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Event: SPIE Astronomical Telescopes + Instrumentation, 2016, Edinburgh, United Kingdom

The instrument control software package for the Habitable-Zone Planet Finder Spectrometer

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ABSTRACT

We describe the Instrument Control Software (ICS) package that we have built for The Habitable-Zone Planet Finder (HPF) spectrometer. The ICS controls and monitors instrument subsystems, facilitates communication with the Hobby-Eberly Telescope facility, and provides user interfaces for observers and telescope operators. The backend is built around the asynchronous network software stack provided by the Python Twisted engine, and is linked to a suite of custom hardware communication protocols. This backend is accessed through Python-based command-line and PyQt graphical frontends. In this paper we describe several of the customized subsystem communication protocols that provide access to and help maintain the hardware systems that comprise HPF, and show how asynchronous communication benefits the numerous hardware components. We also discuss our Detector Control Subsystem, built as a set of custom Python wrappers around a C-library that provides native Linux access to the SIDECAR ASIC and Hawaii-2RG detector system used by HPF. HPF will be one of the first astronomical instruments on-sky to utilize this native Linux capability through the SIDECAR Acquisition Module (SAM) electronics. The ICS we have created is very flexible, and we are adapting it for NEID, NASA's Extreme Precision Doppler Spectrometer for the WIYN telescope; we will describe this adaptation, and describe the potential for use in other astronomical instruments.

Keywords: spectroscopy, instrumentation, instrument control software, Python, Habitable-zone Planet Finder, HPF

1. INTRODUCTION

Over the past two decades, precision spectroscopy at optical wavelengths has been used to discover hundreds of exoplanets orbiting nearby stars. These detections rely on measuring the Doppler radial-velocity (RV) shift induced on a star by a planet in a Keplerian orbit. Current precision-RV spectrometers, such as HARPS[1] and HIRES,[2] have achieved ~1 m/s or better RV stability on G- through early-M-type stars using spectra obtained at optical wavelengths. This precision, however, is insufficient for detecting Earth mass planets orbiting in the Habitable-zones (HZ)[3] of their stars, where planet temperatures would allow liquid water. To search for such planets, the next generation of planet-hunting spectrometers are following two different development paths.

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Software and Cyberinfrastructure for Astronomy IV, edited by Gianluca Chiozzi,
Juan C. Guzman, Proc. of SPIE Vol. 9913, 991338 · © 2016 SPIE
CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2233011

A suite of new near-infrared spectrometers (e.g., HPF,[4–6] Carmenes,[7] SPIRou,[8] IRD,[9] etc.) will provide RV precision of a few m/s at wavelengths from one to a few microns, where the flux of M-dwarf stars peaks in intensity; this RV precision will be sufficient to detect Earth-mass planets in the HZ of these cool, low-mass stars. Alternatively, new optical spectrometers such as NEID,[10] Espresso,[11] and EXPRES[12] will achieve RV precision of a few tens of cm/s, and target Earth mass planets orbiting G and K stars.

The Habitable-Zone Planet Finder (HPF)[4–6] is a near-infrared spectrometer being built to detect exoplanets around M-dwarfs. HPF will operate at the 10 m Hobby-Eberly Telescope at McDonald Observatory, where it will be installed in the basement spectrograph room, and fed via optical fiber from the telescope top-end fiber-head. The spectrometer is designed for long-term stability, with the objective of providing 1-3 m/s RV precision on bright M-dwarfs. HPF covers the bandpass from ∼830 nm – 1300 nm, with a spectral resolution of $R = \lambda/\Delta\lambda \sim 50,000$. The detector system uses a 1.7μm cutoff Hawaii-2RG HgCdTe detector, SIDECAR ASIC, and SAM control electronics purchased from Teledyne Imaging Sensors. Wavelength calibration is provided by a calibration fiber that illuminates the spectrometer parallel to the science fiber. The calibration fiber is fed by a calibration bench equipped with UNe and ThAr hollow-cathode lamps, as well as a custom laser frequency comb (LFC). To achieve exquisite environmental pressure and temperature stability, the HPF optics are enclosed in a custom vacuum chamber, and surrounded by a radiation shield.[13–15] The shield is maintained at 180 K using a passive LN2 system inside the cryostat and an array of actively controlled heater stations positioned on the shield surface.

