The MROI fringe tracker: Closing the loop on ICoNN

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ABSTRACT

The characterization of ICoNN, the Magdalena Ridge Observatory Interferometer's fringe tracker, through labortory simulations is presented. The performance limits of an interferometer are set by its ability to keep the optical path difference between combination partners minimized. This is the job of the fringe tracker. Understanding the behavior and limits of the fringe tracker in a controlled environment is key to maximize the science output. This is being done with laboratory simulations of on-sky fringe tracking, termed the closed-loop fringe experiment. The closed-loop fringe experiment includes synthesizing a white light source and atmospheric piston with estimation of the tracking error being fed back to mock delay lines in real-time. We report here on the progress of the closed-loop fringe experiment detailing its design, layout, controls and software.

Keywords: MROI, optical interferometry, fringe tracker, fringe tracking

1. INTRODUCTION

The Magdalena Ridge Observatory Interferometer (MROI, see paper 8445-23 of these proceedings) will employ a dedicated fringe tracking beam combiner.[1] The Infrared Coherencing Nearest Neighbor (ICoNN) tracker is a pairwise, bootstrapping beam combiner operating in the H and K_s bands. To realize MROI's science goals, ICoNN's performance must be maximized because it will ultimately set the limiting magnitude. Verification of the beam combiner's architecture has been shown previously through the first fringe experiment.[2] The next phase of laboratory experiments characterizing ICoNN will integrate the hardware and software components together.

In preparation for first fringes, the real time process of taking data, calculating a tracking error and sending out the correction signal will be tested via the closed-loop fringe experiment. Performing these operations first in the laboratory allows one to identify software bottlenecks and optimize tracking algorithms prior to final implementation. Interfacing the MROI control system[3] will be further defined in the experiment.

The MROI Automated Alignment System (AAS)[4] responsible for nightly alignment of the array is a critical subsystem of MROI needed for the closed loop fringe experiment. The AAS provides the light source for the experiment and offers calibration and alignment automation. The functionality of these components will be shown within the closed loop fringe experiment.

In this paper we first outline the framework of the closed-loop fringe experiment and detail each component. The experiment has been designed to minimize differences from the final implementation at the observatory. Current progress is shown followed by future plans and expansion of the experiment in the final section.

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2. EXPERIMENTAL CONFIGURATION

A graphical description of the experimental setup is shown in figure 1. In the figure, hardware components are shown as rectangles and software components as elliptical objects. Only a high-level view of the software is shown with each ellipse representing the top-level component running on a particular computer. Individual paths from simulated unit telescopes are shown as solid lines with the dashed lines corresponding to time critical software communication paths involved in closing the loop. The dot-dashed lines are non-time critical software communication paths. The communication paths are labeled with their primary function. The AAS is shown as a diamond shape representing a separate subsystem with its interfaces to ICoNN defined.

The diagram shows two distinct flows: the primary optical path between hardware components, and the time critical data flow between software components involved in closing the fringe tracking loop.

For the primatry optical path flow, collimated light produced by the Magic Optical Box (MOB) is output on a pair of positioning slides. These act as inputs to the beam combiner coming from higher up in the optical train. One slide introduces simulated atmospheric piston error (atmospheric slide, Atm. Slide in the figure) and the other slide simulates a delay line (delay line slide, DL Slide in the figure) used to correct the optical path difference or fringe error between the two inputs. The switchyard aligns the inputs to the beam combiner where path modulation and combination are performed. The periscope optics are used to align the beam combiner to the spectrograph (SPX in the figure). The spectrograph disperses the combined light into a row of pixels on the detector signifying the end of the primary optical path flow.

The time critical software data flow takes over and reads the detector or focal plane array (FPA) using a real-time process shown as FTRealTime. The process is run under the real-time Linux framework Xenomai and represents the brains of the fringe tracker. FTRealTime then calculates the fringe error, conditions the error signal and sends it back to the delay line slide (tracking offsets) closing the loop on ICoNN. FTRealTime is also responsible for setting up the detector and synchronizing reads with the modulation strategy executed by the FTModulator process. Details on the modulation strategy are given in section 3.3.

Other hardware and software flows shown in figure 1 are controlled by the AAS. For alignment, a flip mirror located after the beam combiner is used to direct the combined light to the tilt/shear sensors (TSS). The AAS then uses the beam shutters prior to the beam combiner with the TSS to determine the tilt and shear of the input beams. The tilt and shear are then corrected for with the switchyard. Other software components in figure 1 control the atmospheric slide (Simulator) and perform housekeeping and alignment tasks on the spectrograph (FTDewar and FTAlignment respectively).

