelessly with less than 40 μs latency.
- To diagnose problems while testing the prototype hardware, we needed to capture large volumes of diagnostic telemetry.

The reader should note that the rejection required in the metrology loop is similar to that for more conventional delay lines; the extra disturbance due to rolling on the rough surface of a pipe rather than precision rails is not seen by the trolley owing to the use of compliant wheels.

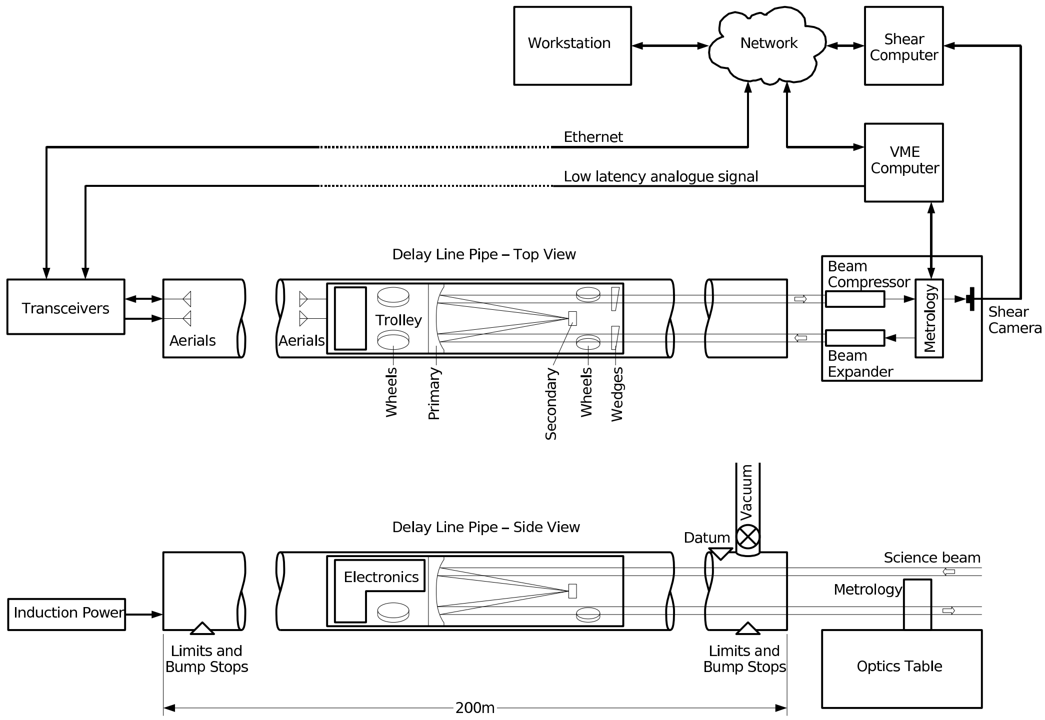

Figure 1. Schematic top and side views of a complete delay line system, showing the physical locations of the major components.

2. SYSTEM COMPONENTS

Each of the delay lines installed at the Magdalena Ridge will incorporate the components listed below. The relative physical locations of these components are shown schematically in Figure 1.

- A "trolley" consisting of a cylindrical "carriage" supporting and enclosing the cylindrical cat's-eye retroreflector.
- 200 m of vacuum pipe to support and guide the trolley, supported on flexure legs to accommodate thermal expansion.
- A laser metrology system (Agilent 5517) to measure the position of the cat's eye by bouncing a laser beam off it. The laser is passed through a beam expander before entering the "near" end of the vacuum pipe (see Figure 1). The beam is reflected from the cat's eye and returns out of the near end of the pipe, whereupon it is re-compressed.
- A shear sensor, which uses a small fraction of the metrology light to sense the position of the metrology beam after it has returned from the cat's eye, and hence the shear of the science beam.
- An inductive power supply to deliver electrical power to the trolley, via a wire lying in the bottom of the vacuum pipe. The wire slides through a long thin transformer on the trolley which inductively couples high-frequency electrical power from the wire to the trolley.
- A distributed control system involving the following components:
  - A "workstation" PC (shared between all trolleys) to act as a supervisor, and provide a user interface for operating the delay line and interrogating delay line telemetry.

