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A new control system hardware architecture for the Hobby-Eberly Telescope[*] prime focus instrument package

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ABSTRACT

The Hobby-Eberly Telescope (HET) will be undergoing a major upgrade as a precursor to the HET Dark Energy Experiment (HETDEX[‡]). As part of this upgrade, the Prime Focus Instrument Package (PFIP) will be replaced with a new design that supports the HETDEX requirements along with the existing suite of instruments and anticipated future additions. This paper describes the new PFIP control system hardware plus the physical constraints and other considerations driving its design.

Because of its location at the top end of the telescope, the new PFIP is essentially a stand-alone remote automation island containing over a dozen subsystems. Within the PFIP, motion controllers and modular IO systems are interconnected using a local Controller Area Network (CAN) bus and the CANOpen messaging protocol. CCD cameras that are equipped only with USB 2.0 interfaces are connected to a local Ethernet network via small microcontroller boards running embedded Linux. Links to ground-level systems pass through a 100 m cable bundle and use Ethernet over fiber optic cable exclusively; communications are either direct or through Ethernet/CAN gateways that pass CANOpen messages transparently. All of the control system hardware components are commercially available, designed for rugged industrial applications, and rated for extended temperature operation down to -10 °C.

Keywords: Hobby-Eberly Telescope, HET, HETDEX, PFIP, control system

1. INTRODUCTION

1.1 The Hobby-Eberly Telescope

The HET is a large, cost-effective telescope located at the McDonald Observatory in West Texas.[1] Its 11 m spherical primary mirror is hexagonally shaped and is made up of 91 identical 1 m hexagonal segments. Currently, the usable aperture of the primary is 9.2 m and the field of view on the sky is 4 arcmin. Both of these parameters are limited by the existing optics used to correct for spherical aberrations.

Unlike more expensive telescope designs, the HET moves in azimuth only and is fixed in altitude at an angle of 55° from the horizon. During observations, the telescope structure and primary mirror are held stationary while a tracker assembly at the top end of the telescope moves and manipulates the Prime Focus Instrument Package (PFIP). The PFIP houses the spherical aberration corrector and a variety of mechanisms, instrumentation and metrology equipment. Motion along six axes is necessary in order to track an astronomical object, keep the corrector's optical axis normal to and on the focal surface of the primary mirror and compensate for the rotating field of view.

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[*] The Hobby-Eberly Telescope is operated by McDonald Observatory on behalf of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München,and Georg-August-Universität, Göttingen

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As originally conceived, the HET is a spectroscopic survey telescope. The current suite of operating science instruments consists of the Marcario Low Resolution Spectrograph (LRS), which is mounted on the PFIP, plus the Medium Resolution Spectrograph (MRS) and High Resolution Spectrograph (HRS), which are remotely located and fed by optical fibers from the PFIP. [2]

1.2 The HETDEX Project

Significant upgrades to the HET are currently in the design and prototyping phases. The upgrades are motivated largely by the requirements of the HET Dark Energy Experiment (HETDEX),[3,4] but will also support the current suite of instruments plus anticipated future additions.

The HETDEX Project consists of three elements:

- The HET wide field upgrade (WFU)[5-7]
- Design, fabrication and deployment of the Visible Integral-Field Replicable Unit Spectrograph (VIRUS)[8-12]
- Execution of the HET Dark Energy Experiment survey using VIRUS on HET

The wide field upgrade includes:

- A wide field corrector (WFC) that will increase the field of view from 4 arcmin to 22 arcmin and the usable aperture from 9.2 m to 10 m
- A new and larger PFIP
- A new tracker with increased load carrying capabilities
- New telescope control software and other improvements to the telescope infrastructure

