MOIRCS : Multi-Object Infrared Camera and Spectrograph for the Subaru Telescope

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ABSTRACT

MOIRCS (Multi-Object InfraRed Camera and Spectrograph) is one of the second generation instruments for the Subaru Telescope. This instrument is under construction by the National Astronomical Observatory of Japan and Tohoku University. It has imaging and multi-object spectroscopy (MOS) capabilities in the wavelength range from 0.85 μm to 2.5 μm with $4' \times 7'$ F.O.V. The focal plane is imaged onto two 2048 × 2048 pixel HAWAII-2 HgCdTe arrays with a pixel scale of $0.''12$ pixel^{-1} through two independent optical trains. The optical design is optimized to maximize K band performance. Unique design of MOIRCS allows multi-object spectroscopy out to K band with cooled multi-slit masks. Twenty-four masks are stored in a mask dewar and are exchanged in the cryogenic environment. The mask dewar has its own vacuum pump and cryogenic cooler, and the masks can be accessed without breaking the vacuum of the main dewar. The two-channel optics and arrays are mounted back-to-back of a single optical bench plate. A PC-Linux based infrared array control system has been prepared to operate HAWAII-2. The first light of MOIRCS is planned in the spring of 2003.

Keywords: Infrared astronomical instrument, near-infrared, multi-object spectroscopy, multi-slit mask, cooled optics, infrared FPA

1. INTRODUCTION

MOIRCS is a near-infrared (NIR) imager and spectrograph to be installed at the Cassegrain focus of the Subaru Telescope. This instrument has been built by the collaboration with the National Astronomical Observatory of Japan and Tohoku University, and the first light is planned in the spring of 2003.

MOIRCS has capabilities of wide field imaging ($4' \times 7'$ F.O.V.) and multi-object spectroscopy (MOS) with cooled multi-slit masks. The major scientific target of MOIRCS is understanding rest-frame optical properties of high-redshift galaxies mainly at z=2–5. With imaging mode of MOIRCS, we can obtain wide field deep NIR images to study color, magnitude, and morphology distribution of the distant galaxies and constrain their stellar mass, stellar population, and large scale spatial distribution with samples large enough to be statistically reliable. With multi-object spectroscopy mode, we can extensively investigate their rest-frame optical emission line properties to constrain their dynamical mass (line width), star formation rate (line flux), and metal abundance (line flux ratio). In order to construct statistically meaningful size of samples, the capability of multi-object spectroscopy is quite essential. Since galaxies at such high-redshift are faint, it takes more than a few hours to obtain high-S/N NIR spectra even with an 8 m-class telescope. Therefore, wide-field imaging and multi-slit

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spectroscopic abilities of MOIRCS can achieve efficient observations to reveal history of galaxy formation and evolution in early universe. Further challenging goal of MOIRCS is to search for extremely high-redshift objects at $z \sim$5–10. We can search a huge volume with MOIRCS to constrain their surface number density by drop-out technique as well as using narrow-band filters tuned to various redshifts. In addition, MOIRCS can be also used in the studies of various objects, for example, extremely red objects (EROs) and brown dwarfs.

In this paper, we describe a design of MOIRCS. Details of each component are described elsewhere in this proceeding[1,2,3] .

2. SPECIFICATIONS

The layout of MOIRCS is shown Figure 1 and the specifications are summarized in Table 1. MOIRCS has wide field imaging and multi-object spectroscopy modes. MOIRCS covers at most $4' \times 7'$ F.O.V. with two 2048 $\times$ 2048 pixel HAWAII-2 HgCdTe arrays (Rockwell Scientific Co.) with a pixel scale of $0.''12$ pixel^{-1}, though actual F.O.V. varies with wavelengths and observation modes. The full $4' \times 7'$ F.O.V. is available in the imaging mode at shorter wavelength, while it is limited within $6'$ diameter to block an extraneous radiation at longer wavelength in the imaging mode and at entire wavelength in the spectroscopy mode.