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- A VME-bus CPU (shared between all trolleys) to read the metrology signal and hence control the cat's eye.
- A low-power PC104 single-board micro on each trolley, to control on-board functions with undemanding timing requirements, and to send diagnostic telemetry to the workstation.
- Two separate radio-frequency (RF) links between the trolley and the external control system, transmitted via aerials mounted at the "far" end of the pipe:
  * A low-latency 900 MHz link used to close the Metrology Loop in Track Mode.
  * A standard 2.4 GHz wireless Ethernet link used for communication between the on-board micro and external control computers.
- A "datum" switch, to act as a fixed fiducial point on the pipe from which to reference the laser metrology measurement.
- Limit switches and bump stops, to ensure the trolley slows down and then stops when it approaches either end of the pipe.

3. SYSTEM MODES

The delay line can operate in one of three highest-level "system modes": FOLLOW, STOP/IDLE and DATUM; these are described below. Changes of system mode are initiated by the workstation, normally in response to user input.

The reader should note that these system modes are distinct from the lower-level Track and Slew Modes. Track and Slew Modes are labels for different behaviours of the delay line axial control loops described in Sec. 4.1. For example, in FOLLOW mode the VME system selects either Track or Slew Mode depending upon how far the cat's eye is from the desired position.

3.1 FOLLOW system mode

In this system mode the workstation commands the VME system to cause the trolley to follow the trajectory defined by the position and velocity data the workstation is currently sending. The VME system decides whether or not the trolley must be in Slew Mode in order to reach the condition when Track Mode can be entered so that the trajectory can then be followed precisely.

3.2 STOP/IDLE system mode

In this system mode the workstation directly commands the trolley to enter Slew Mode with a velocity of zero. In this situation the trolley is stationary but the Metrology Loop is not closed.

3.3 DATUM system mode

In this system mode the VME system is commanded to initiate a sequence that will drive the trolley in a safe way so as to eventually reach the datum position and then acquire datum in a consistent fashion.

4. CONTROL LOOPS

There are several servo loops involved in the operation of the trolley. These are shown conceptually in Figure 2 which includes the loops entirely contained on the trolley and those relying on signals from external components, transmitted to the trolley via the RF data links. The servo loops may be re-configured for different modes of operation, and in general this is done by the onboard microprocessor in response to commands via the ethernet link. A dedicated software tool running on the trolley micro allows the user to adjust digipots in order to tune certain rarely-adjusted servo parameters. The principal servo loops are described in the subsections below.

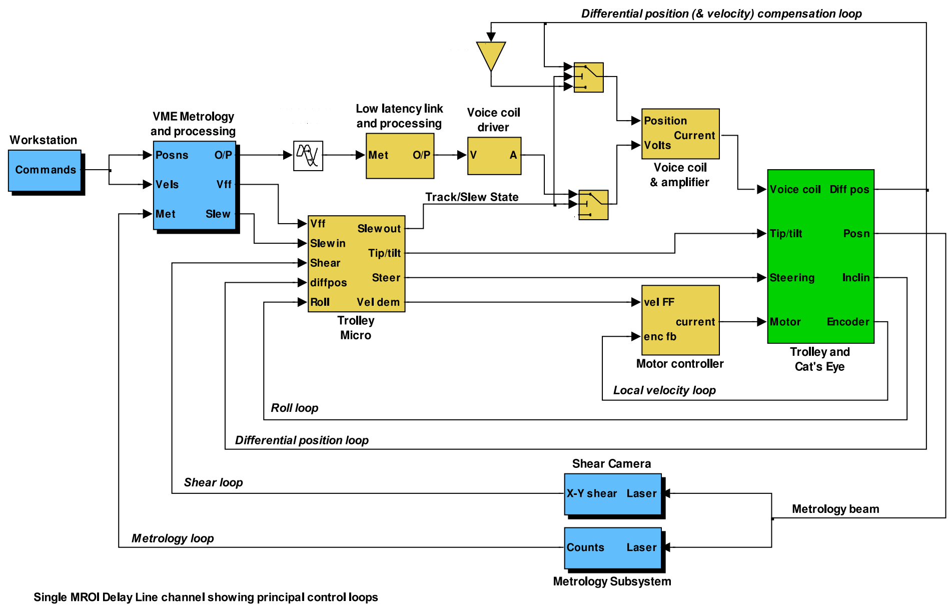

Figure 2. Conceptual diagram of the delay line servo loops. Blocks with drop-shadows are individual subsystems not on the trolley. Not all links between subsystems are shown, only those which are relevant to the servo loops.

