ICONN – THE INFRARED COHERENCING NEAREST NEIGHBOR TRACKER

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Received (to be inserted by publisher); Revised (to be inserted by publisher); Accepted (to be inserted by publisher);

ICONN is a dedicated fringe tracker for the Magdalena Ridge Observatory Interferometer (MROI) that employs a baseline bootstrapping combination scheme utilizing the interferometer’s “Y”-shaped telescope array. The ICONN optomechanics are designed in a modular fashion to combine light from two to ten telescopes while tracking on the nearest neighbor baselines. The software tasked with operating ICONN is designed to interface with the larger MROI software supervisory system. Commands are distributed to high level processes within ICONN, which in turn pass them down internally to lower level threads. The design of ICONN is now complete and laboratory testing has commenced. This paper details the optomechanical and software design of ICONN.

Keywords: instrumentation: interferometry: fringe tracking: baseline bootstrapping

1. Introduction

The improvement of limiting sensitivity is probably the most pressing technical challenge facing the current generation of ground-based optical/infrared interferometrists. In common with the field of adaptive optics (AO), the critical issue is one of sensing the atmospheric fluctuations on a timescale short enough that suitable real-time corrections can be applied and “diffraction limited” data be secured. Unless this can be routinely realized, the ability of an array to study faint targets will be severely compromised.

In principle, any beam combiner that measures interference signals between individual elements in the array can be used to “track” the atmospheric perturbations between those elements, and such fringe tracking usually forms a core component of an array’s real-time control. In practice, in order to maximize sensitivity, most arrays use light in one bandpass to fringe track, while sending other bandpasses to the science instruments.

In the past, two main approaches to fringe tracking have been proposed. The first is characterized by sensing the wavefront perturbations only between nearest neighbor telescopes, but then using them to infer the perturbations between more widely spaced telescopes. This procedure, often referred to as “baseline bootstrapping”1, endeavors to capitalize on the fact that the fringe contrast on the shortest nearest-neighbor baselines will likely be highest, and so fringes on these baselines will be detectable (and trackable) with maximal signal-to-noise. However, an alternative school of thought favors fringe-tracking combiners that measure many short and long baselines simultaneously. In this case, while the instantaneous signal-to-noise on many of the measured baselines may be low, this is compensated for by the multiple bootstrapping paths allowed when dynamically solving for the wavefront perturbations above any given array element (see, e.g. Ref. 2).

In this paper we report on the opto-mechanical design and performance of the MROI fringe tracker3. This instrument, the Infrared Coherencing Nearest Neighbor (ICONN) tracker, has been designed as a nearest-neighbor-only bootstrapping beam combiner that will run in parallel with the MROI’s science instruments. The design of ICONN has had to support a number of MROI-specific constraints, in particular the “Y”-shaped layout of the array, with a central telescope that has three nearest neighbors, the desire to allow expansion from three to ten telescopes without redesign, and a goal to allow for both coherencing and co-phasing fringe tracking modes depending on the target brightness. Other noteworthy features of ICONN include its fringe stepping modulation scheme and its use of spatially dispersed temporally-modulated fringes to measure the group-delay.
We begin with an overview of ICONN’s architecture in section 2, and then focus on the key optical and mechanical features of its design in sections 3 and 4 respectively. The software design of the instrument is reviewed in section 5, while in section 6 we summarize the expected potential of ICONN and the scientific impact resulting from it. Our conclusions are summarized in section 7.

2. System architecture

The MROI array was designed as a traditional "Y" configuration which is optimal for baseline bootstrapping fringe tracking. This technique is illustrated in Figure 1 with a schematic layout of the array. The Unit Telescope (UT) stations are numbered 1 through 3, progressing in order from the vertex to the outer-most station within a given arm. The blue arrows designate the combination partners necessary to bootstrap the array. All '3' UTs have one combination partner, all '2' and '1' UTs have two combination partners, and the vertex UT has three combination partners. Since all '3' UTs have only one combination partner their delay lines are used to apply path length corrections to the 3-2 baselines. The delay lines for the '2' UTs are adjusted for corrections for the 2-1 baselines, and the '1' UT delay lines are adjusted for corrections to the 1-0 baselines.

![Fig 1. Schematic illustrating bootstrapping technique at the MROI. The UT stations are represented by circles labeled 1 through 3, and the nearest neighbor combinations are represented by the blue arrows connecting the stations.](image)

Figure 2 is a schematic of a functional analog of the ICONN fringe tracker for the case of a simplified 3-telescope array. Light from UT stations N1, W0 and S1 is directed to the beam combiner. The combiner then generates two outputs, \( \pi \) radians out of phase with respect to each other (e.g. N1-W0 and W0-N1) for each combination pair. Each of these outputs is sent to a spectrograph where they are spatially filtered and spectrally dispersed into five spectral channels on a detector. The pixel values for the five spectral channels are read out and then the fringe pattern is phase shifted by \( \pi/2 \) radians within the beam combiner. Immediately following the phase shift, the detector is read again and the new pixel data are combined with the earlier measurements to estimate the fringe amplitudes and phases for each spectral channel using a standard “ABCD” estimator. The variation of fringe phase with wavenumber then allows for the group delay between the different combination partners to be computed by the controller and a corresponding offset is then applied to the appropriate delay lines.
2.1. The array optical train

A total of three beam combiners are expected to be placed into operation for the MROI: a visible science combiner, a near-infrared science combiner, and the fringe tracking combiner. Space is available for a visitor instrument as well. The location of these combiners within the MROI optical train is illustrated in Figure 3. Light collected by a UT enters evacuated beam relay pipes and is directed toward the delay lines. Following the delay lines the beams leave vacuum and enter the beam combining area where the appropriate bandpasses are directed to their respective combiners via sets of dichroics and switchyard mirrors. Though the near-infrared science and fringe tracking combiners have similar functional bandpasses, they will not operate simultaneously within a band for any given observation. If the science combiner is making K band measurements, the fringe tracker will receive H band light, and vice versa. We expect that most science cases involving the infrared science combiner will not be installed for several years at least, led us to conclude that adding an H+K fringe tracking mode would not be worth the additional complexity at present.