To support the HPF hardware development effort we have created a custom Python based instrument control software package (ICS) which manages the individual hardware subsystems, facilitates communication between them, and provides user interfaces for interacting with HPF. In this paper we describe the conceptual design of the ICS (Section 2), demonstrate how it interfaces with hardware, and provide examples of software subsystems (Section 3). We also discuss the wrapper interface we have constructed to operate the detector system directly in Linux (Section 4). The ICS design is extremely flexible, and can easily be adapted to other instruments; Section 5 describes how we are adapting the software for use with the NEID spectrometer we are building for the 3.5 m WIYN telescope.

2. THE ICS CONCEPT AND STRUCTURE

The Hobby-Eberly Telescope does not rely on a unified development environment for instrument software, and so imposed very few constraints on the HPF software team, allowing us to construct a software control system from the ground up. We imposed a small number of constraints on our design: it should operate on an enterprise Linux environment, which combines a stable software base with long-term support; it should utilize modern, high-level programming languages; it should be modular and easily adaptable to new hardware subsystems, or even different instruments or observatories; and lastly, it should whenever practical, avoid heavy reliance on third party software packages outside of the core language.

The primary HPF ICS computer is a 12 core AMD Opteron 6000 series server class machine running the CentOS Linux 6.x operating system with the 2.6 kernel, and includes a 16 TB LSI hardware RAID6 storage array. This computer is connected to the various HPF hardware subsystems through a mix of Ethernet, USB, and RS-232 Serial connections. The system utilizes two GigE network cards, one connected to an internal network that communicates with network based hardware, and one which provides external access to our instrument integration laboratory or observatory environment.

The core components of the HPF ICS are written in Python 2.7, and utilize the Twisted[*] network engine to provide low-level, asynchronous messaging capabilities between subsystems. These components utilize object-oriented programming, and rely heavily on class inheritance from low-level Twisted protocols. Figure 1 shows a cartoon schematic of the ICS structure. Broadly, the heart of the ICS is a messaging server, implemented as a Twisted server protocol, that listens on a specified port on the HPF ICS computer. Subsystems, such as `Environment`, `Calibration`, `Fiber`, etc., are implemented as client protocols, and register with the server when they start-up. Each of these clients is responsible for managing a group of related hardware components. In this configuration, both the Command Line Interface (CLI) and Graphical User Interface (GUI) are implemented in

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[*] https://twistedmatrix.com

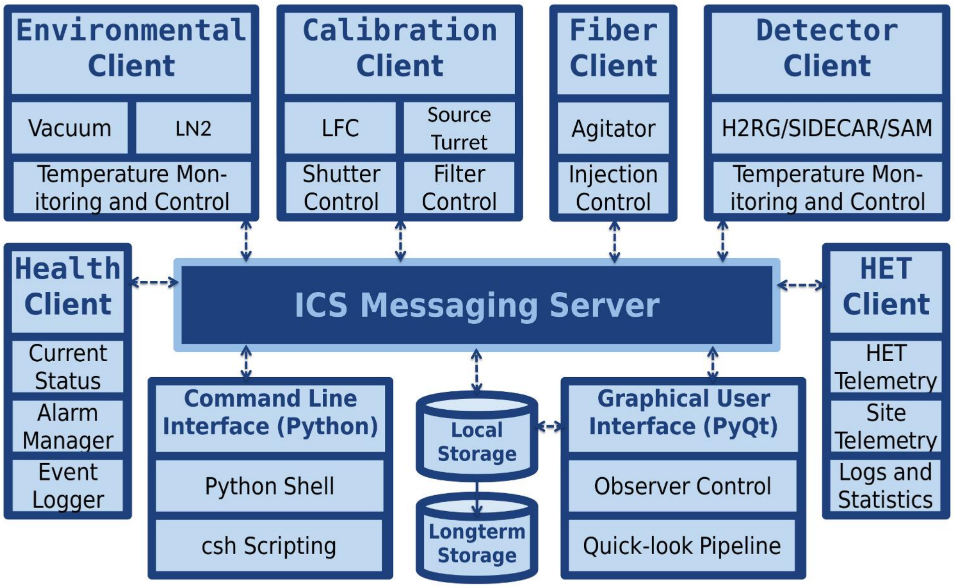

Figure 1. Block-diagram showing communication routing within the ICS. The Messaging Server acts as a switchboard, relaying commands and messages between Clients. Each Client is responsible for hardware or software subsystems, and can operate independently from the other Clients. The `Environmental`, `Calibration`, `Fiber`, and `Detector` clients control and maintain the HPF hardware subsystems. The `Health` and `HET` clients provide software subsystems necessary for HPF operation. The Command Line and Graphical User Interfaces are seen by the Messaging Server as normal clients. All clients inherit a common `client` class that defines the messaging protocol and maintains the low-level socket connections.