4.1 The Metrology Loop

The purpose of the metrology system is to measure the path length between the metrology bench and the cat's eye on board the delay line trolley. The Metrology Loop uses this measurement to position the cat's eye so that the required optical delay is produced and maintained with sufficiently low error.

The metrology system, in combination with the VME system, measures the position of the cat's eye with respect to the laser interferometer and produces an error signal by comparing it with the current demanded position (interpolated from positions sent from the workstation). The magnitude of the error determines which mode the Metrology Loop operates in: Track Mode or Slew Mode. If the error signal is larger than a pre-defined amount then it is assumed that the trolley is sufficiently out of position that it must be slewed to the commanded position and hence Slew Mode is entered; if the error is smaller, then the trolley is in Track Mode. Operation of each of these modes is described in Sec. 4.4.

4.1.1 The Differential Position Loop

This loop is a modified form of the cat's eye local loop discussed later. Its purpose is two-fold:

1. To modify the dynamics of the cat's eye correction in the Metrology Loop Track Mode.
2. To apply small corrections to the trolley velocity so that the carriage remains directly under the cat's eye.

The differential position sensor is a high bandwidth inductive displacement transducer with an analogue output signal which is proportional to the displacement between the cat's eye and the carriage. To modify the dynamics of the cat's eye the signal is used in a feedback loop such that the apparent natural frequency of the cat's eye is very low, approximately 0.5 Hz. This substantially improves the passive rejection to trolley disturbances at low frequency. A velocity term is also derived from the differential sensor signal and used to compensate for the damping effect of the voice coil magnetic field. This improves rejection to trolley disturbances at high frequency. Both of these feedback compensation terms are implemented in analogue processing on the cat's eye voice coil amplifier.

To correct the carriage position with respect to the cat's eye the signal from the differential position sensor is digitized by the trolley microprocessor, scaled and summed with the velocity demand received from the VME system. Thus small corrections to velocity are achieved which reduce any differential position error.

4.1.2 The Cat's Eye Local Loop

The cat's eye local loop is in force when the trolley is in Slew Mode. Its purpose is to hold the cat's eye firmly with respect to the carriage while the trolley is moved under direct command by the VME system (or workstation). The differential sensor signal is used for feedback purposes in the same way as described for the Differential Position Loop but with much higher loop gain to provide the necessary holding force.

4.2 The Shear Loop (Secondary Tip/tilt)

The action of the cat's eye is to return a beam parallel to the input beam regardless of small tilts of the trolley with respect to the input beam. However, if the cat's eye primary is laterally displaced from the input beam the separation between the return beam and the input beam changes. This lateral deviation of the return beam is termed "shear". The purpose of the Shear Loop is to maintain the metrology beam (and hence the science beam) returned from the cat's eye to within 1mm* of the nominal beam axis in the presence of lateral deviations of the delay line pipe of up to ±5mm. This is necessary so that the metrology system continues to work, and that the science beam remains unvignetted.

The metrology beam provides a convenient method for measuring the shear. A small fraction of the return metrology light is redirected via a beam splitter onto the shear sensor. The shear computer then calculates the offset of the centre of the beam from the nominal return position and sends correction signals to the trolley microprocessor. This controls the tip/tilt secondary mirror mounted in the cat's eye in such a way as to reduce any error between the beam centre and the nominal return position. The Shear Loop is a low frequency loop with a bandwidth of a few Hz and it is always closed.

4.3 The Roll Loop

There are only two degrees of freedom that are available to the trolley when it is constrained in the delay line pipe; piston (i.e. motion along the pipe) and roll (about the axis of the pipe). The roll angle of the trolley must be closely controlled for two reasons:

1. The axes of the secondary tip/tilt stage must remain in reasonable alignment to the beam shear sensor.
2. The trolley wheels must follow relatively narrow track zones to cross the pipe joints where the internal surfaces are aligned.

The roll servo loop is entirely contained on the trolley. An electronic tilt sensor measures the roll angle of the trolley. This is digitised and read by the onboard microprocessor which implements a simple algorithm that, taking into account the direction of travel of the trolley, adjusts the angle of the un-powered rear wheel to correct the roll as the trolley travels along the pipe.