2.2. ICONN subsystem components

The main optomechanical subsystems that comprise ICONN are illustrated in Figure 4. These are the switchyard, beam combiner, periscope optics, and spectrograph. The switchyard functions to configure the input phase plane to match that expected by the combiner, and perform alignment duties so that all of the incoming collimated light beams arrive at their relevant combination planes at the correct location, and traveling in same direction. The optical architecture of the beam combiner creates interference fringes from the nearest neighbor beam combinations so as to allow bootstrapping of the array. To reduce the costs associated with near-infrared detectors...
(e.g. the array itself, its read out electronics, liquid nitrogen, dewars, etc.), we aimed to fit as many combiner outputs onto as few detectors as was reasonably possible. The current periscope optics can multiplex up to five combiner outputs onto a single near-infrared array. This is done by folding the linear output pattern of the beam combiner into that of an arc therefore reducing the footprint of the bundle of collimated beams traveling through the spectrograph.

The periscope optics also allow for the tilt and shear of the combined beams exiting the beam combiner to be properly matched to the spectrograph inputs. This ensures that each beam is guided centrally through its pinhole spatial filter and traverses the spectrograph optics with appropriately small aberrations. The spectrograph’s primarily function is to spatially filter and spectrally disperse the combiner outputs into five spectral channels onto the detector. A key design feature of the combiner is that it has been fabricated without any internal degrees of freedom on the individual optical elements. Tilt and shear errors between the light beams from the delay lines and the beam combiner inputs are removed by the switchyard mirrors, while corresponding errors between the combiner outputs and spectrograph inputs are removed by the periscope optics. This is done using an optical arrangement at the combiner output to simultaneously measure the tilt and shear of each combined beam.
3. Optical Engineering

3.1. Switchyard

As illustrated in Figure 3 (the MROI optical train), the beams from each telescope in the array are redirected toward the switchyards through 60° reflections by the M10 turning mirrors. These mirrors affect the beams by changing their direction of travel, decreasing the separation between them, and changing the orientation of the plane of constant phase (see Figure 5). In Figure 5 the beams input to the M10 mirrors are labeled according to telescope location in the array arms (see Fig. 1). The input beam pitch is 609.6mm, and the input phase plane is perpendicular to the direction of travel. Upon reflection from the M10s, the beam pitch is reduced to 100mm, and the phase plane is rotated clockwise by 83.54°. As a result, the beam combiner input pitch and phase plane orientation (see Fig. 6) set the switchyard configuration seen in Figure 4.
Every switchyard mirror can be adjusted remotely in tip and tilt so as to remove relative tilt and shear errors between combination partners in the beam combiner. These errors are measured on a beamline-by-beamline basis at the output of the combiner and will be corrected for on a nightly basis as the last step in an automated alignment of the entire MROI beam-train. The automated alignment of MROI is described in Ref. 7. This full procedure also includes a procedure for correcting the absolute beam shear of each beam. This switchyard configuration redirects the light by 90° while maintaining polarization purity so that the beam combiner tables can be located parallel to one another. This allows for orderly allocation of space with the beam combining area, and simplifies the measurement of optical path offsets between the tables. In the event that a UT or delay line is taken out of service, the switchyard can be quickly reconfigured to allow beams to be input into adjacent combiner inputs. This function is critical in maintaining phasing of the array for baseline bootstrapping, therefore ensuring an entire arm of the array will not be taken out of service due to the loss of a single UT or delay line.

### 3.2. Combiner architecture

The combiner architecture is defined by the topological layout of the array, and the need to realize the baseline bootstrapping combinations depicted in Figure 1. Figure 6 shows a two dimensional layout for a beam combiner that satisfies the requirements of the architecture initially discussed in Section 2. Input beams enter from the upper left and are labeled according to UT station (1/2/3) and arm (N/S/W). The input phase plane at 15° from horizontal connects the input beams via the dashed line. The nearest neighbor and complimentary outputs ($\pi$ radians out of phase) are labeled at lower left and right. Optics within the splitting and combination modules are chosen such that all '3' telescopes have one combination partner, '1' and '2' telescopes have two combination partners, and the W0, or vertex telescope has three combination partners. As will be discussed in Section 4, this has led to a mechanical design that is modular and will permit the array to operate whether it is populated with two unit telescopes or ten. All that is required is the switching of individual optics within a given module.