The multi-object spectroscopy is available out to K band with spectral resolution of 500–2000 by using grisms and cooled multi-slit masks. Up to fifty objects can be observed simultaneously and twenty-four masks can be stored in the cryostat. The multi-slit masks are cooled down to 150 K and are exchanged in cryogenic environment.

Total throughput is estimated to be 34 % in the imaging mode and 20 % in the spectroscopy mode (including reflectivities of the primary (aluminum coating) and the secondary (silver coating) mirrors of the telescope, transmission of the entrance window (96 %, non-coating), reflectivities of two field divide mirrors (gold coating), transmission of the ten lenses (94–99 % per a lens), filters (90 %), and grisms (60 %), and a quantum efficiency of the detector (60 %)). Estimated limiting magnitudes are shown in Table 1.

Table 1. Specifications of MOIRCS

Observation Modes	Imaging and Multi-Object Spectroscopy (MOS)
Field of View (F.O.V.)	$4' \times 7'$
Wavelength Coverage	0.85-2.5 μm
Detector	two 2048 $\times$ 2048 pixel HgCdTe (HAWAII-2) arrays
Pixel Scale	$0.''12$ pixel^{-1}
Spectral Resolution	R=500-2000
Mask Capacity	24 masks (up to 50 slits per mask)
Estimated Total Throughput	Imaging 34 %, Spectroscopy 20 %
Estimated Limiting Magnitudes	Imaging: 1hr, S/N=10 J=23.8mag, H=23.1mag, K=22.3mag Spectroscopy: R=500, 4hr, S/N=5 J=21.3mag, H=20.8mag, K=20.0mag

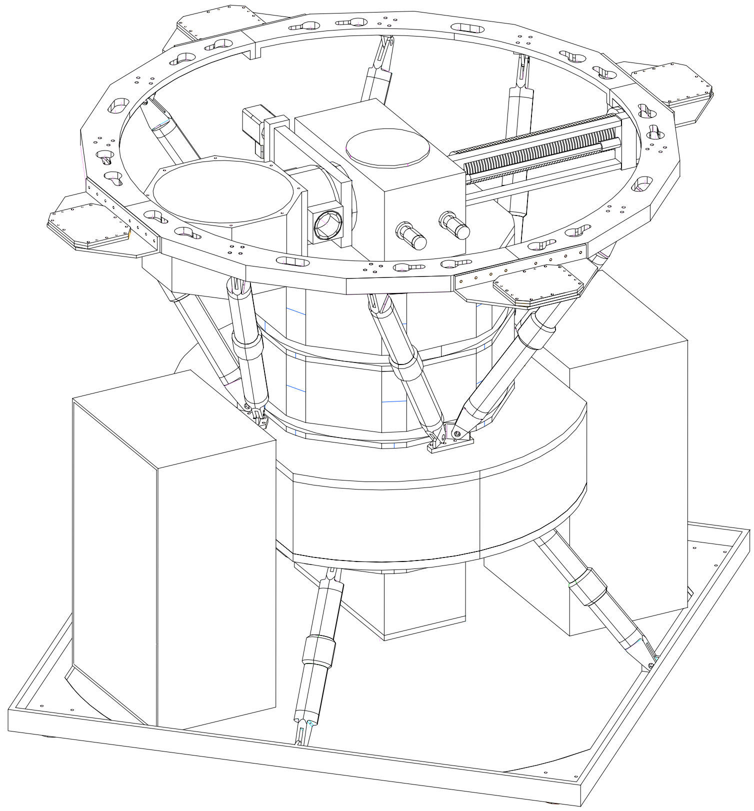

Figure 1. 3D-view of MOIRCS. The overall size of the structure is 2m × 2m × 2m.

