MRO FTT/NAS & FLC

FLC Conceptual Design Report

MRO-TRE-CAM-0000-0103

The Cambridge FTT Team

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Change Record

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0.1	2010-09-01	JSY	Initial version
0.2	2010-09-02	MF	Additional content
0.3	2010-09-03	JSY	Changed dynamic range text for FLC
0.4	2010-09-03	CAH	Small adjustments to content
0.5	2010-09-03	JSY	Revised software section; minor edits
0.6	2010-09-03	MF	Corrections to opto-mechanical sections
1.0	2010-09-03	JSY	Final edits

Objective

This document presents the conceptual design of the FLC system.

Scope

All aspects of the conceptual design of the First Light Camera are described in this document. The conceptual design of the FTT/NAS is presented in a separate report (AD1).

Reference Documents

RD1 Technical Requirements: First Light Camera (INT-403-TSP-0107) – rev 1.0, May 20th 2010

RD2 FTT/NAS vs FLC: Comparison of Technical Requirements (INT-403-ENG-0115) – rev 1.1, May 20th 2010

RD3 Derived Requirements (MRO-TRE-CAM-0000-0101)

RD4 FLC Requirements Compliance Matrix (MRO-TRE-CAM-0000-0105)

RD5 ICD List and Expected Content (MRO-LIS-CAM-0000-0107)

Applicable Documents

AD1 FTT/NAS Conceptual Design Report (MRO-TRE-CAM-0000-0102)

AD2 Technical Requirements: Fast Tip-Tilt/Narrow-field Acquisition System (INT-403-ENG-0003) – rev 2.2, May 20th 2010

AD3 Interface to an MROI System (INT-409-ENG-0020), Allen Farris – version 1.0, August 9th 2010

Acronyms and Abbreviations

AAS Automated Alignment System

ADC Atmospheric Dispersion Corrector

AMOS Advanced Mechanical and Optical Systems (UTM vendor)

BCF Beam Combining Facility

CCD Charge-Coupled Device

CoDR Conceptual Design Review

COTS Commercial Off-The-Shelf

CPU Central Processing Unit

CTE Coefficient of Thermal Expansion

DMA Direct Memory Access

EIE European Industrial Engineering (UTE vendor)

EMCCD Electron-Multiplying Charge Coupled Device

FEA Finite-Element Analysis

FTT Fast Tip-Tilt

FLC First Light Camera

FOV Field-of-View

FTTA Fast Tip-Tilt Actuator

FWHM Full-Width at Half-Maximum

GUI Graphical User Interface

ICD Interface Control Document

ISS Interferometer Supervisory System

MROI Magdalena Ridge Observatory Interferometer

NAS Narrow-field Acquisition System

NMT New Mexico Tech

PC Personal Computer

PCI Peripheral Component Interconnect

PDR Preliminary Design Review

PSF Point-Spread Function

ROM Rough Order of Magnitude

RTOS Real-Time Operating System

TBC To be confirmed

TBD To be determined

UT Unit Telescope

UTE Unit Telescope Enclosure

UTM Unit Telescope Mount

Table of Contents

1 Introduction **4**

1.1 Top level requirements 4

1.2 Relationship between the FLC and the FTT/NAS 5

2 Derived Requirements **5**

2.1 Thermal management 5

2.2 Dynamic range 6

3 FLC System Design **7**

4 Optical Layouts **7**
4.1 Layout constraints 7
4.2 Conceptual layout 8
4.2.1 Tolerancing Analysis and Feasibility 9

5 Camera selection **9**
5.1 Conclusions from FTT/NAS evaluation 9

6 Conceptual Opto-Mechanical Design **9**
6.1 Layout 9
6.2 Mechanical analyses 10
6.2.1 Thermal expansion analyses 10
6.2.2 Earthquake and relocation loads 10
6.3 Optical mount design 10
6.3.1 Focus lens mount 10
6.3.2 Folding mirror mount 11
6.3.3 Earthquake and relocation loads 11
6.4 Camera mount 11
6.4.1 Earthquake load 12
6.5 Focal adjustment 12
6.6 Beam alignment 13

7 Conceptual Thermal Design **13**
7.1 Thermal control 13
7.1.1 Conceptual design of thermal control 14
7.2 Enclosure thermal design 15
7.2.1 Camera enclosure design 15
7.2.2 Camera enclosure sensors 16
7.2.3 Electronics Housing thermal design 17
7.2.4 Additional heat exchange enclosure design 17
7.2.5 Power consumption 17
7.3 Interfaces 17