![Fig. 6. The optical layout of the ICONN beam combiner. The combiner architecture is determined by the topological layout of the array and the requirement for baseline bootstrapping between every telescope and its nearest neighbors.](image)

#### 3.2.1. Path length modulation

Modern fringe trackers rely on a path length modulation scheme in order to sample the fringe pattern at various intervals. ICONN will employ a temporal phase shifting scheme in which the outermost combination partner in any pair of telescopes has its phase stepped relative to its inner combination partner. Phase stepping, opposed to the typical linear fringe sweep for temporal schemes, does not result in the fringes being 'smeared' on the detector and increases the recovered fringe visibility. Phase shifts are introduced within the beam combiner by applying an optimized driving waveform to a piezo-electric transducer on which a flat mirror is mounted$^8$. The location of the bank of modulators is shown in Figure 6 for reference.
The modulation scheme consists of four discrete phase steps $\pi/2$ radians apart from each other. The VLTI MIDI instrument also uses phase stepping to measure the fringe parameters, but scans the fringe in approximately 0.1 seconds\(^9\). At MROI the wavelength is shorter and the steps are considerably faster: at the fastest feedback rates, each step is held for approximately 1.25 ms in order to meet the requirement of sampling the fringe in a minimum of 5 ms. Figure 7 shows measurements of the open-loop phase shifting scheme from the perspective of the modulator-mounted strain gauge for the Ks band. In addition to the phase stepped method, ICONN will have available the traditional linear sweep by driving the PZTs with a triangle wave.

The detector is read out at least once per step (multiple non-destructive readouts per step can be used to allow improved noise performance), but the detector pixels are not reset on every step, in order to decrease the readout time overheads. The “ZABCD” algorithm described by Colavita\(^{10}\) is therefore used to take account of this detector readout mode.

### 3.2.2. Optimized coatings

Custom broadband anti-reflection and beamsplitter coatings were designed at MRO to meet requirements placed on high throughput and fringe visibility contrast\(^{11}\). These coating designs took into account both optical and mechanical constraints. Unlike optical coatings used in more general applications, the coatings used in ICONN precisely control both amplitude and phase variations across the bandpasses. Not only do they have low optical losses, but induce minimal bending of their substrates during the application process. Figure 8 plots the visibilities, $V$, expected for the different outputs of ICONN as predicted by the measured performances of the fabricated coatings and substrates, normalized to those predicted for a combiner using perfect coatings on perfectly flat substrates ($V_{\text{ideal}}$).

The variations seen primarily arise from wavefront errors introduced by the substrates and coatings, non-ideal amplitude and phase responses of the coatings, and differences in their behaviors for the s and p polarization states. The visibility losses due to wavefront errors and group delay effects are both very small with maximum reductions of fringe visibility less than 2% and 0.8% respectively. Polarization effects contribute insignificantly to these fringe visibility losses with reductions in $V$ of only 0.10% or less.
Fig. 8. The calculated visibility (V) of the ICONN combiner based on the measured optical performance if its optical components, normalized by the visibility expected for a combiner using perfect optics (V_ideal). The visibility losses are at worst 3.5%, but for most of the combiner outputs are smaller.

The reader should note that Figure 8 does not include the largest contributor to visibility losses in ICONN which is a result of the architecture of the MROI itself. As mentioned in Section 2, some of the Unit Telescopes will have only one nearest neighbor, some have two, while the central telescope has three nearest-neighbors. The upshot of this is that at some of the ICONN beamsplitter plates, beams with unequal intensities are mixed. At worst this intensity mismatch leads to a visibility reduction of 8% as compared to a combiner mixing equal intensity beams, and this is by far the most significant reduction in fringe contrast (apart from internal optical misalignment) that we expect the design of ICONN to be compromised by. Overall, the custom coatings for the combiner meet the top level science goals for MROI and are well within the error budgets for the overall performance of the array.

3.3. Spectrograph

The spectrograph has been optimized to operate in either the H or K_s-band, and can multiplex up to five combiner outputs onto a single detector array. It primarily functions to spatially filter, spectrally disperse, and detect the resulting dispersed fringe patterns. Figure 9 is an isometric (left) and top (right) view of the spectrograph optical layout. The periscope optics take the linear output pattern of the beams and reconfigure them into an arc pattern. An initial set of off axis parabolas (OAPs) focus the combiner outputs through a set of pinholes and then a second set of OAPs recollimates them. The focusing and collimating OAP pairs are identical and arranged in an optical configuration referred to as Eccentric Mersenne Gregorian (EMG)\textsuperscript{12}. After recollimation the beams are dispersed by a set of Direct View Prisms (DVPs) before being focused onto the detector into five spectral channels. With the exception of the DVPs, all of the optics are reflective and achromatic. The detector is a Teledyne PICNIC array, with 256×256 pixels and a 40 µm pixel pitch. Since each spectrograph can multiplex up to 5 combiner outputs on one such array, a fully populated MROI, with 10 unit telescopes, that used both combiner outputs would require a total of four such spectrographs.
The focus OAPs have identical off axis distances and the same parent parabola with equivalent radius of curvature. Their foci are separated in the focal plane of the detector by laterally displacing them from one another in a direction perpendicular to the optical axis. The left panel of Figure 10 is a spot diagram showing the locations of the resulting dispersed fringe patterns on the detector. The OAP foci are displaced such that the combiner outputs form a 3-4-5 triangle on the array. Since there is no spectral filtering, light from all wavelengths from J through K will be sensed by the detector. However, only the five spectral channels corresponding to the H or Ks-band will be read out for fringe tracking.