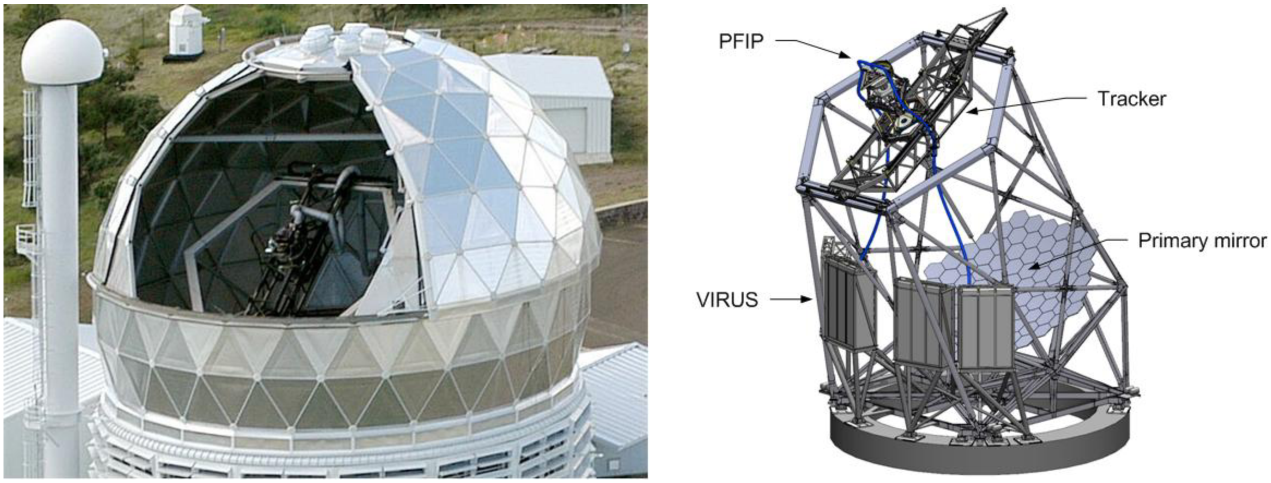
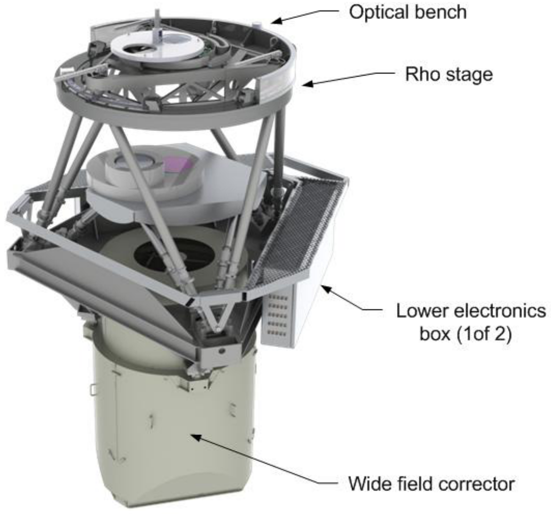


Figure 1. In the photograph at left, the existing PFIP and tracker are visible through the opening in the dome of the HET. The concept drawing at right shows the new PFIP and tracker and also illustrates one of several approaches for mounting VIRUS enclosures on the telescope superstructure.

1.3 The new PFIP design

Figure 2 shows the overall structure of the new PFIP. The optical bench assembly rotates during tracking in order to compensate for rotation of the field of view. The rho stage provides the rotating motion and is essentially a dividing line between the PFIP subsystems that move with the optical bench and those that remain stationary. There are two lower electronics boxes, one of which is visible in the figure. These boxes are the primary enclosures for the PFIP control system hardware and also house the facility calibration unit (FCU).



Subsystems located above the rho stage:
- **Guiding & wavefront sensing probes**
- **Shutter**
- **Intrument changer**
- **VIRUS IFU dithering mechanism**
- **CCD cameras**
    - **- Probe cameras (4)**
    - **- Acquisition camera**
    - **- Fiber bundle camera**

Stationary subsystems located below the rho stage:
- **Atmospheric dispersion corrector (ADC)**
- **Exit window assembly (EXWA)**
- **Moving baffle (MB)**
- **Wide field corrector (WFC)**
- **Entrance window assembly (ENWA)**
- **Tip/tilt camera (TTCAM)**
- **Distance measuring interferometers (DMI) (3)**
- **Facility calibration unit (FCU)**

Figure 2. Structural overview and subsystem list for the new PFIP.

Logically, the new PFIP can be broken down into about a dozen subsystems that can be further divided into two groups depending on location relative to the rho stage. Not shown in the figure are three smaller upper electronics boxes that are mounted just below the rho stage. One houses control system hardware associated with the subsystems located above the rho stage, the second houses CCD cameras that are fiber fed and the third is reserved for future expansion. The primary benefit of the upper electronics boxes is the substantial reduction in the number of cables and hoses routed across the plane of rotation.