the ICS as clients, with the sole function of sending, receiving, and parsing messages. No core control functionality is integrated into either interface, rather they are purely abstraction layers on the ICS backend. At this time, no interactive web-based interface is anticipated, but some instrument health information is currently made available through non-interactive web pages for remote monitoring.

Messages routed between clients follow the HPF messaging protocol of "*SENDER SUBSYSTEM COMMAND*", where each field is white space separated and case-insensitive. *SENDER* is the registered name of the client dispatching the command or message. This facilitates routing of the asynchronous response, in the form of requested telemetry data or an operational message. *SUBSYSTEM* is an optional messaging parameter that specifies the client that *COMMAND* should be routed to. If *SUBSYSTEM* is not included in a message string, which is common for operations occurring through the CLI, the server uses a static look-up dictionary to identify the proper routing. *COMMAND* is the command being issued to a client or the response being returned. It can take the form of *PARAM:VALUE_1:VALUE_2:...VALUE_N* where *VALUE_N* represents arguments or information necessary to execute the command or understand the response in *PARAM*. This is often used when issuing responses in the form of error or warning messages to convey additional information about the current situation. For compact commands and telemetry, *COMMAND* is often transmitted in ASCII text. However, for transferring large data or whole Python objects, *COMMAND* can be transmitted as a serial bytestream through the `pickle` module.

This overall command structure facilitates both detailed routing and information transfer between client subsystems and compact commands from the CLI. For example:

ENVIRONMENT HEALTH WARNING:CRITICAL_LN2:38%

is a message string dispatched by `Environment` to `Health` with a warning that the LN2 tank has exceeded a critical threshold; `Health` will acknowledge the message and trigger a sequence of email and text message alerts to the responsible team members. From the Linux command line, the user could use the CLI to query the LN2 tank level with the command:

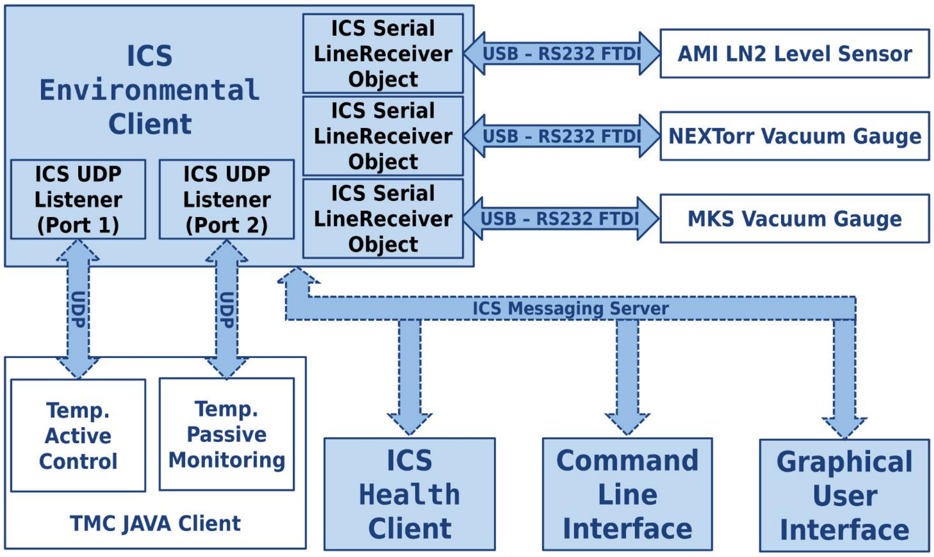

Figure 2. Block diagram for the Environmental Subsystem. The `Environmental` client manages operation of the individual Environmental hardware components through RS-232 serial and UDP multicast protocols that implement the internal command languages of the hardware. Communication to other ICS clients is routed through the `Server` using the HPF messaging protocol.

```
> hpf GETLN2
```

(where /usr/bin/hpf is a symbolic link to the CLI interpreter), and would receive back the message: `LN2:38%`.