The right panel of Figure 10 shows spot diagrams for the five combiner outputs in the spectral channels within the H and Ks bands that will be used. The diagrams for the different combiner outputs are shown adjacent to each other in the figure whereas in reality they are widely separated on the detector as shown in the left panel. The spectra to the left show the five dispersed outputs for the H-band optimized DVPs, while the dispersed outputs from the Ks-Band optimized DVPs at right. Each small box outlined in the vertical arrays labeled 1 through 5 represents a PICNIC array pixel. In both cases the same five spectral channels are read out, and these are highlighted in the figure by the boxes bounding the pixels (blue for H/red for Ks). The optical design calls for diffraction limited performance (Airy disk within a pixel) across both bands for the five spectral channels.

The detector is configured and operated with a controller from Astronomical Research Cameras (ARC) Inc. The controller is comprised of two dual-channel ARC-42 video boards, an ARC-32 clock driver, an ARC-50...
utility board, and an ARC-22 timing board. Communication with the controller is performed through a fiber optic link between an ARC-64 PCI interface board residing on a PC and the ARC-22 timing board on the controller. Details on the software used to interface with the detector and controller are given in section 5.

4. Mechanical design & fabrication

The mechanical design of ICONN is broken down into four subsystems: three warm and one cold. The warm subsystems are the switchyard, beam combiner, and periscope optics. The cold subsystem is the spectrograph. In realizing the optical architecture outlined in section 3, the ICONN optomechanical design is strongly characterized by its modularity. This approach has facilitated its overall design process, procurement for fabrication, pre-alignment, performance testing in the lab and the achievement of the required stability, and will be crucial during installation and alignment at the telescope site.

4.1. Warm optics

The switchyard design features interfaces between optical mount components and the supporting breadboard where the materials have been chosen so as to match their CTEs. This has allowed excellent long term stability, which will be very important for keeping co-alignment of the delay line axes to the beam combiner axes.

The optomechanical components of the beam combiner were designed with two guiding principles in mind. The first was ease of alignment, and the second was stability. It was determined that common to both these philosophies is a minimization of the number of possible adjustments. A close inspection of the combiner architecture illustrated in Figure 6 shows that the 39 individual optics are positioned within nine common optical planes. This architecture lends itself to a modular design philosophy whereby optics are rigidly mounted within common planes, and then those planes are positioned and oriented with respect to one another. Figure 11 is an overview of the combiner hardware. Optics are placed in cells, which are slid into modules (anodized mounts) with other optics that share a common plane. These modules are then located in position and orientation on two large steel plates. The plates are aligned in position and orientation to a reference laser using push-pull screws, and then bolted to the optical table.

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Figure 12 shows two images of the front and back surfaces of one of the populated optics modules. The optical cells are centered within the module by two locator dowel pins. Each cell is pressed into the same plane as the other optics with spring clamps and locked into place in the module using a vertical set-screw. Figure 13 shows the method by which the modules are clamped into place on the steel templates and then oriented with respect to the other modules. The location of each module on the template is identified by a bullet-nosed pin. This guarantees positioning between all modules with a tolerance better than 75 µm. A receptacle at one end of the module is then press fit into place on the template, providing a pivot point about which the entire module can be adjusted in orientation.

A second, eccentric pin is located at the opposite end of the module from the pivot point. The eccentricity of the pin allows the orientation of the module to be adjusted by rotating it. Every module in the combiner has this degree of freedom, and it is used to make all the modules parallel to each other. Spring plungers contact two perpendicular edges of the module, constraining all modules on the template to expand and contract (due to thermal changes) in the same direction. Finally, three L-shaped clamps lock the each individual module into place. Long term creeping is controlled by indexing each module on alignment templates made of the same material as the optical table (mild steel). This means that after alignment is completed, the optical components of the beam combiner are able to hold position and orientation between them on a nightly basis. Thermal tilt stability for the optical components meets the requirement of maximum ±25µrad for an over-night temperature variation of 0.1 °C inside the beam combining facility.
4.2. Cold optics

The ICONN spectrograph employs a modular design approach as well with a build-to-print philosophy for all the opto-mechanical design of the subcomponents installed on the cold plate, including the detector (Fig. 14). All structural materials of the spectrograph were thermally cycled to minimize stresses and consequently distortion during the cool-down process. Following the order that each module appears to the incoming beams from the periscope optics, they are: entrance windows, EMG OAPs 1, pinholes, EMG OAPs 2, DVP flipper mechanism, focus-OAPs and detector. Appropriate indexing of each module on the cold plate, minimal creeping between thermal cycles and an alignment procedure with minimal adjustments are also characteristics of the ICONN spectrograph design. For convenience, the pinhole module is installed at the point of symmetry of the cold plate (physical point on the cold plate that is kept unchanged during cool-down and warm-up cycles) and requires no adjustment. It is held in position using an athermal spring cell design.

The OAPs (for EMGs and focus) were diamond turned using a technique in which custom designed jigs allowed for the full parabola to be turned. The monolithic diamond turned mirrors each have the interface to its associated mount (EMGs and focus OAPs) precisely machined on its back. This scheme has allowed multiple sets of mirrors to be produced out of the same blank. The OAP segments were cut off the monolithic diamond turned mirrors using a wire-EDM technique (electro-erosion machine). Appropriate residue-free masking was applied to protect the reflecting surface of the segments. Clocking of each OAP to its location on the mount is achieved through dowel holes bored on the monolithic diamond turned mirror and associated mount.