Details of each component of ICoNN and the AAS involved in the experiment are now given.

2.1 ICoNN

The primary responsibilities of ICoNN in the closed loop fringe experiment are:

- Modulate and combine light
- Spatially filter and spectrally disperse combined light
- Read out detector and determine fringe error
- Control delay line slide.

The first two responsibilities are performed by hardware, the second two by software.

The interferometer array configuration was designed to employ the baseline bootstrapping technique.[5] Baseline bootstrapping offers a higher signal-to-noise ratio for fringe tracking due to the increased fringe contrast on the shorter baselines. For MROI, the nearest neighbors are phased from the inside outwards, as shown in figure 2(a). In the figure, all '1' elements are phased to the central element 'W0'. All '2' elements are phased to their respective '1' neighbors and so on. This combination scheme is performed in the beam combiner shown in figure 2(b).

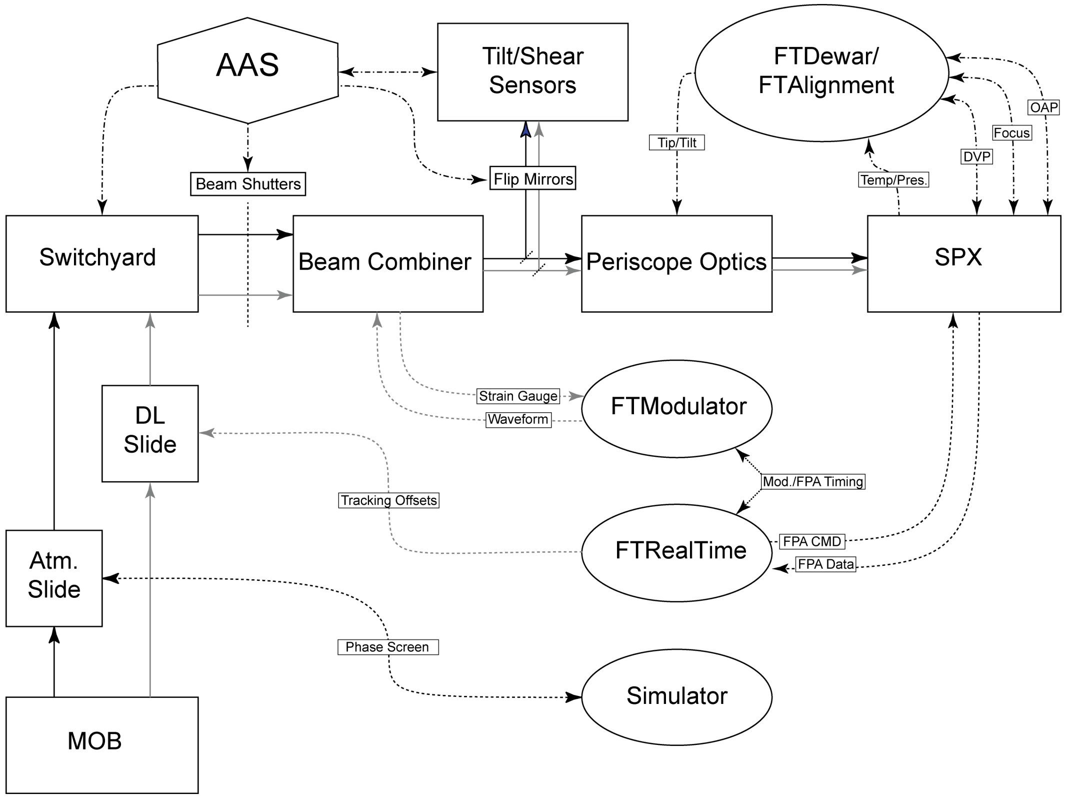
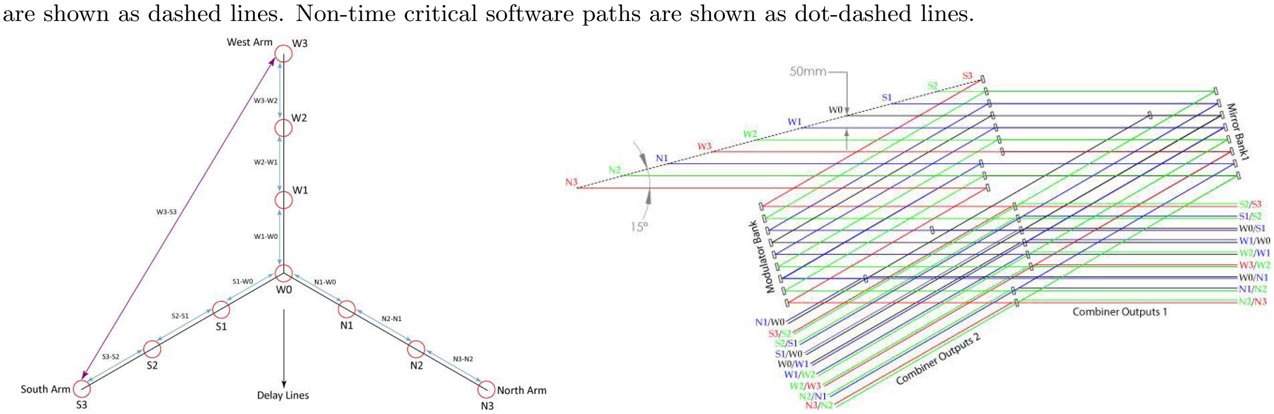