The PFIP subsystems contain approximately 30 motion axes. Over half of them will be motorized and will require smooth, precise motion over a range of speeds. Other electrical/electronic hardware requirements include analog and digital I/O, position encoder interfaces, solenoid valves for pneumatic actuators, digital communications links and DC power sources and distribution. Additional requirements driven by anticipated future additions to the instrument suite will be similar in scope. Finally, the PFIP requires facilities support in the form of AC power, instrument/pneumatic air, coolant and communications channels. Because the PFIP is located at the top of a large telescope that rotates, all connections to it must pass through a 100 m long cable wrap.

2. PFIP CONTROL SYSTEM HARDWARE

2.1 Design goals and constraints

Most of the subsystems in the new PFIP are essential for normal operation of the HET and will become part of its future infrastructure. Although the PFIP is a completely new design, many of the design goals and constraints for the control system hardware were driven by experience with the existing systems. For the purpose of this discussion, we make a distinction between design goals, which are guidelines to be followed whenever possible, and constraints, which are hard and fast and must be adhered to.

Design goals

- Define a hardware architecture and a standard set of components to be used throughout the PFIP
- Run all supervisory control functions on ground-level computers that use the Linux operating system
- Minimize the number of cables and hoses connecting ground-level systems to the PFIP and use fiber optic cable for all communications links
- Use Ethernet sockets and ASCII protocols for communicating with the PFIP
- Use commercial off-the-shelf (COTS) hardware that is:
  - modular
  - designed for industrial environments
  - intended to have a long product life cycle
- Use a small number of suppliers that offer:
  - a range of products meeting our requirements
  - easily accessible technical support staff
  - shipping from stock
- Minimize required spare parts
- Build small prototypes to facilitate:
  - early hardware evaluation and testing
  - software development and testing on the real hardware

Hardware constraints

- Guaranteed operation at low temperatures down to -10 C
- Absolute position encoding on all motion axes
- No stray light generation near the optical path
- No significant heat generation near the optical path
- No point-to-point RS232 serial communications
- No stepper motors

For many of the PFIP subsystems, the amount of available space is very limited. This leads to an additional broad constraint requiring small, lightweight components and, in some cases, a high degree of miniaturization in the design of mechanisms and their associated electronics.

2.2 Hardware architecture

Figure 3 illustrates the overall architecture of the PFIP control system hardware. Within the PFIP, motion controllers and modular IO systems are interconnected by a Controller Area Network (CAN) bus using the CANOpen messaging protocol. Because existing USB-over-fiber extenders have been problematic, small microcontroller boards running an embedded Linux operating system are used as Ethernet-USB gateways for CCD cameras that have USB interfaces only. Links to ground-level systems pass through a 100 m cable bundle and use Ethernet over fiber optic cable exclusively. All communications between ground-level systems and PFIP subsystems are either point-to-point via Ethernet or go through Ethernet/CAN gateways that pass CANOpen messages transparently.

Of the approximately 30 motion axes in the PFIP, 15 will be motorized and will require smooth, precise motion over a range of speeds, including very low speeds. A few examples are:

- Smoothly and accurately follow a velocity trajectory, e.g. shutter control
- Move to an absolute position and hold accurately, e.g. guiding and wavefront sensing probes during normal tracking
- Smoothly and accurately follow a multi-axis position and velocity trajectory, e.g. guiding and wavefront sensing probes during nonsidereal tracking