This ICS messaging system is conceptually simple, and lightweight in both code length and computer resource usage. We began commissioning this software in our instrument integration laboratory in August 2015, and have found the system to be extremely robust to bugs in hardware protocols or upset situations in actual hardware components. *Clients that are managing multiple hardware subsystems do so in a non-blocking way, so that a problem with one hardware component is isolated from the remaining components.* A simple demonstration of this feature occurs when engineers working on the cryostat physically disable or disconnect a vital hardware component, such as a vacuum or temperature monitor, without disengaging that ICS client first. While any functionality provided by that component is lost, the remaining ICS operations continue without interruption. In the next two sections, we provide examples of two clients, `Environmental` and `Detector`, to demonstrate the ICS flexibility in interacting with a variety of hardware systems.

3. THE ENVIRONMENTAL CLIENT: A TYPICAL EXAMPLE

The HPF spectrometer optics must be maintained in an extremely stable temperature and pressure environment in order to achieve our RV stability requirements. The ICS `Environmental` client is responsible for operating and monitoring the hardware that maintains this environment, and for providing feedback through the user interfaces and telemetry logs. This subsystem utilizes several of the communication protocols we have implemented for the ICS as generic classes, and so we present it here in some detail to demonstrate how these protocols combine together to manage related groups of hardware components from a variety of manufacturers.

The `Environmental` subsystem includes three hardware systems that monitor and maintain the cryostat vacuum pressure. An MKS PDR 900 Vacuum Gauge Controller connected to a digital vacuum transducer and a SAES NEXTorr NIOPS-03 Power Supply connected to a D 100-5 ion pump provide independent measurements of the vacuum pressure inside the cryostat. An American Magnetics Liquid Level Controller 186 monitors the fill level of HPF's internal LN2 tank. Each of these controllers are operated over RS-232 DB9 ports using the serial command languages implemented by their manufacturers. The controllers are connected to the ICS computer USB bus using USB to RS-232 cable adapters implementing the FTDI chipset.

We created a generic `SerialProtocol` class in Twisted to generalize tasks including connection to and disconnection from hardware, transmission and receipt of serial message strings, and generic logging and error handling. `SerialProtocol` also implements a command *queue* using Twisted `Deferred` objects to ensure that commands are sent to and received from the hardware in a sequential nature; without this *queue*, asynchronous communication would cause collision on the serial connection. Custom hardware protocol classes (`AMILL186Protocol`, `NEXTORRProtocol`, and `MKSPDR900Protocol`) inherit the capabilities of `SerialProtocol` and override generic message handling methods to implement the command language of each individual device. Because each of these protocols is instantiated as a unique object, an independent *queue* is maintained for each hardware component; communication to an individual component is serialized, but the `Environmental` client as a whole remains asynchronous and non-blocking.

`SerialProtocol` is written so that customizing it for a specific piece of hardware typically involves only implementing the hardware command language as a `key:value` dictionary with a `key` for each recognized command; each corresponding `value` contains information about the command format and any associated parameters, and a regular expression constructor that parses any return message from the hardware. This parsing is automated; returned data and a corresponding time stamp are stored in the protocol object for later retrieval, and can also be written to an automatically generated telemetry file if desired. The `Environmental` client uses Twisted `LoopingCall` objects to regularly retrieve telemetry from each of these devices (e.g. current pressure, LN2 level, etc.) on user specified intervals, typically a few seconds.

The `Environment` client also connects to the Temperature Monitoring and Control (TMC) subsystem, which is running as an independent JAVA process that we inherited from the APOGEE spectrograph.[16] This TMC can operate completely independently of the ICS, to which it appears as a standalone hardware system, and was originally implemented on a Raspberry Pi single-board computer, connected to the ICS computer via the internal HPF network. Communication of commands and telemetry to and from the TMC is done via UDP Datagrams, implemented on a multicast address. We have recently ported the TMC process to the main HPF computer to address stability issues that occasionally occurred with the Raspberry Pi, but have retained the UDP communication.