4.4 Control loop action

The VME system decides on the basis of the current system mode (set by the workstation) and the position error whether the trolley should be in Slew Mode or in Track Mode and instructs the trolley accordingly. The action of the control loops in these two modes is described in detail in the following sub-sections.

*A more relaxed requirement applies in Slew Mode, where we are only interested in maintaining a metrology signal.

4.4.1 Track Mode

In Track Mode the VME system determines the trolley velocity and also the correction required to the cat's eye position. The trolley velocity is sent over the network link but the cat's eye correction is sent over the low latency link. The control actions carried out in Track Mode are as follows:

- The workstation calculates trajectory information for a delay line and sends a set of velocity and position data every second to the VME system via the Ethernet. These data are the desired trajectory for times in the near future, sampled every tenth of a second.
- The VME system calculates the difference between the current cat's eye position (provided by the metrology system) and the desired position determined by interpolation of the trajectory information provided by the workstation. This "position error" is used to calculate a rate correction which is converted to an analogue voltage for transmission over the low latency communications link. The VME system also passes on interpolated velocity values to the trolley microprocessor over the network link to provide the velocity feed-forward function.
- To correct any deviation in the carriage velocity the voltage from the differential position sensor is digitised at 10 Hz sample rate by the trolley micro and combined with the velocity feed-forward term to modify the velocity command to the motor controller.
- To control the apparent spring rate of the cat's eye flexures (and thereby increase its isolation from the carriage in the axial direction) a small amount of positive position feedback from the differential position sensor is applied to the voice coil amplifier.
- To compensate for "drag" between the voice coil armature and magnet (caused by eddy current losses in the aluminium coil former) a small amount of velocity feedback derived from the differential position sensor is applied to the voice coil amplifier.
- For normal operations, the Shear Loop is constantly operating, ensuring correct beam separation.
- For normal operations, the trolley Roll Loop is constantly operating though with only small and very occasional corrections required.

An example of the tracking performance obtained with the prototype trolley is shown in Figure 3.

4.4.2 Slew Mode

In Slew Mode the cat's eye must be slaved or locked to the carriage to avoid large or uncontrolled motions. The carriage velocity is controlled by the VME system (or by the workstation, when using a special override facility). The control actions carried out in Slew Mode are as follows:

- The trolley microprocessor accepts a communication from the VME system to switch to Slew Mode and signals the trolley circuitry controlling the cat's eye. The velocity received from the VME system is passed directly to the trolley drive controller.
- The cat's eye local loop is engaged and the cat's eye command signal is effectively held at zero (corresponding to its centre of its travel between the mechanical limits). The cat's eye is held firmly upright as the trolley is moved.
- For normal operations, the Shear Loop is constantly operating, ensuring correct beam separation.
- For normal operations, the trolley Roll Loop is constantly operating though with only small occasional corrections being applied.
- The VME system determines an appropriate velocity and acceleration or deceleration based on the magnitude of the position error, i.e. the difference between the demanded trolley position and the current trolley position. When the position error is sufficiently low the VME system will command a switch to Track Mode.