8 Conceptual Electronics Design **17**
8.1 Computer interface 17
8.2 Electronics Interface 18
8.2.1 Custom electronics interface 18
8.3 Camera Enclosure 20
8.4 Heat Exchange Enclosure 20

9 Conceptual Software Design **20**
9.1 Software requirements . . . 20
9.2 Definition of software tasks . . . 21
9.3 Software architecture . . . 22
9.3.1 Programming language . . . 23

10 Interfaces **23**
10.1 Specific Interface issues . . . 24

11 CoDR Summary **24**
11.1 Optical layout . . . 24
11.2 Camera selection . . . 24
11.3 Opto-mechanical design . . . 25
11.4 Thermal design . . . 25
11.5 Electronics design . . . 25
11.6 Software design . . . 25
11.7 Conclusions and route forward . . . 25

1 Introduction

The First Light Camera (FLC) system will be used for commissioning and integration of the first AMOS-delivered Unit Telescope (UT) at the Magdalena Ridge Observatory Interferometer (MROI). The FLC will be a precursor for the more capable Fast Tip-Tilt/Narrow-field Acquisition System (FTT/NAS), whose conceptual design is described in AD1. Because of delays in procuring the FTT/NAS under previous contracts, the FLC is being procured to coincide with the arrival of the first UT. The FTT/NAS will be delivered later and will replace the FLC for regular MROI scientific operations.

The FLC will be operated in two distinct roles:

- A standalone role, independent of the MRO ISS, which will primarily be used for commissioning and acceptance testing of the UTM. In this role the FLC will be used for manual target acquisition and to develop pointing models and perform open-loop tracking tests;
- A role where it operates under the control of the MRO Interferometer Supervisory System (ISS) and performs the NAS functions (for example automatic target acquisition and tracking) that are anticipated for the FTT/NAS system. This role will be used when integrating the UT with the ISS, prior to delivery of the first FTT/NAS system.

In the standalone role, the FLC will be controlled from its own GUI, capable of being displayed either on an MRO-owned computer in the interferometer control room or from an MRO-owned laptop.

1.1 Top level requirements

The top-level requirements associated with the FLC system are presented in detail in RD1 and a comparison with the FTT/NAS requirements is presented in RD2. The following list briefly summarises the main top-level requirements:

- Support of operating modes – operation with or without the ISS;
- Support for UTM pointing and tracking tests;
- Field of view $\geq 60''$
- Pixel scale: 0.15–0.25 arcsec/pixel
- Support of range of exposure times (down to 5 ms) and frame rates (up to 10 Hz);
- Sensitivity $\geq 10^{\text{th}}$ magnitude;
- Computation and logging of centroids of a user-selectable star;
- Stability of opto-mechanics of 1 arcsec over $\Delta T = 5$ °C;
- Operability at temperature $T \geq -15$ °C.

Note that we will be requesting that the requirement to operate without a chilled water supply be waived.

1.2 Relationship between the FLC and the FTT/NAS

We review here the relationship between the FTT/NA system and the FLC. The two systems will be delivered sequentially and will share certain hardware and software. The FLC will arrive at the MROI site roughly a year earlier than the complete FTT/NA system, and the main distinction between the two systems will be their respective roles. The FLC is being designed primarily to facilitate acceptance testing, system integration, and evaluation of the UTs and the ISS, whereas the FTT/NAS will be responsible for providing the full functionality needed for acquisition and slow and fast guiding of the UTs during interferometric science observations.

We have chosen some aspects of the FLC design to be in common with the FTT/NAS, even where this is not mandated by the top-level requirements for the two systems. This approach minimizes the design effort required, and allows some interchange between the delivered systems. For example the same EMCCD camera will be used for the FLC and the FTT/NAS. As a result it will be possible to run the FLC software with the FTT/NAS hardware, e.g. on the second or subsequent UT, in order to access the commissioning-specific software functionality that has been requested by the UT vendor.

The commonality between the FLC and FTT/NAS is further described in Sec. 3 and subsequent sections which deal with particular aspects of its design.

2 Derived Requirements

A set of "derived requirements" and error budgets have been calculated as part of our conceptual design work on the FTT/NA and FLC systems. Most of these relate to the FTT/NAS, but a few are applicable to the FLC. The paragraphs below summarise the derived requirements that are relevant to the FLC. These have been calculated from the top-level requirements specified by MRO on the basis of a minimal set of assumptions about the FLC conceptual design. Only the results of the calculations are presented in this document; descriptions of the methods and reasoning used are provided in RD3.