Just as with the serial hardware, we have implemented a generic class that handles the basic multicast communication. Customized protocols (`TMCHeatProtocol`, `TMCTempProtocol`) inherit this class and override methods that parse received packets into individual telemetry data components. The TMC includes its own JAVA frontend, which is useful for engineering operations, but the TMC backend can also accept multicast commands from the ICS that have been dispatched from the CLI or GUI. In this way, we can easily script temperature set-point changes across one or all of the individual channels the TMC controls.

4. THE DETECTOR CLIENT: LINUX BASED CONTROL OF A HAWAII-2RG

The HPF detector subsystem uses a Teledyne Imaging Sensors Hawaii-2RG (H2RG) 1.7μm-cutoff 2048×2048 HgCdTe detector,[17] controlled via a SIDECAR ASIC and a SAM electronics card. This hardware is mounted in the Inner Sanctum sub-assembly of a GL Scientific[†] cryostat that has been modified to mate to the HPF camera sub-assembly. The standard Teledyne SIDECAR-SAM ribbon cable is too short for use with the HPF cryostat, so the SIDECAR connects to the SAM using a custom cable assembly manufactured for us by Cryoconnect/Tekdata Interconnections Ltd[‡]. The cable is approximately 1.5 m in length, and incorporates fixtures and a hermetic seal to pass through the HPF radiation shield and outer vacuum chamber, where it connects directly to the SAM mounted on an exterior support strut on the side of the vacuum shell.

HPF will use the detector hardware in the full frame, slow readout mode. We have carried out extensive testing and characterization work on an engineering grade array using a GL Scientific test cryostat in our Penn State detector laboratory. The SAM provides both USB 2.0 and a high-speed GigE interface for both hardware configuration and data acquisition. Our primary test setup uses the USB interface to connect to a Windows PC running the Teledyne HxRG software,[18] which functions reliably, and has allowed us to extensively characterize the detector and its operations.[19] Integrating this USB interface and the Windows HxRG software into the

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[†] http://www.glscientific.com

[‡] http://www.cryoconnect.com

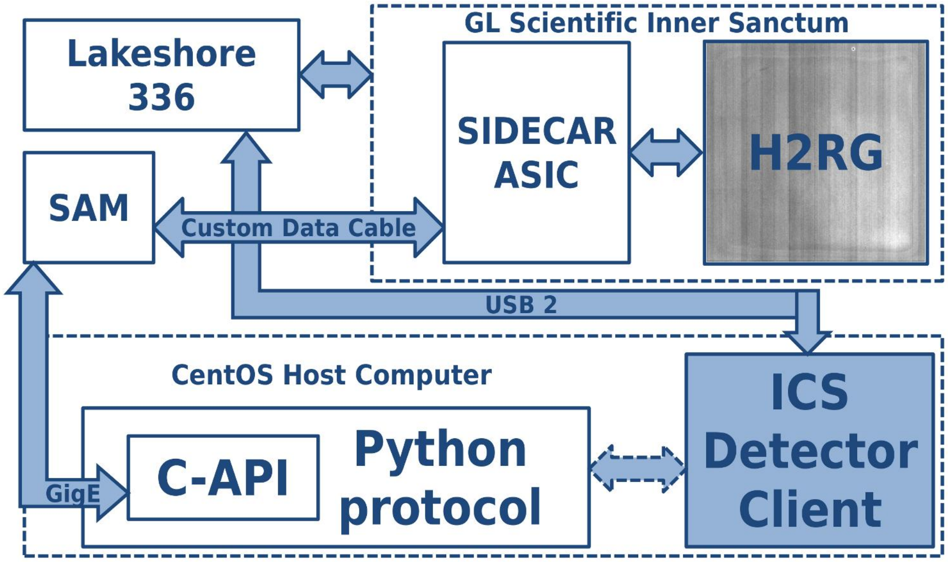

Figure 3. Block-diagram showing communication routing within the Detector subsystem. Temperature control of the GL Scientific detector housing is provided by a Lakeshore 336 controller, which communicates through a `Detector SerialProtocol` object. The SAM/SIDECAR/H2RG are connected using standard cables, with the addition of a custom extension necessary to accommodate the large HPF cryostat. The SAM is controlled directly from the HPF Linux ICS computer using the Teledyne C-API, wrapped in a python protocol for ease of integration into the ICS `Detector` client.