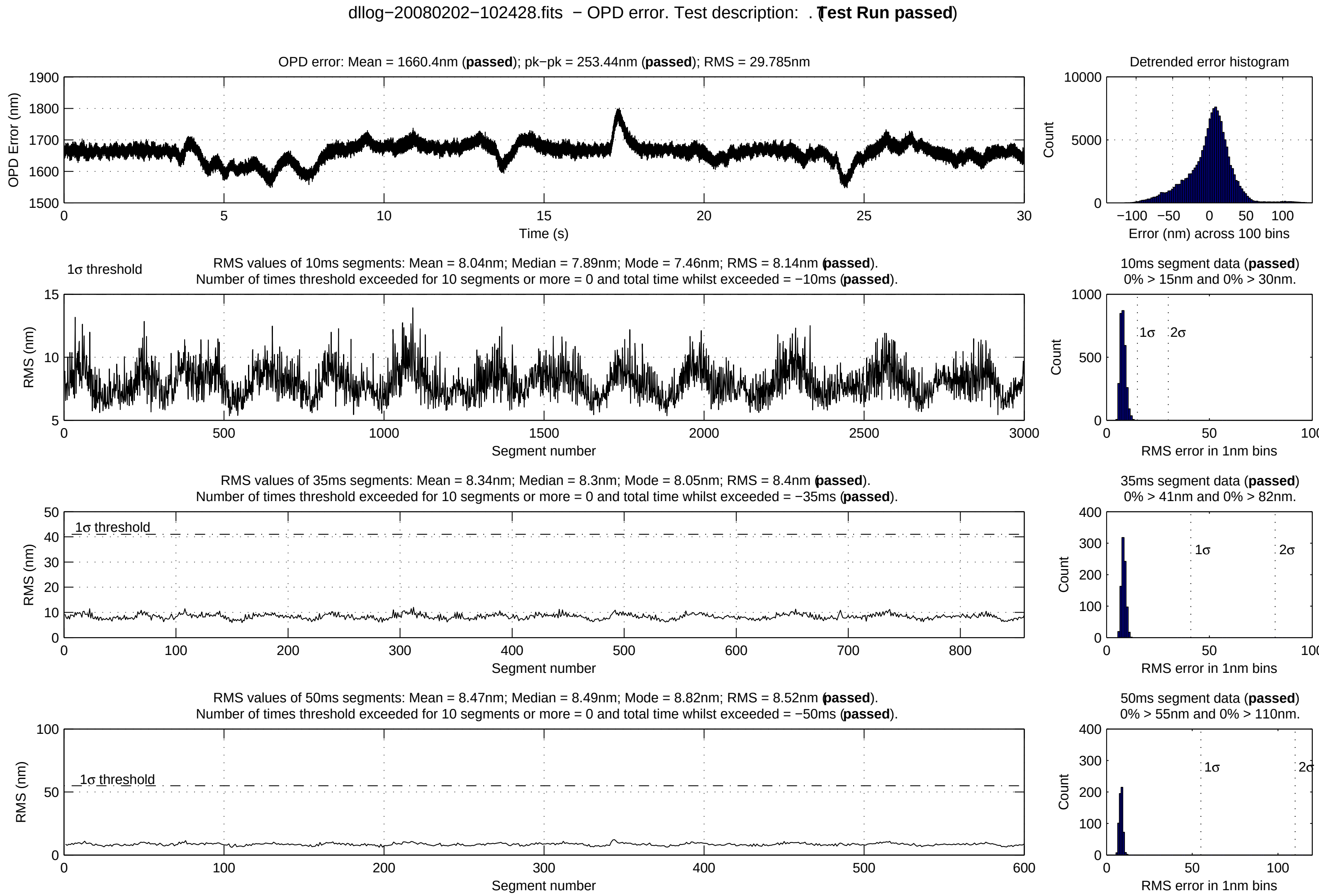

Figure 3. Plots demonstrating the OPD performance of the prototype trolley as obtained with the control system described in this paper. For the test shown, the delay line was commanded to follow a constant 1 mm/s velocity trajectory. The figure contains plots of (top left) the OPD error, (top right) a histogram of the de-trended OPD error, and for segment lengths of 10, 35 and 50 ms, rows consisting of (left) the sequence of segment RMS OPD error values, and (right) a histogram of the segment RMS values.

5. CONTROL SYSTEM

The control system is a distributed, event-driven system, comprising software running on the computers listed in Sec. 2. Multiple delay lines can be controlled using a graphical user interface on the workstation computer.

The actions of the various control computers are coordinated by means of a custom network messaging protocol (see Sec. 6). All delay line subsystems make use of a common C library, "dlmsg", which facilitates composing, transmitting, receiving and decoding delay line network messages. A telemetry server running on the workstation handles buffering and logging of status and telemetry messages (defined below). The telemetry server is implemented as an object which can be embedded in any application, using event-handling facilities provided by the free GLib library.

The control system architecture and associated messaging protocol (which are described in more detail below) were designed with the following aims in mind:

- Provide the capability to record all control signals (hardware and software), for debugging the prototype delay line
- Facilitate possible re-use of the architecture and/or code
- Use well-defined message protocols, and document these thoroughly
- Provide a flexible messaging system, that allows e.g. adding/changing signals with minimal knock-on effects

5.1 Platforms

The VME system is an x86 processor VME-bus system running the QNX Neutrino real-time operating system. We had previous experience with QNX and so were confident that it would deliver the sub-30-microsecond interrupt latency required. We plan to develop a version of the VME software that runs under Xenomai real-time Linux, which has been adopted as a standard by MRO. The other delay line control computers all run the GNU/Linux operating system (Linux kernel version 2.6). The trolley micro is a PC104-bus system with an ARM-compatible processor, the other Linux systems having standard Intel x86 architectures.