A DVP flipper mechanism approach was chosen for the dispersing elements due to there being insufficient space for a prism wheel or slider inside the cryostat. In this design, H and K, DVPs are grouped together in a V-shaped (90° angle) monolithic aluminum cell. The DVPs are assembled in an arc, following the input beam pattern introduced into the spectrograph. Each DVP is made of a pair of circular concentric prisms with a center separation of 1 mm. All apex angles are different between DVPs. The first prism in the optical train is made of
Infrasil 301 and the second is made of BaF₂. During assembly of the prisms in the mount, there is the need to control:

- Concentricity between pairs of prisms
- Relative center separation between pairs of prisms (longitudinal direction)
- Relative rotation between pairs of prisms
- Relative position between DVPs in the mount (arc)
- Relative rotation between DVPs in the mount (in order to correct the direction of dispersion – parallel and perpendicular).

The mounting cell will guarantee the prisms to be optically concentric to within tolerance at both ambient and cryogenic temperatures inside the spectrograph. It will also correct the center separation when cooled to cryogenic temperatures. The mounting cell will also preserve critical alignment of all prisms even after a number of thermal cycles. Also important is that the cell should not allow thermally induced stress to build up in the prisms. These design drivers can be achieved using a spring finger cell design for each individual prism. The internal diameter of each cell is specified to lightly load the prism radially at room temperature and to have enough flexure to load the prism at cryogenic temperature without producing any stress beyond the material limit. Figure 15 shows the DVP flipper mechanism and a typical pair of spring finger cells for DVP prisms.

Following the DVP flipper mechanism is the focus-OAP module, which is responsible for taking light from the DVPs and focusing it onto the detector. It is composed of five identical OAP aluminum segments, i.e. with identical off-axis-distance, diameter and center thickness. As with the EMGs and DVPs, these segments are arranged in an arc and are slightly displaced when assembled on the front plane of the mount to separate their foci on the detector surface (recall Fig. 9). Figure 16 is the 3-D mechanical model of the Focus OAP mount, showing the back (left) and front (center) surfaces. Due to fabrication errors present in the cell of each OAP segment and in the mount support for the cells, and also considering assembling errors involved in positioning and orienting the segments correctly, individual motorized adjustments in tip and tilt are required (to center the wavelengths in the rows and columns of the array).

Due to limited space for implementing a tip/tilt mechanism for each of the five OAP segments, azimuth rotation is introduced around a pair of C-flex bearings using a Cedrat piezo-actuator (Figure 16 right). Rotation in
elevation is possible through the use of a hinge flexure driven in a push-pull configuration by a pair of Cedrat piezo-actuators. A range of ±150 μm of linear spot motion on the detector plane is required for both tip and tilt rotations at cryogenic temperatures. A minimum of 12.5 μrad of resolution is required for the fine-tuning (based upon the 40 μm pixel pitch of the detector). The focus-OAP module has been prototyped successfully in the laboratory, at both room and cryogenic temperatures, to verify that the hinge flexure and Cedrat piezo-actuators meet the requirements.

Figure 16. Cartoon of the focus-OAP module (back at left/front at center). The tip-tilt cell is illustrated at right. Laboratory testing has verified the cell design and chosen piezo actuators meet specifications for spot motion on the detector plane.

Figure 17 shows the dewar spectrograph during assembly and test in the laboratory. Full alignment in translation and orientation of the spectrograph on the ICONN optical table is possible through appropriate adjustment blocks and bolts. The dewar hold time exceeds 30 hours of steady temperature without the need to re-fill the vessel with liquid nitrogen.

Fig. 17. ICONN spectrograph during assembly and test.

5. Software Architecture

5.1. Context

The principal role of the ICONN control software is to perform real-time processing of fringe data in order to derive correction signals, which are sent to the MROI delay lines to compensate atmospheric piston fluctuations. The software is also required to carry out a number of other functions, including: automated fringe searching after the MROI switches to a new observing target, continuous capture and streaming of engineering monitor
data, and occasional calibration of the open-loop drive signals for the ICONN path modulators and alignment/adjustment of the periscope mirrors, focus OAPs and focus stage. Alignment of the ICONN switchyard mirrors is handled by a separate MROI sub-system, the Automated Alignment System (AAS), as part of the overall start-of-night alignment of the interferometer beam-trains.

When deployed at the MROI, the ICONN control software will be interfaced to the interferometer's high-level supervisory control system (ISS; Interferometer Supervisory System), which configures and starts the MROI sub-systems at the start of the night, sequences observations, collects science and engineering data, handles fault conditions, and provides user interfaces for telescope operators and scientists. Communications with the ISS, and between ICONN components deployed on different computers utilizes a gigabit Ethernet network. A dedicated low-latency RTnet Ethernet link is used for communications between ICONN and the delay lines, as described below.

Interfacing of the MROI sub-systems to the ISS is accomplished via a custom software framework, the Generic System Interface (GSI). This generates network interface code in either the Java or C programming language given a set of spreadsheets defining the high-level object-oriented interface to a system or set of related systems. These spreadsheets define the commands (methods) and parameters implemented by a system, as well as the properties of monitor data items published by the system.