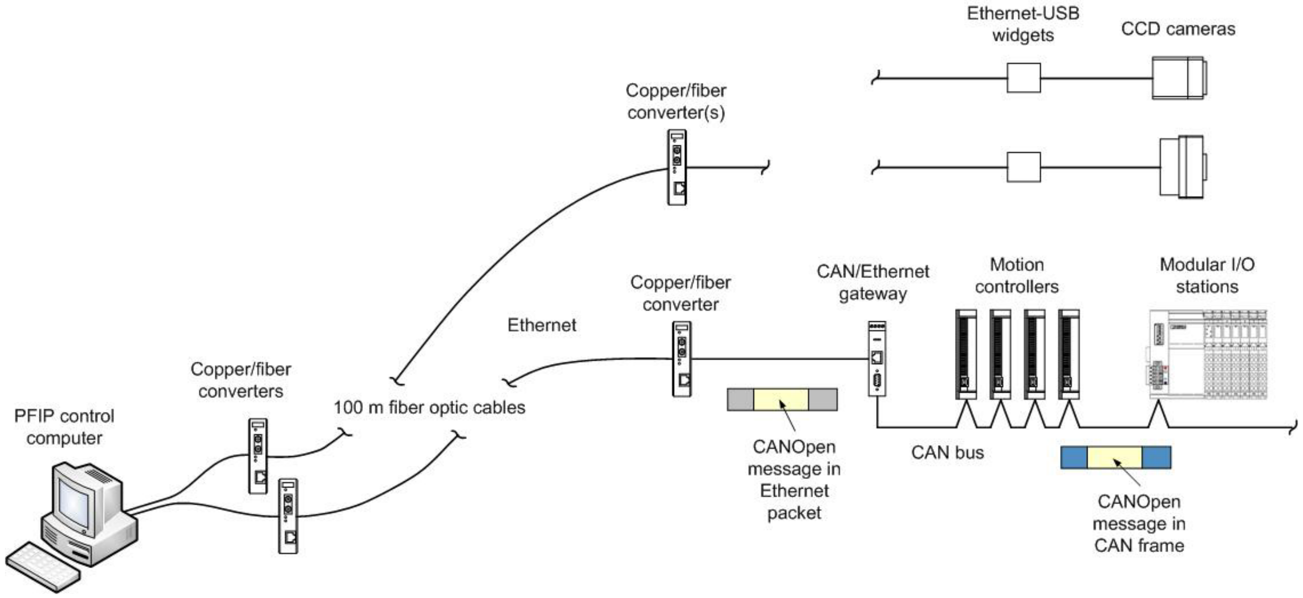


Figure 3. Overall architecture of the PFIP control system hardware.

The motors used in the PFIP subsystems are Maxon EC series brushless DC (BLDC) servomotors, which can be configured with optional gearheads, magnetic incremental encoders and electrically operated brakes as required. In order to achieve smooth motion at low speeds, sinusoidal commutation is necessary. Consequently, an optional incremental encoder must be used along with the standard Hall effect sensors already built into the motors. When mounted on the motors, the incremental encoders also provide position feedback to the control loops in the motion controllers.

All of the motion controllers are Maxon EPOS2 50/5 Positioning Control Units. In addition to providing closed loop control of current, velocity and position, these controllers have an interpolated motion mode that enables following a programmed multi-axis trajectory. They also have analog and digital I/O that are accessible via the CAN/CANOpen interface and a programmable capability to automatically respond to some of the digital inputs, for example positive/negative limits, home position, quick stop and drive enable/disable. Even though it might be slightly less expensive to use a mix of controllers, our intention is to use a single part number throughout the PFIP and to stock a single type of spare.

Other I/O, including interfaces for position encoders and temperature sensors in addition to generic digital and analog I/O, are handled by modules from the Phoenix Contact Inline Modular I/O product line. Flexible I/O stations are built up by adding one “slice” at a time with each slice containing some specialized additional functionality. In the PFIP application, each station includes a CAN/CANOpen bus coupler that enables all of the I/O to be accessible directly through the CAN bus or through an Ethernet-CAN gateway. The gateway is an IXXAT CAN@net II/Generic TCP/IP Gateway that uses a simple ASCII protocol for configuration and for passing CANOpen messages in both directions.

In this application, the hardware devices attached to the CAN bus take direction from the PFIP Control Computer (PCC) in a master/slave arrangement. Considering a multi-axis move as an example, the PCC would configure several motion controllers for the desired motion, and then trigger them simultaneously by sending a single CANOpen message. The motion would then be carried out independently by the controllers until completed or interrupted. In preliminary testing, the measured round trip time for a message from the PCC to reach a device in the PFIP and for a response to return is about 6 ms using 100 Mbps Ethernet and 1Mbps CAN bus speeds. This is comparable to the scan or loop time for a programmable logic controller, i.e. fast enough for near real-time performance. Consequently, we are not currently using a real-time or deterministic implementation of Ethernet for the links to the PFIP, although this could be changed later if necessary.