The delay line control code is written in ANSI C (C99). The software makes extensive use of GLib — the low-level core library that forms the basis of GTK+ and GNOME. GLib provides abstract data types such as hash tables and linked lists, as well as an event handling system and an object system.

6. CONTROL SYSTEM INFORMATION FLOW

The flow of information between the components of the control system is shown in Figure 4. Many of the signals are transmitted as messages over Ethernet; there are four categories of message:

1. Commands:
   Sent by the workstation to subsystems in response to user input, e.g. to change system mode
2. (Command) Data:
   Information needed in real-time to close the servo loops described in Sec. 4
3. Status (transmitted from subsystem to the workstation):
   - Subsystem state information
   - Delay line performance metrics
   - Information to display for the user
   - Command acknowledgements
4. Telemetry:
   Diagnostic information transmitted from subsystems to the workstation

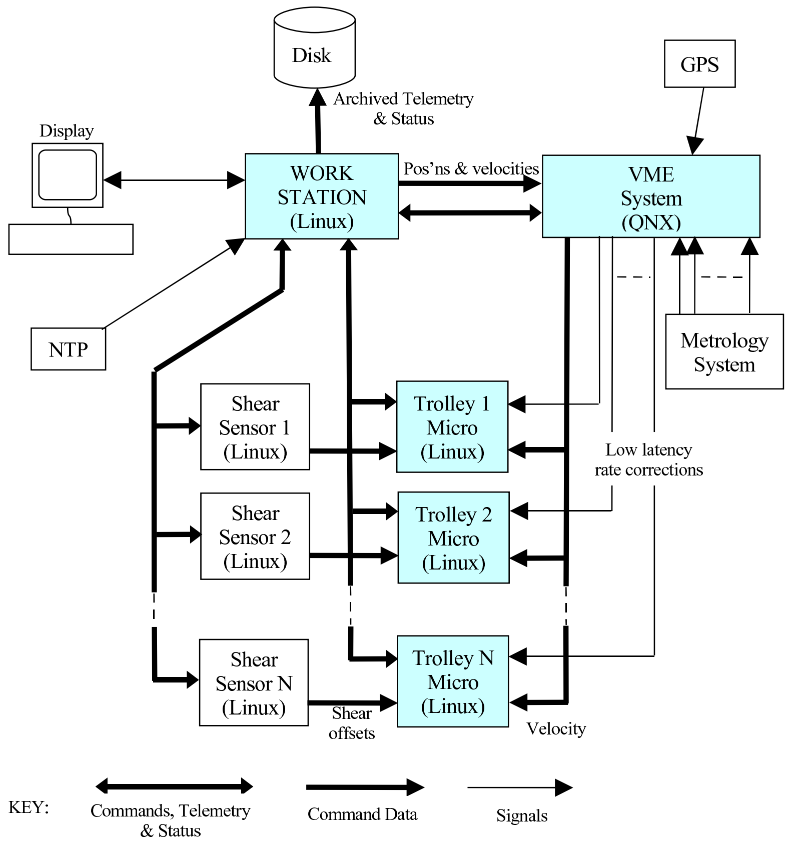

Figure 4. Information flow in the control system for the prototype delay line. In this diagram, "signals" are control signals transmitted via interfaces other than Ethernet.

The messaging protocol described below is summarised in Table 1. The workstation acts as a server, listening for connection attempts on a pre-arranged TCP/IP port. Each subsystem connects to the server, establishing its own socket connection which it subsequently uses to transmit status and telemetry to the workstation. The workstation uses the same connection to send commands in the opposite direction. A separate socket connection is made for each command data stream.

Table 1. Summary of delay line messaging protocols. Note that copies of command data are transmitted to the workstation by the originating subsystem, as telemetry, in order to log the data. Commands are logged directly by the workstation.

Msg. type	Source	Destination	Msg. Rate /Hz	Use of content
Status	TRLYn, VME, SHEARn	WKSTN	10–30	System-level control, displayed, logged
Telemetry	All	WKSTN	1–30	Logged
Command	WKSTN	VME, SHEARn, TRLYn	Async.	Obey command
Command Data	WKSTN, VME, SHEARn	VME, SHEARn, TRLYn	10-200	Close loop

6.1 Message Formats

Inter-subsystem messages are encoded using the locally-written "Serialise" library , and transmitted using sockets over TCP/IP. The Serialise library implements a compact yet flexible binary representation. Serialise implements messages that are automatically self-describing in the sense that the receiving software can deduce the contained data types/lengths and their order/grouping from just the message itself.