The ICONN software has been designed for a phased implementation, where individual software components are developed to support laboratory tests of prototype and final hardware, and subsequently integrated with each other and with the ISS. Upgrades of the hardware from the initial configuration, such as the addition of further detectors and baselines, can also be accommodated.

5.2. Overall architecture

The ICONN control software consists of the following components, each providing a distinct subset of the overall functionality. Each component corresponds to a system type with a defined interface to the ISS. Systems are required to have a type name which is unique amongst all MROI sub-systems – this is ensured by prefixing the names with “FT” for Fringe Tracker.

- **FTSystem**: receives commands from the ISS, manages the high-level modes of the system and sets sub-system parameters consistently. For example, FTSystem is responsible for switching between fringe searching and tracking modes on fulfillment of the appropriate conditions, and configuring the path modulation and detector read out to suit the observation waveband and cycle time specified by the ISS.

- **FTModulator**: generates the periodic drive waveform for a path modulator, tied to synchronization pulses (also used by the camera read out) from a timing board. The component also captures and publishes time-stamped modulator strain gauge data.

- **FTCamera**: configures the camera read out scheme (e.g. number of subframes, subframe location(s), exposure time etc.) for a particular fringe camera. FTCamera activates or deactivates a sequence of exposures when commanded to do so by FTSystem. During an exposure sequence, FTCamera deinterlaces the raw pixel data and makes it available to FTFringeEngine in real time.

- **FTFringeEngine**: performs real-time fringe data processing (fringe detection or group-delay/phase tracking as set by FTSystem), and thence transmits offset demands to the delay lines over the dedicated low-latency link.
- **FTDewar**: interfaces to the filter wheel and DVP wheel actuators and to the dewar temperature and pressure sensors. This component publishes sensor data, and executes actuator motions in response to commands from FTSystem.

- **FTAlignment**: interfaces to the tip-tilt actuators for the focus OAPs (in the dewars) and the periscope mirrors (on the beam combiner optical table), and executes actuator motions in response to commands from FTSystem.

In addition to the functions listed above, all of these components individually stream monitor data to the ISS Data Collector, which imports the data into a central database and publishes a subset to the operator interfaces.

The functional components have been grouped into a smaller number of processes, based on the programming languages used and to facilitate communication and resource sharing between related components. In order to use the GSI, each process must have a single parent system instance, hence two additional components are needed as containers. These are FTRealTime, which contains an FTFringeEngine instance and one or more FTCamera instances representing individual fringe cameras, and FTModulatorController, which contains one or more FTModulator instances representing individual modulators. As FTSystem, FTDewar and FTAlignment are all Java systems they have been grouped together for simplicity. FTModulator and FTRealTime are implemented in C. These component groupings are shown in Figure 18 in the form of a UML class diagram.

Figure 18: The components of the ICONN software, expressed as a UML class diagram. Each green rectangle represents a class (type) and lists one or two example methods of that class. The software consists of three processes, each comprising a single instance of a parent type (e.g. FTModulatorController) and
one or more instances of subordinate classes. Each class provides a distinct subset of the overall functionality. High-level commands are received by FTSystem from the ISS supervisor and translated into lower-level commands to the other components. All components publish engineering monitor data to the ISS.

5.3. Real-time architecture

The key performance requirement for ICONN is the need to close the fringe tracking servo loop with an update rate as fast as 200 Hz, with a small overall latency. In order to achieve sub-millisecond latency on every servo cycle, the software runs under the Xenomai real-time operating system (version 2.6). Although a soft real-time system would be suitable for coherencing at frame rates below 50 Hz or so, we have exploited our experience with using Xenomai in more demanding applications\textsuperscript{13,14} to deliver latencies that are comfortably short enough for phase tracking too. Xenomai has two important properties that are exploited in this project:

- It runs in “hard real time”. Consequently it reacts to hardware inputs and controls hardware outputs with minimal and predictable delays. This is a very useful property for introducing a computational element to servo loops, as is needed for ICONN.

- It coexists with Linux. This means that the richness of the Linux system infrastructure is available to the software whenever hard real time performance is not required.

Both Linux and Xenomai have a “user-space” and a “kernel space” component:

- Kernel space contains the core system functionality, such as hardware interfaces and memory management. Code running in kernel space has few restrictions on what it can do.

- User space is where the user interacts with the system. There are more restrictions on what code is allowed to do in user space, but it is much harder for user space code to crash the system. Floating point operations are available in Xenomai user space, whereas they cannot be used in kernel space. We have designed the ICONN software to use the minimal amount of kernel-space code, to make the code more robust and easier to debug.

A number of APIs (Application Programming Interfaces) are provided by Xenomai. These provide services such as clocks, interrupt handling, thread synchronization, and communication across the barrier between user space and kernel space. We have chosen to use the Xenomai “POSIX skin” API, which overloads many of the standard POSIX system calls with replacements that exhibit real-time determinism when used in the appropriate context. The Xenomai POSIX API has the following advantages:

- It facilitates porting to other real-time operating systems, in particular the forthcoming Xenomai 3 and standard Linux with the PREEMPT_RT kernel patches (these endow Linux with limited real-time capabilities);

- Source-code-level compatibility with the MROI Generic System Interface framework, which uses the POSIX threads API;
Availability of a POSIX-compatible message queue API for inter-thread communications (between any pair of real-time or non-real-time threads, and within or between kernel space and user space). We have used this API extensively for thread synchronization rather than the traditional, but error-prone approach of thread locking using mutexes.