3. OPTICAL DESIGN

For imaging and spectroscopy in K band, all the components of MOIRCS inside the cryostat are cooled to 77 K. The optical system is designed to work at the temperature with consideration of a refractive index change of lens materials at 77 K and thermal contraction of the lenses. The detail of the optical design is given elsewhere.[1]

Figure 2 shows an optical layout. MOIRCS consists of two sets of identical optics. A gold-coated roof mirror placed just below the focal plane splits the light from the telescope. Divided light enters two identical optical trains after reflection from two gold-coated fold mirrors. Each optical train has four-lens collimator and six-lens camera sections. The collimator with a focal length of 620 mm generates a parallel beam and a pupil image of 50 mm diameter. The camera with a focal ratio of f/3.9 makes an object image onto the detector with a pixel scale of $0.''12$ pixel^{-1}, which adequately samples a point-source image under the best seeing condition at the summit of the Mauna Kea. The broad band filters (e.g. z, J, H, K), narrow band filters, order sorting filters, grisms, and cold-stops are mounted on the turrets which are located in the collimated section. In order to switch imaging and spectroscopy modes easily, grism is used as dispersive element in the multi-object spectroscopy mode. The spectral resolutions from 500 to 2000 are targeted with the grisms. For a short exposure with integration time less than readout time of the arrays, shutters are installed near the pupil image. The lenses are made of CaF_2, BaF_2, Fused Silica, and ZnSe that have an excellent transmission in the near-infrared wavelength. All these lenses except for a large CaF_2 window are coated with anti-reflection coating. Its reflectivity ranges from 1.5 % to 2.5 % per surface depending on the materials and wavelength.

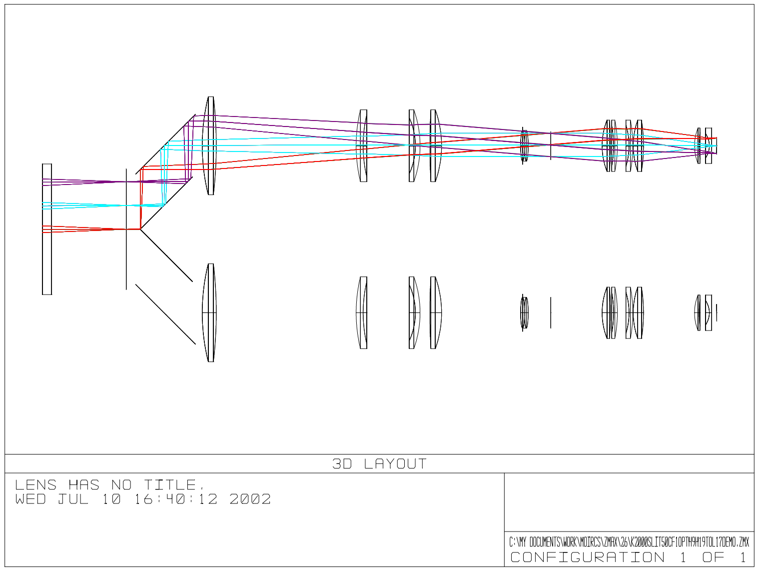

Figure 2. Layout of the optics. Rays are drawn only for one channel.

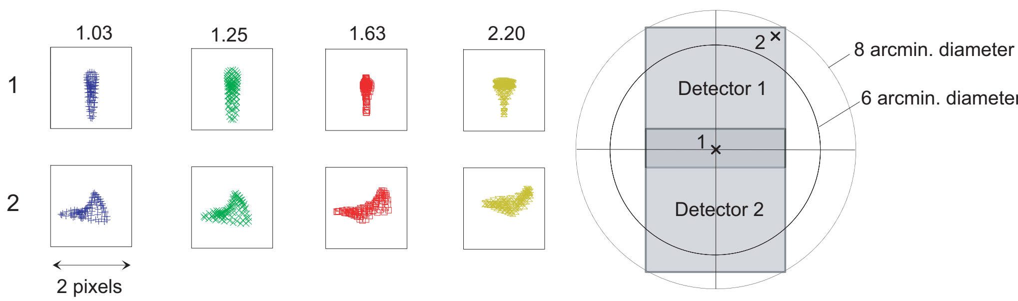

Figure 3. Spot diagram of the optics and F.O.V. of MOIRCS. Two squares in right figure represent scaled detectors at Cassegrain focal plane, while two circles correspond to 6′ and 8′ diameter respectively. The upper column and lower column in left figure represent the field positions shown in right figure. The horizontal arrangement shows wavelength in μm. Boxes correspond to two pixels.