The Ethernet-USB widgets are small embedded ARM single board computers from Technologic Systems. The boards are industrial grade, wide temperature range products that have 100 or 1000 Mbps Ethernet interfaces plus USB2.0 ports, and they boot to Linux in less than 3 seconds. The manufacturer provides a Linux kernel for the ARM core processor that includes drivers for the on-board I/O, and they also provide a cross-platform toolchain for developing user applications. Custom driver and interface software developed by McDonald Observatory will be used to obtain images from the CCD cameras and transfer them to ground-level computers through either dedicated Ethernet links or industrial grade switches. This software is currently functional and is undergoing testing and characterization with the actual cameras. Using a widget with 100 Mbps Ethernet and USB 2.0, preliminary testing indicates that the image transfer time is limited by the cameras.

The absolute position encoders used in the PFIP subsystems have SSI interfaces with Gray coded outputs, and are accessed via SSI interface modules in the I/O stations. The SSI interface modules can provide 5 VDC power for the attached encoders, but 24 VDC encoders may also be used at the expense of additional space and wiring. Position encoders with CAN/CANOpen interfaces or with 0-10 VDC analog outputs can also be accommodated. The latter can be read through the analog inputs on the motion controllers or through analog input modules in the I/O stations. The primary constraint affecting the choice of encoders is the amount of available space. In the guide probe and wavefront sensing subsystems, for example, we are currently using a Hengstler absolute rotary encoder that the manufacturer claims is the smallest currently available.

In general, the PFIP motion control systems and the I/O stations operate from 24 VDC power sources. For larger inertial loads like the shutter, 48 VDC is available and is compatible with the EPOS2 50/5 controllers. For subsystems located above the rho stage, we are distributing 24 VDC power from an enclosure several meters away because of space and cabling limitations.

All of the hardware components described here are guaranteed to operate at low temperatures down to -10 C or better, which complies with the specifications for the PFIP and HET. Both Maxon and Phoenix Contact offer a broad range of products that meet these temperature requirements and are designed for levels of quality, reliability and ruggedness required for industrial automation systems. All items selected for use in the PFIP are either stocked in the United States or readily available from the manufacturer within a reasonable delivery time, and all of the suppliers provide technical support from locations in the United States.

Finally, there is a great degree of flexibility inherent in this overall architecture. It is very easy to make significant changes by simply adding or deleting motion controllers, I/O slices, Ethernet-USB widgets or power supplies. The components are sufficiently small and lightweight that it is possible to include spares in the initial design for use as plug-and-go replacements or for future expansion needs. By using a small number of standardized hardware components for all subsystems, we are also minimizing the number of spares that will need to be purchased and kept on hand at the observatory.

2.3 CAN/CANOpen networking

The decision to use the Controller Area Network (CAN)[13-15] bus as a local network within the PFIP was driven by our selection of the Maxon motion controllers and the availability of a CANOpen bus coupler for the Phoenix Contact modular I/O. In addition, the availability of an Ethernet-CAN gateway that uses a simple ASCII protocol over Ethernet made it possible to construct an overall communications architecture that was consistent with our design goals.

CAN is a robust, 2-wire, differentially driven, serial bus that is well known for its use as a network in automobiles. Its first applications were in textile production machinery, and it is now found in a wide range of applications including ships, trains, medical equipment, elevators, industrial machinery, factory automation, and telescopes. Some of its most important characteristics are:

- High speeds up to 1Mbps
- Near real-time performance
- Collision avoidance through the use of prioritized arbitration
- Error detection and notification
- Automatic retransmission
- Detection and deactivation of defective nodes
- Up to 128 nodes per bus

CAN includes a low-level protocol or messaging scheme using frames that carry 0-8 bytes of data as a payload. This small frame size, when combined with collision avoidance, greatly increases the ability of the network to transfer information in embedded control applications that do not require moving large blocks of data.

CANOpen[14,15] is a higher level protocol that is used on top of the CAN protocol, i.e. CANOpen messages become the data payload in CAN frames. In particular, CANOpen provides mechanisms for:

- Detecting and starting up CAN nodes (CAN controllers in devices on the bus)
- Configuring and operating devices
- Reading/writing single data items in expedited messages
- Transmission of multiple data items in a single 8-byte message
- Transmission of data blocks longer than 8 bytes using segmented messaging

CANOpen also provides standardized device "profiles" that define the data and messages used by specific categories of devices such as motion controllers, position encoders and I/O modules.[15] Each device contains a well-defined "object dictionary", essentially a database or register file, that holds the device's identifying information, configuration parameters and data. Each entry is addressed by a 16-bit index and, in the case of entries with multiple data fields, by an additional 8-bit subindex. Independent of the type of device, the information in the object dictionary is accessible using a small set of standardized CANOpen message types.