There are three software components involved in closing the fringe tracking loop, all of which run under Xenomai. FTCamera and FTFringeEngine both run on the same standard PC and their user-space threads coexist in the same process, sharing an address space. The delay line metrology software, responsible for closing the position loops for all MROI delay lines, is also used to apply fringe tracking corrections. The metrology software runs on a separate VME-bus computer. The separation between FTCamera and FTFringeEngine is for modularity, allowing further FTCamera instances to be added as extra fringe cameras are incorporated into ICONN (the initial implementation uses a single camera). The Xenomai add-on RTnet is used for hard real-time communication between the fringe tracker and delay line computers, over a dedicated point-to-point Ethernet link.

We have implemented a stateless message protocol on top of UDP for bi-directional communications over this low-latency link. Messages from the fringe engine contain offsets or fringe search trajectories to be applied by the delay lines. Messages from the metrology system contain time stamped delay line position measurements, for potential use by the fringe tracking servo. We have measured worst-case round-trip latencies at 90–100 µs for a point-to-point RTnet link carrying these messages. This measurement includes the interrupt response time at both ends of the link, therefore we would expect a one-way transmission to complete in under 50 µs.

Besides communication with the delay lines, the other potential bottleneck in the servo loop is the latency associated with transferring pixel data from the camera controller to computer memory and activating the data processing task. Our implementation minimizes this by taking advantage of the Direct Memory Access (DMA) capabilities of the camera controller PCI interface card and Xenomai’s ability to run a custom kernel-space interrupt handler with minimal latency (measured as ~5 µs under typical conditions). Fortuitously, the ARC-64 card can be configured to signal an interrupt on the PCI bus when transfer of a frame into computer memory is complete. We have written a custom interrupt handler that simply signals a real-time user-space thread in FTCamera that new data is available. The PCI card writes frames using DMA into a circular buffer in the host computer memory, whose start address can be found by calling a function in the ARC user-space software library. The user-space FTCamera thread determines the address of the latest frame by counting frames and multiplying the frame count by the known frame data size. The frame size is a function of the read out parameters, which are also managed by the FTCamera software component.

The FTCamera user-space thread timestamps the frame (using a NTP-synchronized clock provided by Xenomai) and copies the pixel data to another circular buffer, rearranging the data into a more convenient order for subsequent processing as it does so. A message queue is used to signal the FTFringeEngine real-time user-space thread that a new frame is available for processing. This processing thread waits until new frames from one or two cameras are available (depending on the instrument configuration), then processes the data from a short sequence of recent frames baseline-by-baseline to yield a set of delay estimates. Offset commands to the delay lines are derived from these and sent using RTnet from the same thread. While the FTFringeEngine thread is processing data, the FTCamera thread(s) are suspended, waiting for notification of the next frame.

Both raw pixel data and the results of fringe data processing are made available to non-real-time threads by means of circular buffers, with message queues used to transmit a pointer to the head of the buffer. These threads publish monitor data to the ISS over the network or display it in a graphical user interface. The architecture of the real time processes, and communication within them, are shown in Figure 19. An overview of the ARC “Leach” controller is given in section 3.3.
5.4. Timing and synchronization

Phasing of the detector reads with the path modulation, maintaining the periodicity of the open-loop modulator drive signals, and use of the correct modulator position by the data processing algorithm are all crucial to successful operation of ICONN. To achieve these goals, three synchronous clocking sources are used: a one pulse per second clock, a 10 MHz clock, and a frame rate clock.

The one pulse per second clock (1 PPS) and 10 MHz clock are generated by a Symmetricom bc635PCI-U timing card hosted in the fringe engine computer. The 1 PPS clock is used to align other clocking sources to GPS time and hence synchronize the modulation and detector read out to GPS time for convenience. The 1 PPS acts as a trigger to the modulator waveform synthesizer. The 10 MHz clock is used as the PLL reference clock for the modulator waveform synthesizer. Hence this clock determines the base frequency for the synthesized waveforms.

The frame rate clock is generated by the modulator synthesizer and its period is the duration of a modulator hold position. This clock is used to trigger the detector read out. Once read out is complete the detector frame (typically comprising multiple reads of each physical pixel) is transferred into computer memory with minimal latency as described above.

The fringe engine determines the modulator position at the time of each detector read within the frame by dead reckoning. The inferred modulator position is used to estimate the fringe phase, and also to discard data close to the modulator steps (step pyramid modulation) or turn-around times (triangle modulation). Inference of the correct position relies on synchronization of the modulation and detector read out, repeatability of the modulation, and a model for the detector read out timing.
5.5. Algorithms

The ICONN real-time software is structured so that alternative delay estimation algorithms can be integrated straightforwardly, and algorithms can be tested independently of the real-time code. As the algorithms run in Xenomai user-space real-time, they can use the computer’s native floating point capabilities. The initial implementation pre-processes the raw pixel data to remove the reset level and average multiple reads, assembles the ABCD measurements needed to extract the fringe amplitudes and phases for each spectral channel, and then uses the algorithm of Basden & Buscher\textsuperscript{15} to estimate the group delay on each baseline. These data are then used to compute “best estimates” of the offsets to be sent to the delay lines for coherencing of the fringe data.

A noteworthy feature of the real-time software is that it can be configured to generate fake camera data on the fly, and pass this to the data processing routines in exactly the same way as real data would be transferred. We have written code to generate fake camera data containing idealized fringes and used this to test our implementation of the Basden & Buscher algorithm.