Figure 3 shows expected spot diagram of the imaging mode. Spots for the center and edge of the F.O.V. at 1.03 μm, 1.25 μm, 1.63 μm, and 2.20 μm are shown. The squares represent 2 pixel boxes. Because there is not significant chromatic aberration we do not need refocusing for the different wavelength.

Image quality of the spectroscopy mode is as good as the imaging mode with low spectral resolution grisms. However, the image degrades with high spectral resolution grism occurs because of the field curvature of the collimator, and an effective spectral range is limited by the image degradation. The imaging performance analysis of the collimator shows that any point at the edge of the telescope secondary mirror is imaged within 0.3 mm square box at 2.5 μm on the cold-stop, while the pupil diameter is 50 mm. Extraneous radiation added by the aberration is estimated to be less than 3 % of the radiation from the sky.

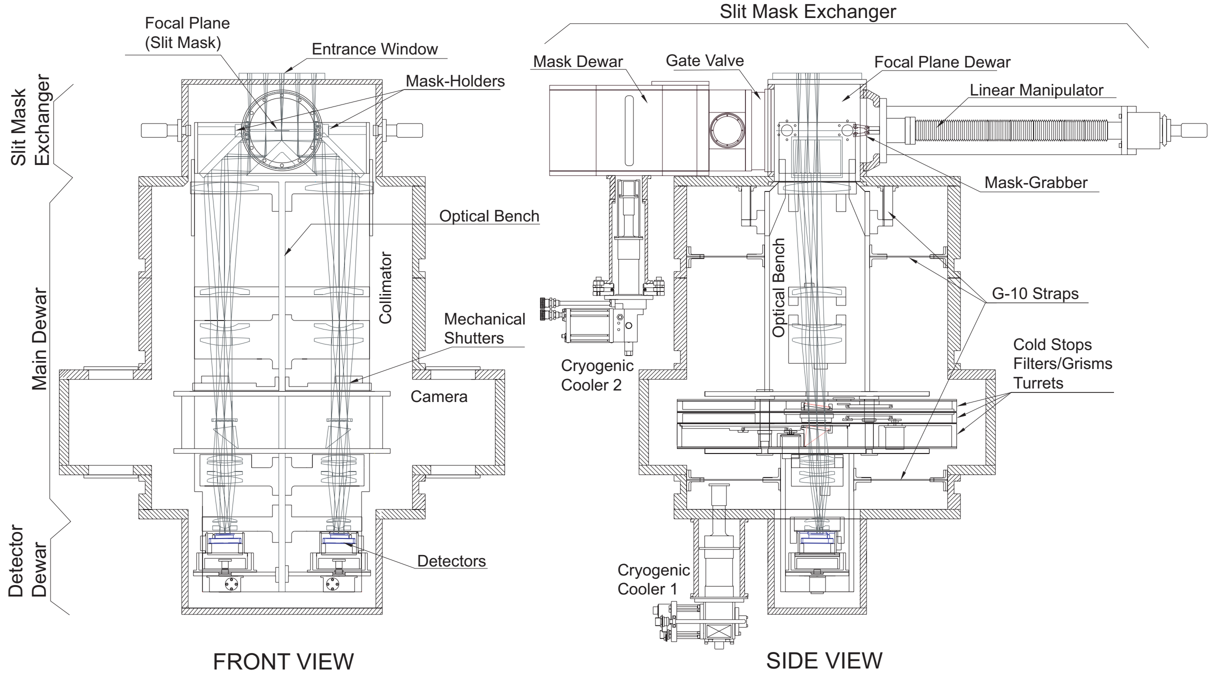

Figure 4. Inside structure of the MOIRCS cryostat, front view (left) and side view (right). Turrets and G-10 straps are shown only in the side view.