We have defined formats for command, command data, telemetry and status messages that add another layer of self-description which labels each data item and, for telemetry and status, provides meta-data such as the units and timing of each measurement.

6.2 Commands & Command Data

We have distinguished between commands and command data (henceforth we will refer to command data as "data" where this is unambiguous): the former are sent from the workstation to the delay line subsystems, usually asynchronously. The latter (e.g. shear offsets) are used to close servo loops in the system (see Sec. 4). Typically command data are transmitted at a fixed rate from one specific subsystem to another. The relevant servo loop is activated or deactivated in response to commands from the workstation to the subsystem receiving the data; typically the data is always sent whether the system state requires it or not.

Command acknowledgements are incorporated into the status messages transmitted to the workstation. There are no explicit acknowledgements for data messages.

Commands and their corresponding acknowledgements are logged in the same file as telemetry and status information — see Sec. 7. Command data are logged by sending a copy of the data from the originating subsystem to the workstation as telemetry.

6.3 Telemetry & Status

We define telemetry to consist of "measurements" made primarily for diagnosing problems with the delay lines. We treat measurements from all physical sensors in the delay line system as potential telemetry data. Telemetry can also include values of variables within the delay line control software.

Telemetry is digitised and buffered locally before being transmitted (in "chunks" at intervals of 0.033 to 1 s, chosen to be a convenient interval for the transmitting subsystem) over the Ethernet to the workstation, where it is buffered prior to optional archiving. Each telemetry chunk may contain many data samples. Multiple chunks of telemetry (each containing a different signal) are concatenated into a single network message.

Each status message contains a heterogeneous set of numerical and boolean values. In the simplest variation of the message format, these have a common timestamp. However, it is permissible to concatenate several status units (each of which can contain multiple items) in a single message, each unit having an independent timestamp. We define "status" to consist of information used by the control system and by the user in controlling the delay lines. By this definition status includes:

- Information (mostly boolean) about the state of a subsystem, which typically changes in response to commands.
- Command acknowledgments, to provide near-immediate feedback on whether each command was accepted.
- Information about whether the delay line is performing acceptably (e.g. OPD jitter)
- Information that should be displayed in real time (e.g. trolley position)

Status messages are sent at regular intervals (at a rate of 10 or 30 Hz). The message format allows these to contain arbitrary boolean and numerical status items.

Special components of each status message indicate whether any commands have been received since the previous status message was issued, and for each such command, whether the command and any associated parameters are valid, and whether the command will be acted on. In this way the status message incorporates command acknowledgement(s). Any subsequent changes of state in response to a command will be indicated by (regular) status messages, i.e. changes in the boolean status items.

To determine whether a command has been obeyed, certain agreed status items must be sent by each subsystem. Subsystems may transmit any further status items, and any telemetry streams; these will all be handled transparently by the workstation without changes to code or configuration files.

7. LOG FILE FORMAT

The log file format written by the workstation telemetry server is based on FITS[3] binary tables. Matlab (used to implement the telemetry analysis software) has a built-in capability to read these. They can also be read into C, Python and IDL programs using third-party libraries. FITS binary tables are part of the core FITS standard (which is in widespread use in astronomy), and provide a framework (meta-format) for storing heterogeneous data in a compact binary form.

FITS files consist of any number of header/data units (HDUs), each of which represents an image, binary table, or ASCII table, together with associated metadata. Headers are always encoded in ASCII, and contain a set of keywords and associated values. Certain keywords have special meanings according to the FITS standard (for example they describe the structure of the data part of the HDU), but other application-specific keywords can be included. The delay line format is based on a set of "conventions" (in FITS parlance) which define the keywords and binary table columns present in the tables of a delay line log file.

Telemetry, status and command logs for all active trolleys are saved to the same FITS file. Data from different delay line subsystems are written to independent binary tables, to allow for the possibility of (dis)connections to/from the telemetry server. Multiple recordings (i.e. data timespans) can be accommodated in a single file, but normally separate files are used.

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