6. Expected potential

The overall design philosophy of the MROI has been to seek to optimize every sub-system in the array so as to achieve an overall gain in sensitivity of around a factor of 100 over contemporary interferometric arrays (see Buscher et al, this volume). Individually, each sub-system (e.g. the unit telescopes, the beam relay system, the delay lines, etc) may only improve on existing implementations by a small factor, perhaps through enhanced throughput or by reducing fringe contrast losses, but their cumulative effect can still be large.

Several aspects of the design of ICONN reflect this optimization. By separating out the function of fringe tracking from the science instrument, ICONN is able to capitalize on a pairwise optical design that maximizes the instantaneous fringe contrast in comparison to combiners that mix larger numbers of beams at once. Because ICONN is designed primarily for group delay tracking, it is able to use longer exposure times than is typical for a high-accuracy science instrument or a cophasing fringe-tracking combiner. These design considerations may recover as much as one magnitude of sensitivity for the system as compared with typical fringe-tracking implementations. In addition, by using unpolarized light, ICONN will have available twice the amount of light compared to the FINITO fringe tracker\textsuperscript{16} on the VLTI. These gains will be available regardless of how resolved the target may be since, at the MROI, reconfiguration of the array layout will allow the nearest neighbor baselines to be scaled so as to ensure that the fringe contrast (aka correlated flux) on the tracking baselines remains high.

7. Current Status

ICONN is currently being integrated and tested by means of a series of laboratory experiments termed the closed-loop fringe experiment (CLFE)\textsuperscript{17}. The CLFE is an on-going laboratory demonstration of ICONN and its functionality and acts as a testbed, in conjunction with a numerical simulator, for fringe tracking algorithm development as well as further hardware and software prototyping. Demonstration of fringes with real-time compensation of a varying phase fluctuation will be performed using a complete opto-mechanical set-up and software suite. The laboratory set-up for the CLFE is shown in Figure 20. In the figure, broadband collimated light is output from the fiber/ OAP assemblies mounted on a pair of piezo ultrasonic motor slides from Nanomotion. One of the slides may be used to introduce known shifts in the OPD with the other slide acting as a delay line, tracking OPD shifts. Light from the fiber/ OAP assemblies is directed through the mock switchyard, propagated through the combiner and into the spectrograph using the periscope optics, where is spatially filtered, spectrally dispersed and detected. The CLFE takes advantage of the modular design of ICONN, which allows simulated telescopes to be added, removed, or re-located straightforwardly to suit the desired experiment.
The CLFE is currently in its initial phase during which the cold optics are not used and the dispersing element is located external to the dewar. The first major objectives are to demonstrate synchronization of the path length modulation and the detector read out, and to close the fringe tracking loop around synthesized piston fluctuations.

We have implemented preliminary versions of the ICONN software components for use in the initial phase of the CLFE. The main difference from the expected final implementation is that the network interfaces to the ISS shown in Figure 18 are not present. Instead each process has its own user interface (implemented using GTK+ or Curses) and a capability to record engineering data to a local file.

In the CLFE a Nanomotion slide is used to apply path corrections, as a proxy for the MROI delay lines. Hence the delay line metrology software is replaced with a temporary component that presents an identical RTnet interface for receiving offsets from the fringe tracker. This interface accepts offset commands and applies them to the slide. This is done with higher latency than for the real delay lines, in part because offsets are transmitted from the delay line proxy computer to the slide servo controller (a Galil DMC-4123) over non-real-time Ethernet.

Subsequent experiments will add the cold optics and test throughput and stability of the overall instrument design. The software will also be developed towards its final implementation, including implementing all of the components and integrating these with each other and with the ISS. We also expect to add additional baselines in order to develop and test the baseline bootstrapping algorithms.

8. Conclusion

The MROI fringe tracker ICONN serves as the heart of the interferometer and ultimately determines the array's limiting magnitude. The baseline bootstrapping scheme implemented within ICONN provides a means to stabilize fringes on shorter nearest neighbor baselines where the visibility is higher building up to longer baselines. This will allow the MROI to fringe track faint targets with long baselines. ICONN has been designed as a modular
instrument to suit the various commissioning needs of MROI as not only more telescopes are added to the array, but other beam combining instruments as well. The primary role of the software is to determine the tracking offsets and command the delay lines in hard real-time while still interfacing with the interferometer's high-level control system. Real-time operations are performed under Xenomai and use an RTnet link to ensure hard real-time communication with the delay lines.

Currently ICONN is undergoing a series of laboratory developments in which all hardware and software are being integrated. During this process, the modular design scheme in which minimal adjustments are available and strict tolerances are imposed on the opto-mechanics has proven to produce a stable instrument. The software in which camera data is processed under Xenomai and values relayed to a simulated delay line using the RTnet protocol have been shown to perform successfully.

9. Acknowledgments

The Magdalena Ridge Observatory was funded by Agreement No. N00173-01-2-C902 with the Naval Research Laboratory and is funded through an institutional revenue bond from the New Mexico Institute of Mining and Technology (NMT). The MROI is hosted by the NMT at Socorro, NM, USA, in collaboration with the University of Cambridge (UK). Our collaborators at the University of Cambridge wish to also acknowledge their funding via STFC in the UK.

10. References

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