4. CRYOSTAT

The MOIRCS cryostat consists of a slit-mask exchanger, a main dewar, and a detector dewar (Figure 4). The dewars are made of aluminum alloy. This cryostat provides a vacuum and cryogenic environment for the detectors and all the optical components inside the cryostat. Two cryogenic coolers are mounted on the system. One cooler cools the detectors and optical components down to 77 K, while the other cools the stored slit-masks down to 150 K. A few layers of super-insulation will be used to reduce the external thermal radiation.

Both sets of optical trains and detectors are mounted on back-to-back the optical bench plate which is 20 mm thick aluminum alloy (6061-T651). In order to stabilize the structure of the optical bench and lens mounts at 77K, we made a heat treatment for them. The procedure of the treatment consists of rough machining, quenching in liquid nitrogen, aging, and final machining. The bench is suspended from the inner surface of the main dewar with epoxy glass-fiber (G-10) straps which have low thermal conduction, low-thermal contraction, and stiffness in the cryogenic temperature. Three wheels for filters, grisms, and cold stops are placed in the collimated section of each optical train and cryogenic motors drive these wheels.

The cryostat and electronics boxes are mounted on the 2m-cube frame with supporting braces (Figure 1) and are installed to the Cassegrain flange automatically. The total weight of MOIRCS including the support frame will be 2 metric tons.

Finite element analysis (FEA) has been done during structural and thermal designing processes in order to examine the effects of thermal contraction and to verify that structural deflections due to an instrument orientation and atmospheric pressure are within an allowable range.

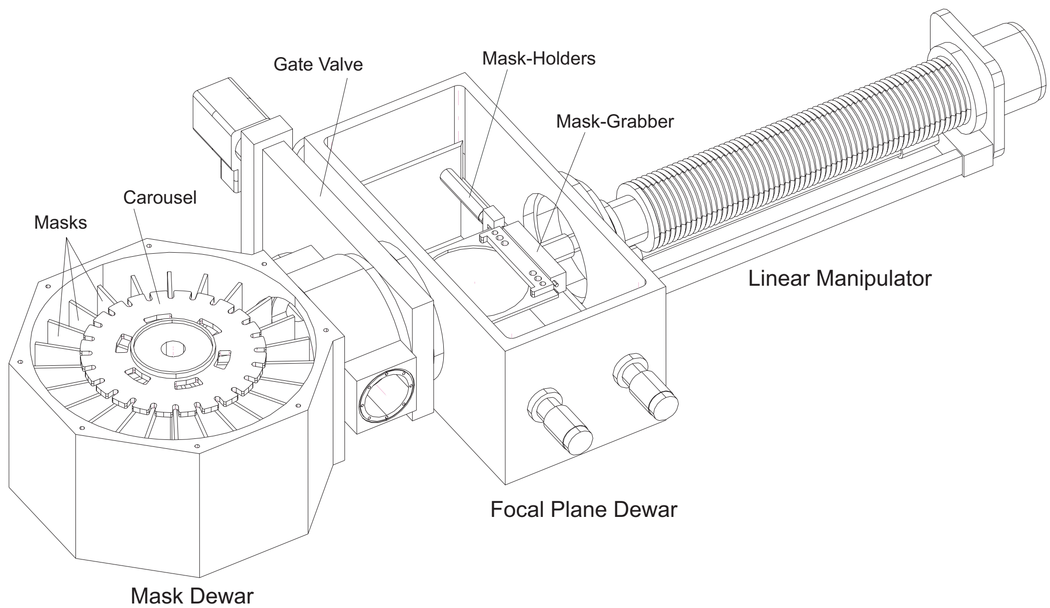

Figure 5. 3-D view of the slit mask exchange system. An octagonal dewar at left is the mask dewar, a rectangular dewar at center is the focal plane dewar, and a bellows at right is the linear manipulator. A slit mask is held at the focal plane as in the figure.