Figure 1. Block diagram of the closed loop fringe experiment. Hardware components are shown as rectangles and software components as circular objects. Light paths are represented by solid lines with time critical software communication paths are shown as dashed lines. Non-time critical software paths are shown as dot-dashed lines.



(a) (b)

Figure 2. Left: MROI array configuration. The array is phased from the inside out on the nearest neighbor baselines. Right: Beam combiner optical trace performing nearest neighbor combinations.

Prior to combination, the outer partner's phase is modulated relative to its inner partner. The modulation scheme involves stepping the modulator in increments introducing a $\pi/2$ phase shift into the resulting fringe pattern.[1,6] One period of the fringe is to be recorded for the fringe tracking algorithm requiring four steps of the modulator. The modulation occurs on the bottom left bank of mirrors in figure 2(b).

Inside the spectrograph the combined light is spatially filtered by focusing the beam through a pinhole and recollimated using a set of off-axis parabolas (OAPs) shown as EMG1 and EMG2. The recollimated light is spectrally dispersed by a set of direct view prisms (DVPs), and focused onto the detector, a Teledyne PICNIC array, into a row of five pixels with a set of focus OAPs. Readout of the detector is done by an Astronomical

Research Cameras (ARC) Inc. Leach controller comprised of a 250MHz fiber optic timing board (ARC-22), a clock driver board (ARC-32), two dual readout infrared video boards (ARC-42), and an utility board (ARC-50). The Leach controller will be used to perform multiple nondestructive reads in several different readout modes reducing the readout noise.[7] It must also be synchronized with the path modulation. The spectrograph optics are shown figure 3. The focus OAP prototype in the figure is removed for operation.

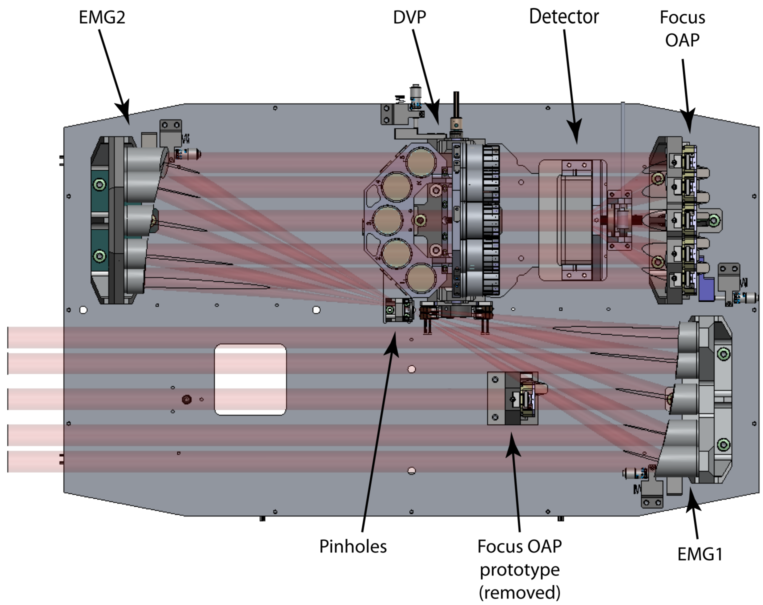


Figure 3. Layout of the spectrograph optics. Light enters the spectrograph from the bottom left and is spatially filtered by focusing it through pinholes using a set of EMGs. The recollimated beams are spectrally dispersed with DVPs and focused onto the detector in row of five pixels using the focus OAPs.

Once the detector is read by Leach controller, the data flows to the FTRealTime process. The process builds a 5×4 data frame of pixels and modulator steps and calculates the fringe error by either a group delay tracking algorithm or a cophasing algorithm. The fringe error is conditioned and sent to the delay line slide to minimize the optical path difference. Because the delay line slide can accept updates faster than they can be determined by the process, the fringe error signal is conditioned to provide a smooth response.