HPF ICS would require either adding a dedicated Windows computer to the instrument for the sole purpose of detector operations, or running a Windows virtual machine on the main HPF CentOS computer. While both options are possible, and have been used in recent years by other instruments such as RATIR[20] and FourStar,[21] our preferred solution was to utilize the GigE interface directly from within the Linux OS. Linux based control of the SIDECAR has been demonstrated previously using the third-party ISDEC control electronics,[22,23] which are being utilized in several instruments currently under development.[24]

For HPF, we are implementing Linux based control of the SIDECAR and H2RG directly through the Teledyne developed SAM electronics;[18] *this will be one of the first times such control has been used on-sky in an astronomical instrument.* The HxRG software from Teledyne includes a C-API to facilitate native Linux access to the SAM over GigE, and replicate the low-level command and control functionality available through the Windows GUIs and socket interface. We added a second test computer to our detector laboratory, running a clone of the main HPF CentOS environment, for the purpose of developing and testing this HxRG capability for HPF. This computer has a HP FH969AA Gigabit Network Interface Card dedicated to detector testing, connected to the SAM using a Cat5e cable.

To more easily integrate this capability of the HxRG C-API into the HPF ICS, we constructed a Python `HxRG` class that provides low-level methods that use the `ctypes` library to wrap each C function (Figure 3). This `HxRG` class also provides a suite of additional methods that accept keyword arguments and script the low-level methods in order to carryout standard higher level operations. This implementation simplifies and improves robustness of routine detector operations, most of which can be handled through a small set of dedicated methods: `HxRG.startup`, `HxRG.configure`, `HxRG.setExposure`, `HxRG.startExposure`, and `HxRG.shutdown`. `HxRG.configure` includes the capability to load a pre-determined set of bias-voltages that have been optimized for a specific detector. Extending the `HxRG` class to provide functionality for additional configurations not currently used for HPF (e.g. Fast-mode, Window-mode, alternative detector form factors, etc.) should be straight forward. The box labeled H2RG in Figure 3 shows a single-frame readout from 32 channels of our engineering H2RG that we obtained using our Python software. We expect this development to continue throughout 2016.

The `HxRG` class acts as the H2RG/SIDECAR/SAM hardware protocol for the `Detector` client. `Detector`

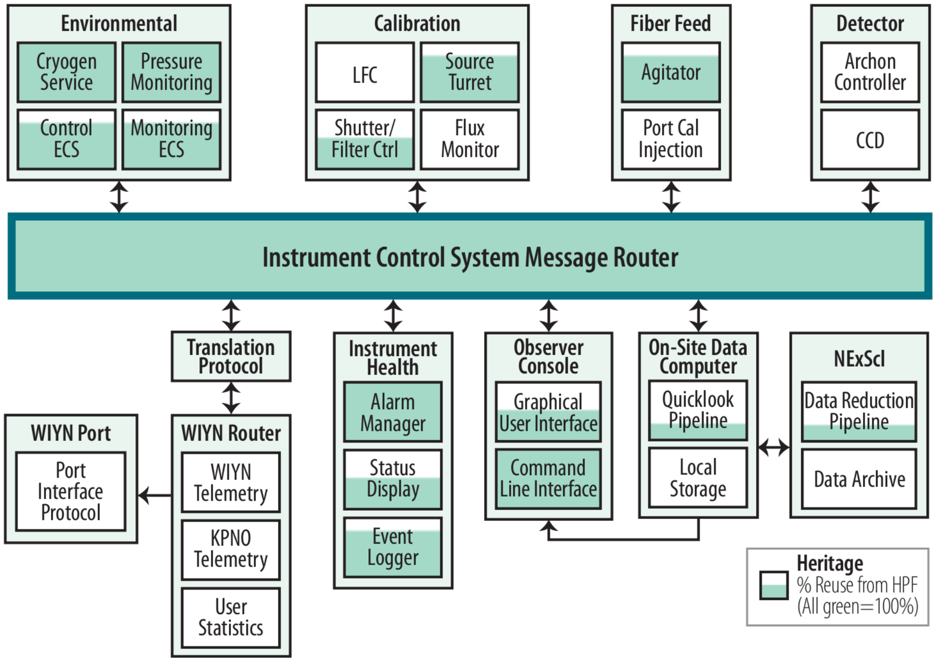

Figure 4. Block-diagram showing the ICS structure for the NEID spectrometer on the WIYN Telescope. The flexibility of the HPF ICS facilitates significant code re-use for NEID.