5. SLIT MASK EXCHANGE SYSTEM

5.1. Exchange Mechanism

The major challenges with cooled multi-slit spectroscopy up to K band are how to provide a new mask during the observation in cryogenic environment and how to replace the stored masks without thermally cycle of the cryostat. The multi-slit mask exchanger consists of a carousel in which twenty-four masks are stored, a mask-grabber attached to a linear manipulator, and four mask-holders (Figure 5). The carousel is installed in the mask dewar which is separated from the focal plane dewar where a mask for observation is held. There is a gate valve between the mask dewar and the focal plane dewar. This gate valve isolates the mask dewar so that it can be opened without breaking vacuum of the main dewar during the mask replacement. The mask dewar has its own vacuum pump and cryogenic cooler. In order to minimize the thermal conduction between the cooled masks and the mask dewar, the carousel is supported in the mask dewar by spoke-wheels made of thin stainless steel. The linear manipulator moves the mask-grabber between the focal plane dewar and the mask dewar under the vacuum environment. A stepping motor controls the position of the mask-grabber, and some sensors monitor the position of the mask-grabber.

The procedure for mask exchange is as follows: (1) masks are cooled down to 150 K in the mask dewar, (2) the gate valve opens, (3) the manipulator with mask-grabber goes to the carousel and pulls out a proper mask, (4) the mask-grabber brings the mask to the focal plane, (5) the four mask-holders grip the mask. The mask-grabber releases the mask, and the manipulator retracts, (6) then, an exposure starts. After the exposure, the steps (5) through (3) are reversed. For a new mask, the carousel is rotated and new steps repeat from (3).

5.2. Slit Mask

A multi-slit mask is 180 mm diameter aluminum sheet with 70 micron thickness. Figure 6 (left) shows the mask with mask frame and mask-grabber. Slits are cut with an electric discharge machining (EDM). Figure 6 (right) shows an enlarged view of the slit mask cut with the EDM. More than 50 slits can be placed on a slit mask. The minimum width of a slit is about 100 μm which corresponds to $0\farcs2$ at the focal plane. Relative slit positions have to be accurately controlled to cover the entire 180 mm F.O.V. The effect of the thermal contraction and optical distortion will be corrected by software.

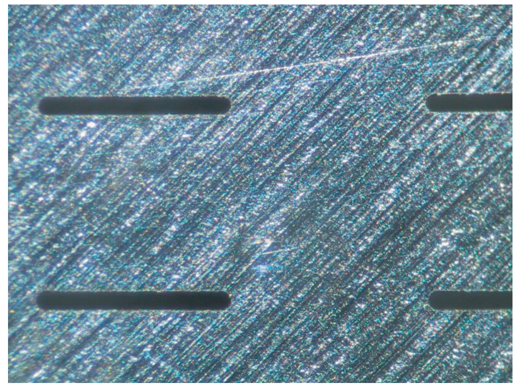

Figure 6. Mask with mask frame and mask-grabber (left), the enlarged view of slit cut (100 μm $\times$ 1.1 mm slits) (right).

6. DETECTOR SYSTEM

In order to control HAWAII-2 arrays flexibly and acquire data efficiently, we have developed a new infrared array control system, Tohoku University Focal Plane Array Controller (TUFPAC).[3] Figure 7 shows a schematic diagram of the system. A personal computer with Linux OS controls two HAWAII-2 arrays with commercially available DSP boards installed on the PCI bus. The first unit of TUFPAC uses on-chip amps in a 4-channel readout mode. A 32-channel readout system is being designed for fast readout required in high background observation. TUFPAC is capable of controlling eight HAWAII-2 arrays simultaneously. The pins of PGA of a ceramic package that are not wired to HAWAII-2 arrays, are used for a heat sink to stabilize the array temperature. Two small Pt resistors are directly soldered to ZIF socket pins to monitor the temperature.