CANOpen messaging is fairly straightforward, and the object dictionaries are consistent in structure and well documented. For a given device, once an application programming interface has been developed (or is obtained from the manufacturer), the software development effort can be focused on higher level tasks such as configuring devices, reading and writing data, checking status and handling errors.

2.4 Early prototyping and testing

We have constructed a number of small-scale prototypes in order to evaluate and test hardware in configurations that are as realistic as possible. As an example, Figure 4 shows a bench test system that was built for evaluating shutter and guide probe motion concepts. The shutter test bed included a dummy load that was dynamically equivalent to a larger and much thinner half-disk used in a rotating shutter design concept. The guide probe test bed included a rotary absolute position encoder, and was later equipped with magnetic limit sensors.

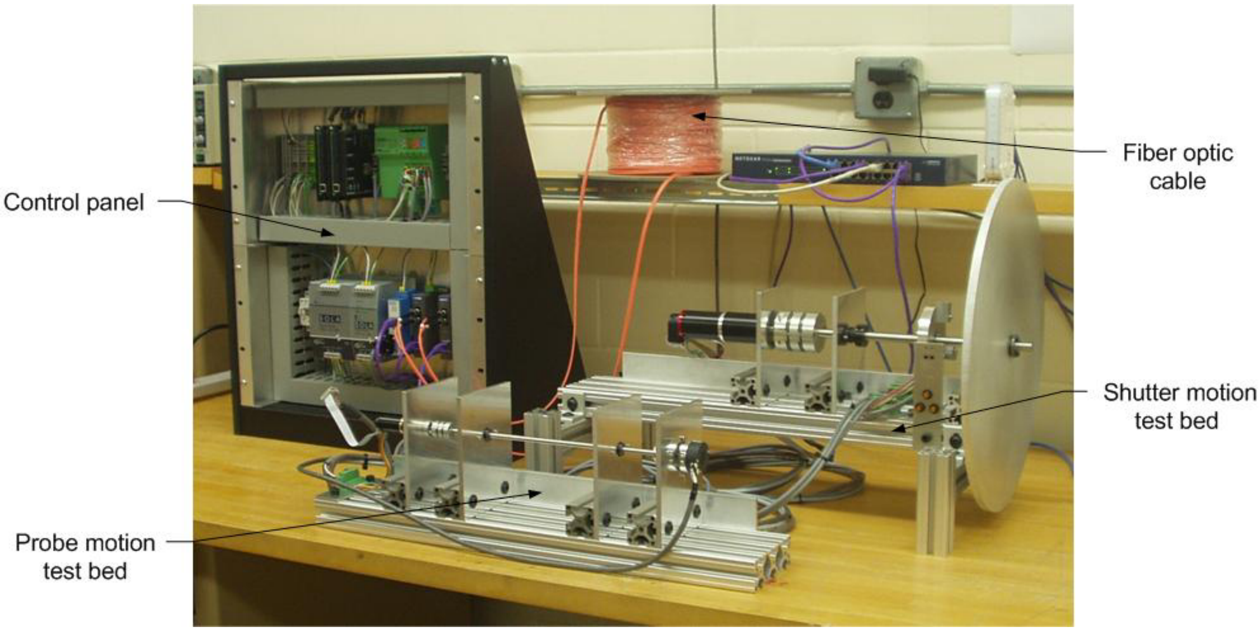


Figure 4. Motion control and communications bench test system.

Shown on the left in Figure 4, and in more detail in Figure 5, is a multi-axis control panel containing motion controllers, an I/O station, Ethernet copper/fiber media converters, a CAN-Ethernet gateway and DC power supplies. To closely approximate the configuration at the telescope, all communications to and from the control panel pass through a 100 m spool of fiber optic cable. This particular set of hardware has been used almost continuously for software development and testing for the past year.