parses CLI and GUI commands to the detector hardware, and also controls the Lakeshore 336 temperature controller that maintains the temperature of the Inner Sanctum structure. We do not use our TMC system to control the Inner Sanctum temperature because it cannot provide sufficient power to maintain the H2RG and SIDECAR temperatures, and because the GLS thermometers are incompatible with the TMC. The Lakeshore is connected to the ICS cabinet via USB 2.0, and requires a `cp210x` kernel module rebuilt from the Silicon Labs v3.x source code (the v2.6 module included as default in CentOS 6.x does not support Lakeshore communications). A custom `Lakeshore336` hardware protocol inherits the serial communication capabilities described in Section 3 and implements the Lakeshore serial communication language.

5. ADAPTING THE ICS TO NEID

NEID is a visible-light, Doppler spectrometer selected by NASA in 2016 to provide next-generation radial velocity measurement capabilities for exoplanet and related science, as part of the NASA and NSF supported NN-Explore[§] program. NEID is being developed by a team led by our group at The Pennsylvania State University, along with collaborators from the University of Pennsylvania, the University of Colorado, the NASA Goddard Space Flight Center, and Macquarie Univeristy, Australia, and the Physical Research Laboratory, India. The spectrometer is currently under development, and is scheduled to be commissioned on the WIYN 3.5 m telescope in 2019. Following a successful commissioning, NEID will provide ground based radial velocity followup for planet candidates discovered by TESS,[25] and will lead the push to identifying Earth-mass Habitable-zone planets around G and K stars.

NEID has many hardware similarities with HPF, so the ICS we have already developed for HPF can be readily adapted for use at WIYN. Figure 4 shows the ICS block diagram for NEID, similar to Figure 1, with shading for

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[§] http://exep.jpl.nasa.gov/NNExplore

each client subsystem indicating the fraction of code that will be re-used from HPF. This re-use provides real cost-savings to the NEID project, and also leverages the operational robustness in our ICS that follows from years of HPF laboratory testing and HET operations that will occur prior to NEID commissioning. The WIYN telescope uses an asynchronous communication system written in C for managing telescope subsystems and instruments that is conceptually similar to our ICS design. We will interface with this existing software infrastructure through a simple Python translation protocol, that will convert between our ICS messaging protocol and the WIYN messaging protocol, and establish communication via TCP sockets. Development of the NEID ICS will occur during 2017 and early 2018.

6. SUMMARY AND FUTURE WORK

We have created an instrument control software package (ICS), implemented as a client/server messaging system using Twisted Python, and are using it to control the Habitable-zone Planet Finder spectrometer. This system has been demonstrated over the past year in our Penn State instrument integration laboratory, where it has proven to be a robust, modern solution to instrument software control. The core messaging system, including many of the client subsystems are complete, and we are continuing to implement the remaining systems as hardware arrives and is integrated into the instrument.

We have also developed the capability to communicate with our Hawaii-2RG/SIDECAR/SAM detector subsystem in Linux from within the ICS infrastructure. This software is functional now, and additional development to expand the feature set is planned for the remainder of 2016.

The flexibility of the ICS we have developed allows it to be easily adapted to new instrumentation, or integrated into existing systems. Beyond HPF, the first beneficiary of this development effort will be the NEID spectrometer that will be installed on the WIYN telescope in 2019. In this capacity, our ICS can significantly reduce the development effort required for new instruments, and also facilitate the update of existing older instrumentation to more modern computing standards.

ACKNOWLEDGMENTS

This work was partially supported by funding from the Center for Exoplanets and Habitable Worlds. The Center for Exoplanets and Habitable Worlds is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. This work was performed in part under contract with the California Institute of Technology(Caltech)/Jet Propulsion Laboratory (JPL) funded by NASA through the Sagan Fellowship Program executed by the NASA Exoplanet Science Institute. HPF development is supported by NSF grants AST 1006676, AST 1126413, and AST 1310885. NEID development is supported by JPL subcontracts 1531858 and 1547612.

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