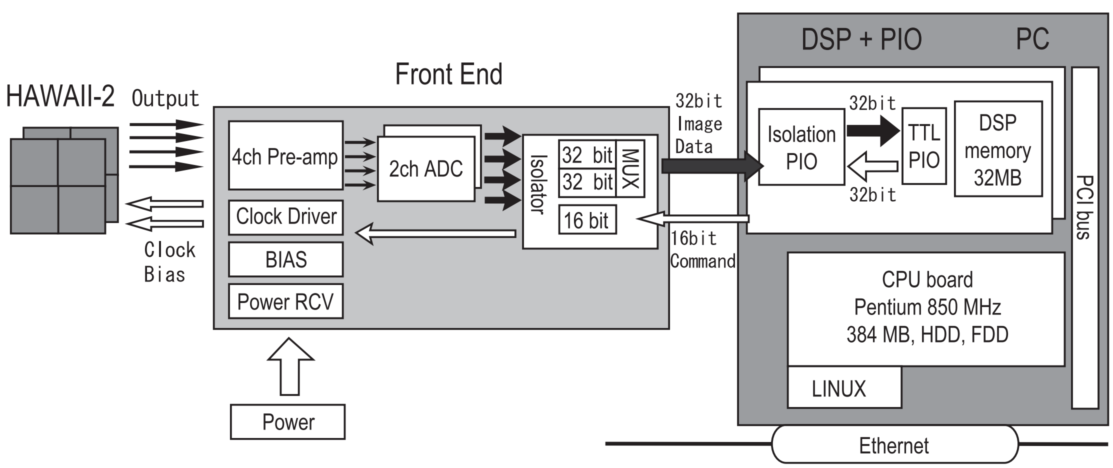

Figure 7. A schematic diagram of the system configuration of TUFPAC.

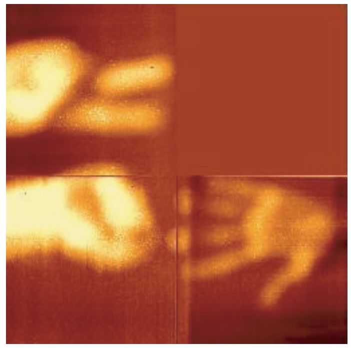

Figure 8. An image of the engineering-grade array.[3] The upper right quadrant is not wired.

We are conducting performance tests of both the engineering-grade and science-grade HAWAII-2 arrays with TUFPAC.[2] Array performances such as stability of bias frames, readout noise and dark current are evaluated at 78 K. The optimum value of well depth, readout speed, and dynamic range are searched by changing bias voltages. Tests of the engineering-grade array have been finished, while the performance tests of the science-grade arrays are ongoing. The science-grade arrays are planned to be installed in the MOIRCS cryostat in the fall of 2002. Figure 8 shows an image taken by the engineering-grade array.

7. CONTROL SOFTWARE

The MOIRCS software is divided roughly into three components; a program that controls the assembly (OBE) of each housekeeping component, a program that runs HAWAII-2 array controller/readout electronics and a program that oversees the entire system and its sequential operation, and is responsible for higher-level interlock (Figure 9). The last resides in the MOIRCS/OBCP. The MOIRCS/OBCP program connects MOIRCS with the Subaru Observation Support System (SOSS) via SOSS interface (SOSS/IF).

The software installed for controlling each device of OBE is as follows: Slit Exchanger Controller, Filter/Grism Turret Controller, Temperature Controller, Vacuum Pump Controller, Cryogenic Cooler Controller, and Power Supply Controller.