At the fastest feedback rates, corrections are made in 5ms intervals. Reaching this rate requires a data frame to be made within 5ms resulting in the minimum hold time of a modulator step being 1.25ms. This will be detailed more in section 3.3.

ICoNN's hardware and software in the closed loop fringe experiment is implemented as close to the final configuration required by the observatory as possible with a few exceptions. The communication channel between the fringe engine and delay line slide must be altered to accommodate the delay line slide conditioning. The delay lines used at the observatory will be able to accept updates faster than the delay line slide.[8] The switchyard layout must also be reconfigured to fit on one optical table.

2.2 AAS

The AAS has three critical responsibilities for the closed loop fringe experiment:

- Provide a coherent light source
- Remove tip/tilt and shear from the individual beams
- Perform spectral calibration.

A coherent light source is provided via the Magic Optical Box (MOB) shown in figure 4. The MOB is comprised of a laser source and white light source that are injected into a two input by two output fiber coupler. A 12mm collimated beam from each fiber output is made with an off-the-shelf reflective collimator. One reflective collimator is mounted on the delay line slide and the other on the the atmospheric slide to simulate inputs from an unit telescope.

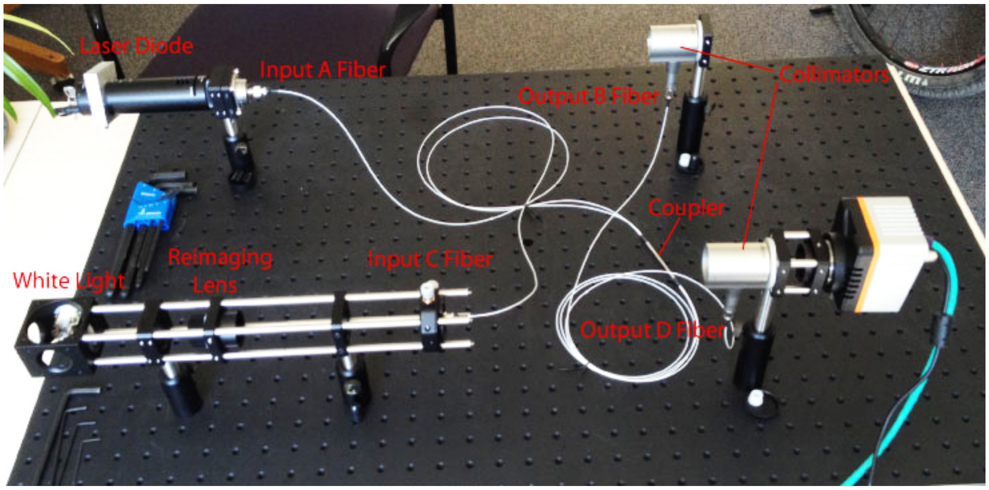


Figure 4. The MOB. Light from a laser source and white light source are fed into separate fibers. After a fiber coupler, outputs contain light from both sources.

Removal of tip/tilt and shear from each of the input to the beam combiner is performed by the Tilt and Shear Sensor (TSS). The TSS is located at the output of the beam combiner and light is directed to it via a flipper mirror. Beam shutters located prior to the beam combiner are used to allow only the reference beam through initially, followed by the its combination partner. Alignment error is determined by an algorithm and corrected for with the switch yard mirrors.

Because only five pixels are used for the fringe error calculation, the bandpass of interest must be precisely located within those pixels. The AAS spectral calibrator will perform this task. Spectral calibration is done in a manner similar to that in a fourier transform spectrometer.

All responsibilities of the AAS in the closed loop fringe experiment, aside from the flipper mirrors, will be implemented in their final configuration. No other modifications will be needed when relocated from the laboratory to the observatory.

3. CURRENT PROGRESS

This section highlights the current progress on the various components of the closed loop fringe experiment.

3.1 Hardware

Shown in figure 5 is the ICoNN hardware in the laboratory. The optomechanics of the beam combiner and switchyard are complete. The spectrograph was delivered in November 2011. Fabrication of the optics and optic mounts located in the spectrograph is partially complete (refer to SPIE 8445-92 of these proceedings for more information). The periscope optics interfacing the beam combiner and the spectrograph are being finalized. All ICoNN hardware components required for the closed loop fringe experiment are to be delivered by the end of 2012.

As shown in figure 4, the MOB is complete and currently being tested. The other AAS interfaces to ICoNN, namely the beam shutters and flipper mirrors have been completed and are entering the testing phase.