The right hand side of Figure 5 shows a small two-axis test stand used for software development and also for testing and characterizing prototypes of mechanical mechanisms. Given the modularity of the motion control and I/O station components, these test stands are easily expanded to include additional motion axes, position encoder interfaces and I/O as required.

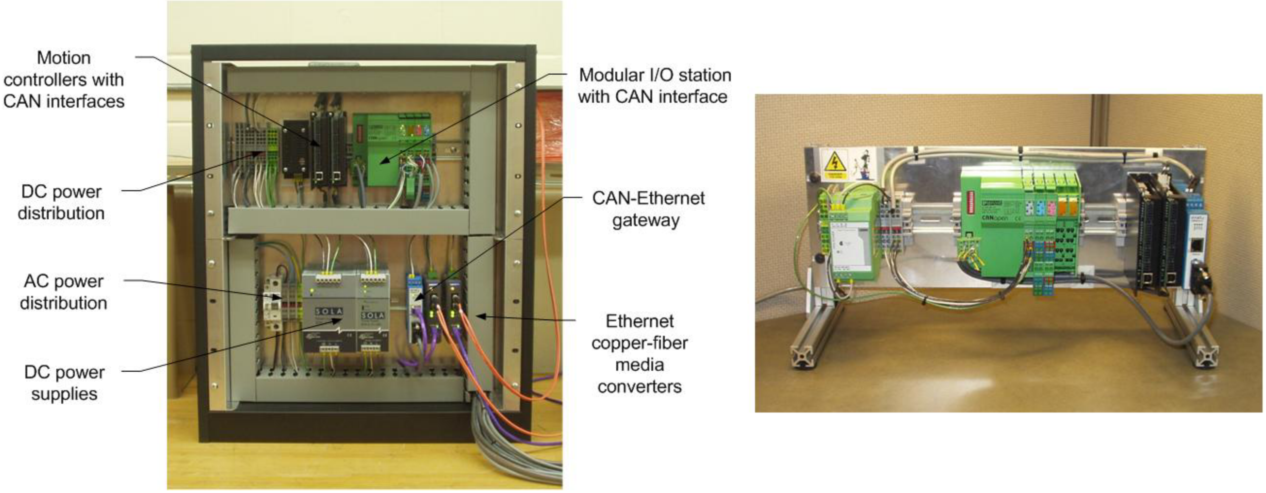


Figure 5. At left, test system control panel with components identified. At right, a small two-axis test stand with DC power supply, I/O station, motion controllers and CAN-Ethernet gateway

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To configure and operate individual motion controllers, Maxon provides a free software package, EPOS Studio, that runs on a Windows PC connected to the motion controller through a USB cable. This software provides access to the CANOpen object dictionary in the controller and also provides capabilities for control loop tuning, data logging and charting. Although we anticipated a need for simulations to optimize the control loops for various loads, the autotuning capabilities included in the Maxon software have met our needs to date.

Early on, we were able to configure and operate the motion controllers through a USB-CAN gateway module using custom Python scripts along with a Python wrapper and Windows DLL provided by the manufacturer, ESD Electronics. Similarly, Python scripts and sockets programming were used with the Ethernet-CAN gateway from IXXAT. In both cases, the primary function of the scripts was to assemble properly structured CANOpen messages and pass them to either DLL or socket functions. In the process of developing the scripts, a great deal was learned about CANOpen messaging that proved valuable to later software development efforts.

3. SUMMARY

A control system hardware architecture has been defined for the Hobby-Eberly Telescope's new Prime Focus Instrument Package. In this architecture, the PFIP is treated as a stand-alone remote automation island, and ground-level systems communicate with it via Ethernet over 100 m fiber optic cables. An added benefit of this configuration is that it permits the new PFIP to be completely assembled and tested as a unit on the ground before it is lifted into place on the telescope.

The new PFIP control system consists of modular components that are designed for rugged, wide temperature range, industrial applications. A high degree of flexibility has been incorporated into the design in order to make changes, repairs and future expansion as easy as possible.

Small-scale prototypes and test beds have been constructed in order to evaluate and test electronic components and mechanical mechanisms in configurations that are as realistic as possible. These have also been used to facilitate software development and testing on the same hardware that will be used on the telescope.

PFIP assembly and testing are scheduled to be completed in the summer of 2011. On-site installation and commissioning will take place in the fall.

ACKNOWLEDGEMENTS

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