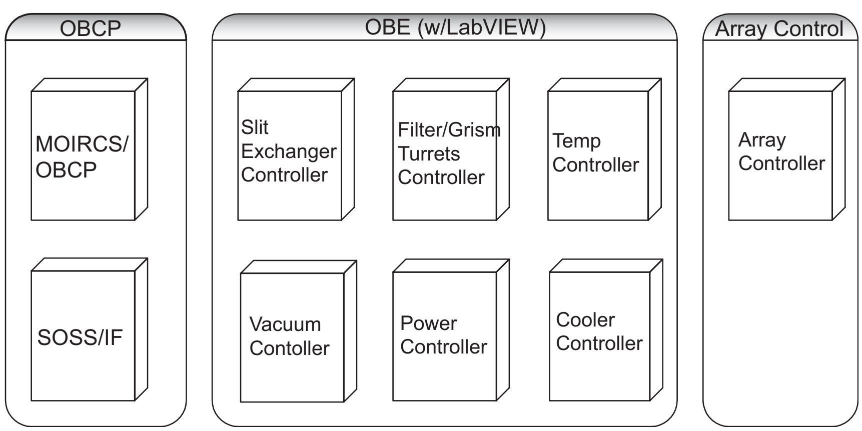

Figure 9. Main Components of the MOIRCS software.

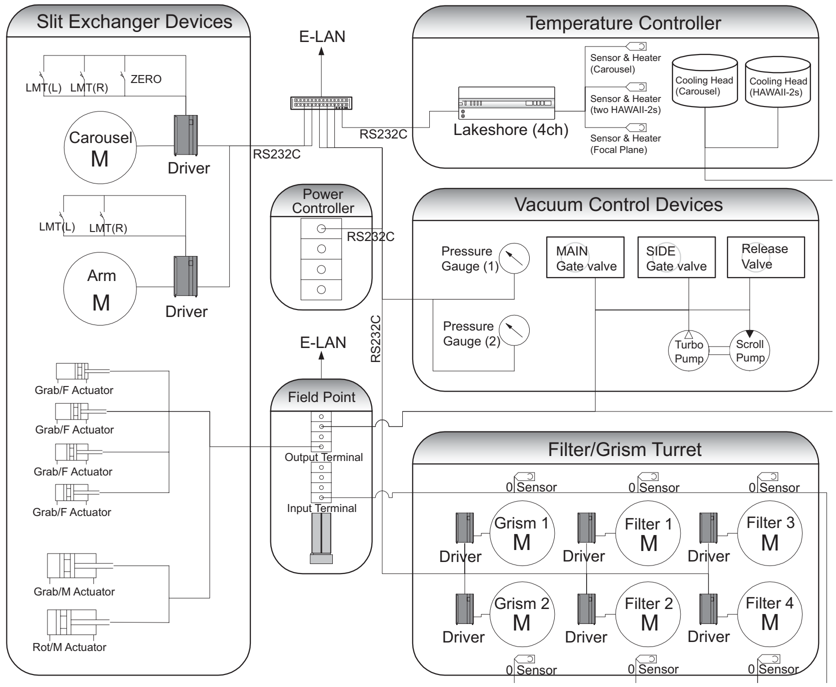

Figure 10. Partial block diagrams of network connection for MOIRCS/OBE control.

Each device is controlled either through RS232C connected to a 32-port terminal server from Lantronix or through relays connected to Field Point Distributed I/O from National Instruments, Inc (Figure 10). The terminal server and Distributed I/O are in turn controlled by TCP/IP through Ethernet. All the controls are made through the LAN to avoid undesired interference between the devices and the control computer. The reason to avoid direct access of I/O is because an I/O access with a wrong address may reset the computer inadvertently. The use of terminal server is to handle as many RS232C devices as we would like without excess cabling. Controlling devices that requires speed, such as real time closed loop control of real time, may suffer from this type of control through a network. However, for housekeeping control of many slow devices, this method has practical merits such as safety of operation and simplicity of installation and maintenance.

The control software for OBE is developed with LabVIEW of National Instruments, Inc. We take advantages of its graphical programming language for fast and easy programming of quite a few housekeeping components needed for MOIRCS.

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