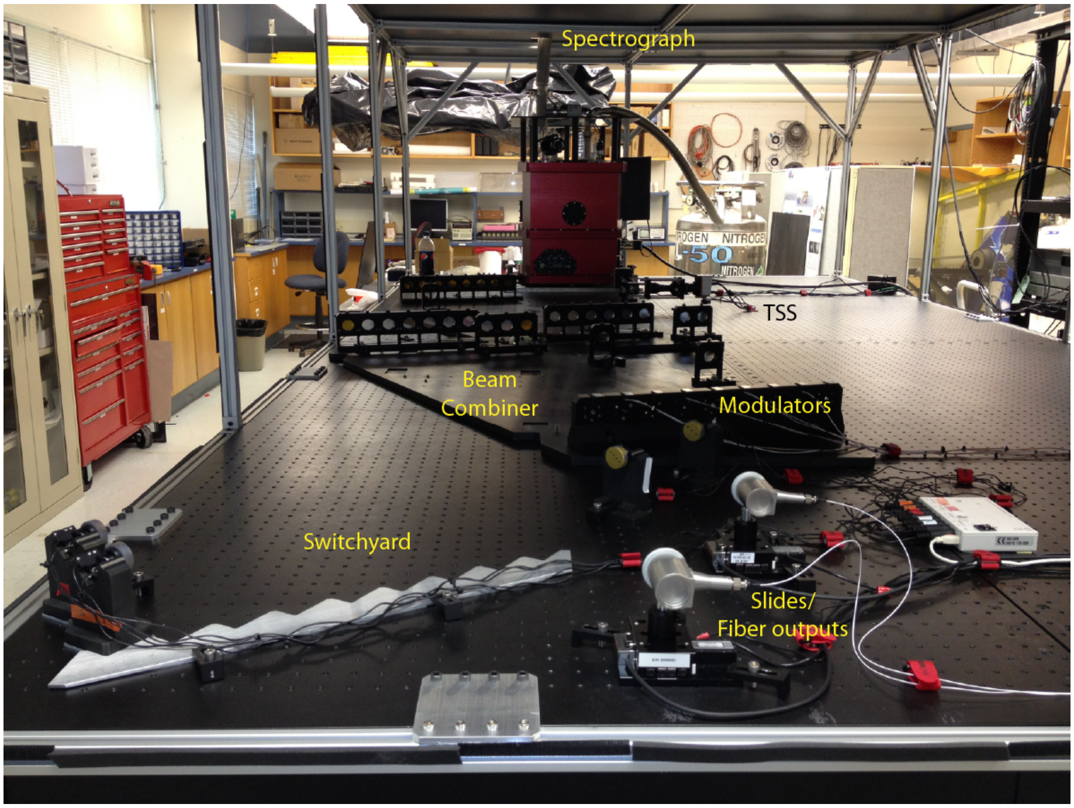


Figure 5. Picture of hardware comprising ICoNN in the laboratory.

3.2 Software

Much of the effort behind the closed loop fringe experiment has been focused on software infrastructure. The relationship between the modulator driver, fringe engine, camera read out, and spectrograph monitoring system along with the overall interaction with the Interferometer Supervisory System (ISS)[3] has been defined. These definitions are organized into five functional components operating under three unique processes:

- FTSystem
  - FTDewar - Spectrograph housekeeping, DVP interface
  - FTAlignment - Periscope optics alignment, focus OAP alignment
- FTModulatorController
  - FTModulator - Modulation scheme
- FTRealTime
  - FTCamera - Camera interface and setup, data collecting
  - FTFringeEngine - Data processing, fringe error conditioning

FTSystem receives commands from the ISS and distributes them to the various components while all three processes report to the ISS however. Figure 6 shows this organization as a unified modeling language class diagram.

The FTRealTime architecture is shown in more detail in figure 7. The complexity is due to the need to retrofit a hard real time response capability to commercial camera software written by Astronomical Research Cameras (ARC) Inc.

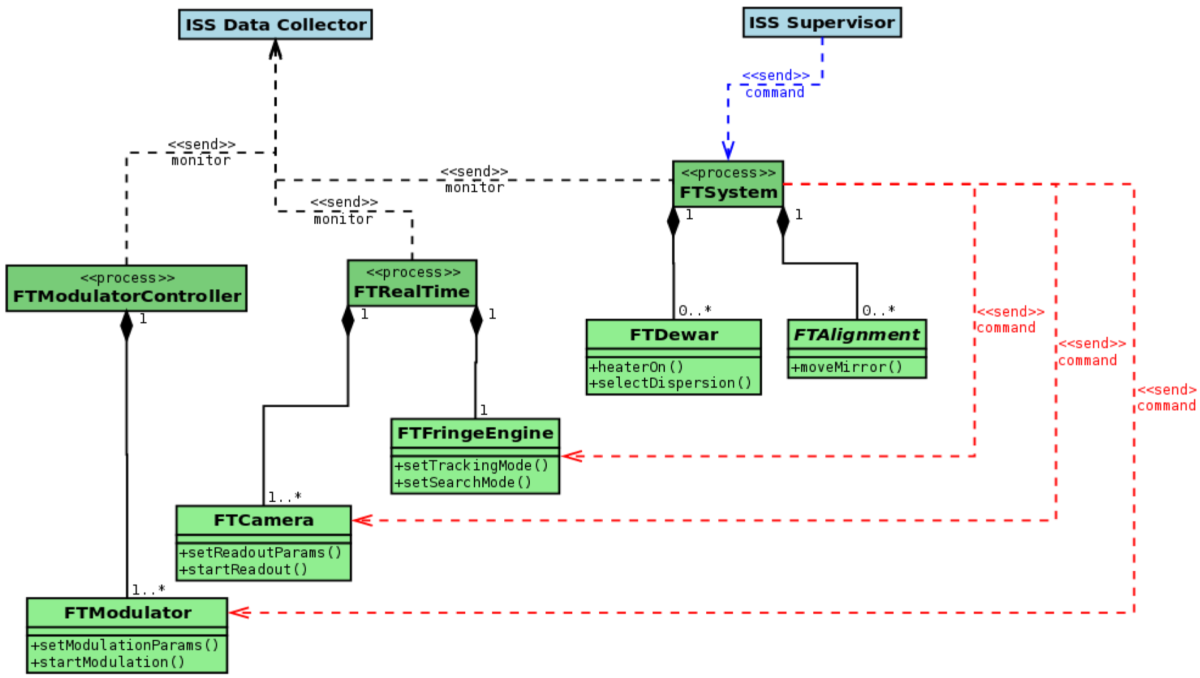


Figure 6. The ICoNN software structure shown as an UML class diagram.

The detector is configured, controlled and run by the Leach Controller, which in turn is controlled by a PCI card in the host computer. The PCI card also serves to upload microcode to the Leach Controller, transfer camera data to computer memory via Direct Memory Access (DMA) and generate interrupts when these transfers are complete.

The PCI card communicates with two software drivers. One is the unmodified ARC driver, which performs housekeeping functions such as configuring the camera and initiating readout. The other is a custom Xenomai driver, whose sole purpose is to intercept PCI card interrupts with hard real time latency and forward those notifications to both the ARC driver (for compatibility) and to a custom hard real time Xenomai library.

The ARC driver interfaces with ARC's C++ Application Programming Interface (API) to allow users to control the camera. In this application it is used for the abovementioned housekeeping tasks. There is also a C wrapper for compatibility with C code used to interface with the Interferometer Supervisory System (ISS). Both the ARC API and the C wrapper will need to be customised to implement the custom camera readout requirements of the project.

The Xenomai driver, on the other hand, just notifies code in the custom Xenomai library that an interrupt (and hence camera data) has arrived. It does so with hard real time latency. The library code reads the camera data from memory where the PCI card left it and passes it to FTFringeEngine code that also runs in hard real time. The fringe engine uses the data to calculate delay line offsets, including the signal conditioning necessary to optimize delay line slide (or, ultimately, delay line trolley) response. The offsets are passed back to the library and finally sent to the delay line slide computer using RTnet, a hard real time ethernet framework.

Overall control of the code in FTFringeEngine and FTCamera is managed by non-real-time FTFringeEngine methods and FTCamera methods respectively. These in turn interact with a user interface or other sequencer such as FTSystem.

3.3 Modulators

The modulators used within ICoNN will be operated in two different modes: calibration mode and operation mode, both shown in figure 8. In calibration mode, the driving waveform is optimized by an iterative algorithm,

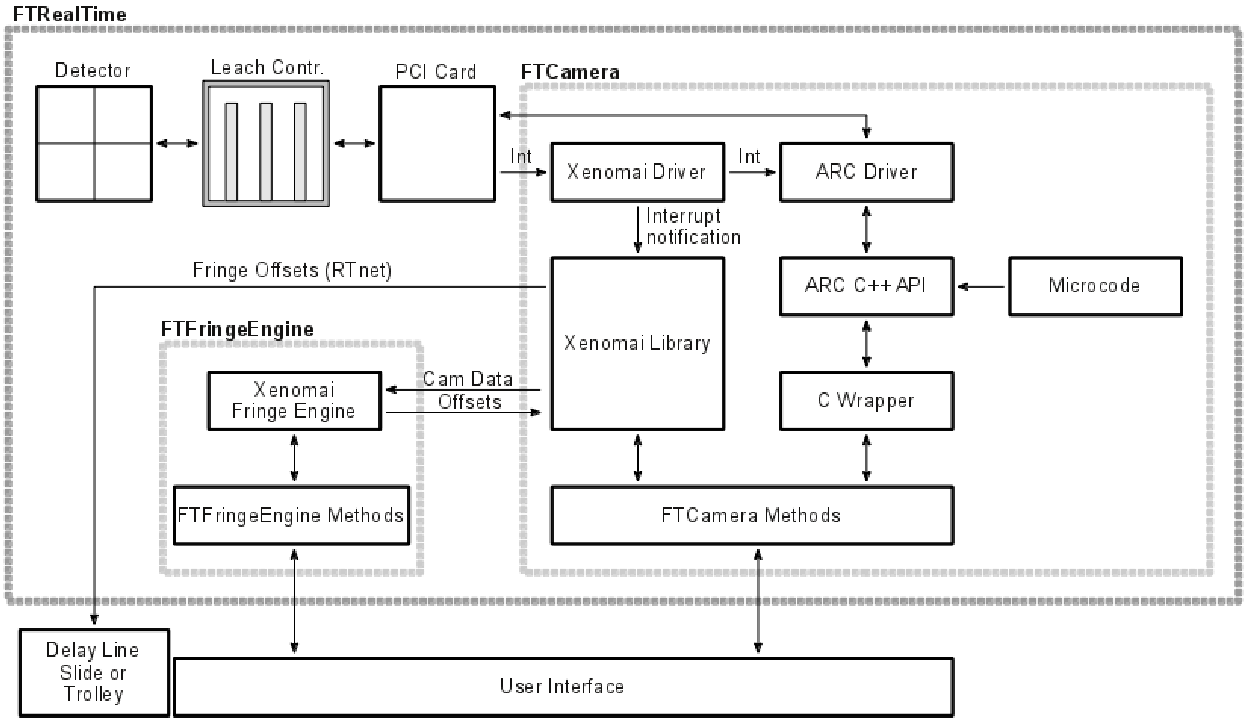
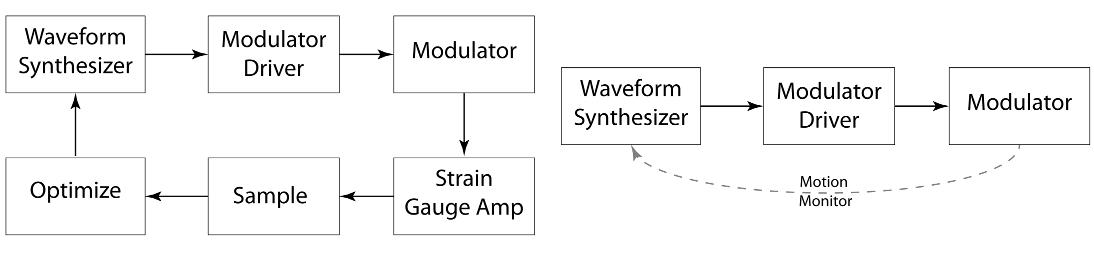


Figure 7. Expansion of the FTCamera process and its components.

producing a long term stable output.[6,9] In operation mode, the optimized waveform drives the modulator in open loop; no feedback mechanism is used, only a motion monitor. The motion monitor has the same components as the feedback loop in calibration minus the optimize component.



(a) (b)

Figure 8. Modes of operation for the modulators. On the left is the calibration mode in which the driving waveform is optimized iteratively. In operation mode on the right, the modulator is run open loop with only a means to monitor the motion in place. No corrections to the motion are made.

To optimize a waveform, the ideal waveform is first expressed as a Fourier series and a target waveform is constructed from a number of the coefficients. The target waveform is then used to drive the modulator and its response recorded via an onboard strain gauge. A period of the modulator response is reconstructed from the strain gauge response. The driving waveform coefficients' amplitude and phase are then adjusted on an iterative basis until the measured response has converged to the target waveform.

Figure 9 shows results from the optimization process. In the figure, the black line shows the target waveform, the red line the modulator response as measured by a laser metrology system, and the blue line the reconstructed strain gauge response. The reconstructed waveform has less than a 5nm standard deviation from the target waveform. The amplitude of the step size shown is 200nm which, due to the beam combiner layout, corresponds to a $\pi/2$ shift in fringe phase for H band. The hold time of a step is 5ms.

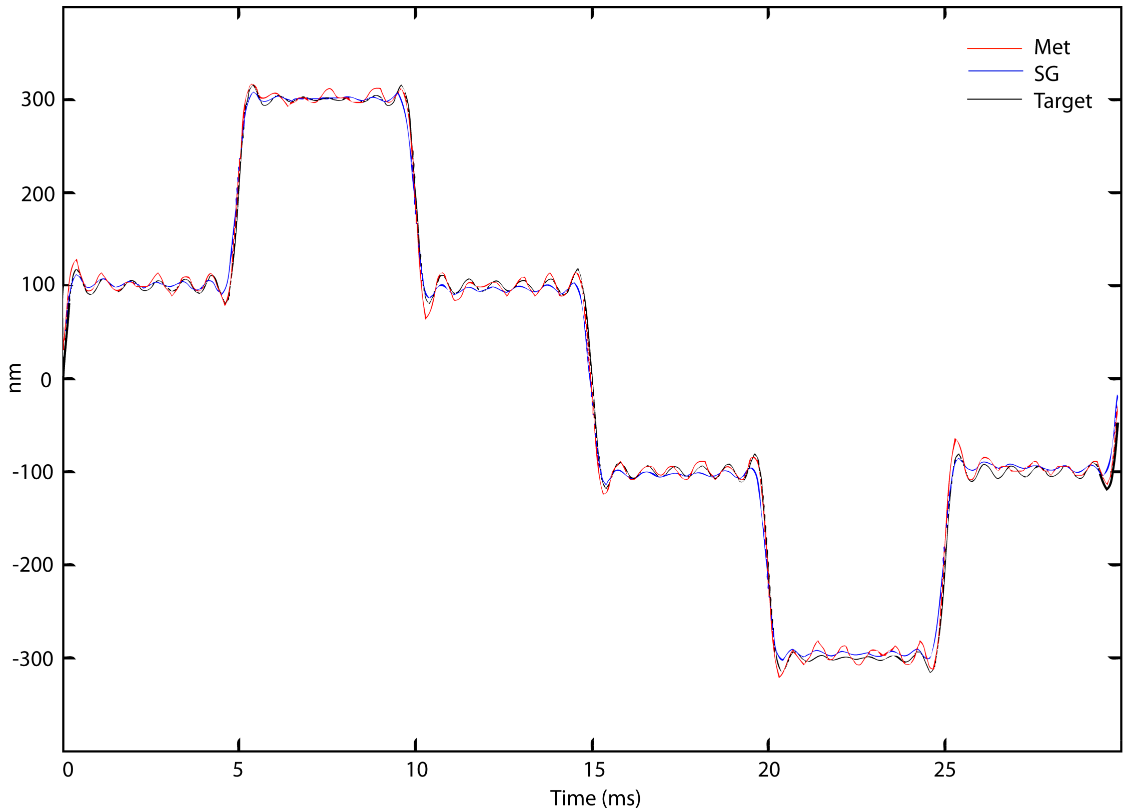


Figure 9. Optimize modulator waveform. Plot shows the target waveform (black), metrology readout (red), and the reconstructed strain gauge readout (blue). The reconstructed response has less than a 5nm standard deviation from the target waveform.

Continuous monitoring of the optimized waveform showed it had less than a 19nm RMS error at any one point in time from a stationary phase shift over a six hour period. Quantizing the fractional visibility lost as $V_{\text{red}} = exp\left(-\sigma^2_{\text{hf}}\right)$ where σ^2_{hf} is the high frequency mean squared phase error across the wavefront[10] and assuming a single detector read per $\pi/2$ phase shift, this corresponds to a recovery of over 97% of the true visibility. The traditional triangular modulation, where the detector is integrated while the fringe pattern is phase shifted recovers less than 82% for a single read during the phase shift.

Due to hardware issues, the smallest period waveform with the largest step size for K_s has not been shown. A paper presenting thorough results of the modulator experiment will be prepared for publication once these issues are resolved.

4. FUTURE PLANS

Once all hardware components have been received, alignment of the spectrograph to the beam combiner and progress toward first light on the cold detector in the laboratory will commence. Tracking algorithm development has been ongoing within an end-to-end numerical simulator of the MROI beam train. Software development is progressing and demonstration of closed loop fringe tracking in the laboratory environment will be shown in 2013. At this point the experiment will be expanded. The initial phase of the closed loop fringe experiment will only involve two inputs. To test enhanced algorithms that support baseline bootstrapping, multiple inputs will be used.

ACKNOWLEDGMENTS

The Magdalena Ridge Observatory is funded by Agreement No. N00173-01-2-C902 with the Naval Research Laboratory (NRL) and an institutional revenue bond from the New Mexico Institute of Mining and Technology (NMT). 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.

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