2.1 Thermal management

For the purposes of our conceptual design, we have assumed that the FLC sensor will be an electron-multiplying CCD (EMCCD), identical to that which will be used for the FTT/NAS. As a result, a number of the derived requirements for the FLC have been determined from the top-level heat dissipation requirements and the specifications of the candidate EMCCD cameras described in AD2, through use of the same thermal analyses. We have assumed that the FLC camera head will be placed inside an environmentally-controlled enclosure such that:

- The camera enclosure temperature is controlled to protect the camera and to reduce heat dissipation to the environment when operating at night. Unlike the FTT/NAS camera head, there is no requirement to ensure that the exterior surface temperature of the camera enclosure be maintained within 2 °C of ambient.
- The camera environment be controlled at all times, even though the camera may not be switched on. This will ensure that the camera can be switched on without first having to warm up or dry the enclosure;
- Heat will be removed from the camera and the enclosure by fluid at a controlled temperature and flow rate, and that this heat will be exchanged into one of the coolant loops available in the telescope enclosure.

Under these assumptions the derived requirements on the FLC camera head are as follows:

1. A maximum enclosure internal air temperature of 30 °C;
2. A minimum enclosure internal air temperature of 0 °C;
3. A coldest enclosure internal component temperature of -5 °C (so as to always remain above the dew point);
4. An emissivity of the outer surface of camera enclosure > 0.7;
5. A residual camera heat dissipation rate of 20 W (based on the likely limitations of removing 15 W by unforced heat exchange with a fluid while maintaining a temperature in the camera enclosure of <30 °C);
6. A camera enclosure space envelope of roughly 340 mm wide × 300 mm deep but no more than 350 mm high;
7. A CPU and interface power dissipation allowance of 180 W;
8. A camera interface and controller power dissipation allowance of 70 W;
9. A power consumption allowance of 350 W.

2.2 Dynamic range

We have assumed that the FLC camera has a read noise of 50 electrons, that its exposure time will be adjustable independently of the frame rate, and that the maximum and minimum exposure times used will be 1 second and 1 millisecond respectively. We have also assumed the use of a Cousins R-band filter, with half power points at 570 nm and 730 nm respectively.

Under these assumptions, if the EMCCD gain remains switched off, the range of target magnitudes that could be observed in the best seeing (3 pixel image FWHM, i.e. 0.45–0.75″ for the specified range of pixel scales) would be from 2.5 to 16.2[1]. For seeing a factor 2 worse this magnitude range becomes 1.0 to 14.8. Since the FLC is only required to reach 10$^{\text{th}}$ magnitude sensitivity, it might be desirable to include several magnitudes of attenuation (using a pupil mask or neutral density filter) as a permanent feature of the design in order to allow observations of naked-eye stars.

[1] This magnitude range differs from that specified in RD3 since we have here assumed the use of a specific filter to delimit the range of wavelengths collected by the FLC sensor.

3 FLC System Design

In this section we present a high-level overview of the proposed FLC system conceptual design and outline the reasoning that has led us to select this system architecture. Our concept is based around a commercial off-the-shelf back-illuminated EMCCD camera. A camera of this type is not required to meet the modest limiting sensitivity specification for the FLC, but we have chosen to use the same camera as will be needed for the successor FTT/NAS system.

EMCCD camera manufacturers all specify that their cameras must be operated at a temperature above 0 °C, in a non-condensing environment. As a result the camera will need to be enclosed and a thermal control system be supplied to maintain the temperature and humidity inside the camera enclosure at all times. This system must extract heat from the enclosure and dump it to a chilled fluid loop in order to prevent the camera overheating and to minimise heat dissipation to the air. Because all of the requirements for operating the camera in an enclosure are the same for the FLC as for the FTT/NAS (except for the restriction on the external surface temperature) it is envisaged that the same enclosure design and thermal control will be used for the FLC system.

The thermal control and interfaces for the FLC will be identical to those of the FTT/NAS design and will use the same interface electronics at the FLC computer to monitor temperatures and dew-point within and external to the camera enclosure.

The initial alignment tolerances and night-time stability required of the opto-mechanical components for the FLC are not as demanding as the FTT/NAS and so mounts bolted directly to the Nasmyth optical table will be sufficient to meet these requirements. The camera mount will be the same as the that used for the FTT/NAS design.

A range of V-band magnitudes from 2.5 to 16.2 (in the best seeing) for the target star can be accommodated simply by adjusting the exposure time independently of the frame rate. If brighter objects are required to be observed, a means of attenuating the signal (such as a pupil mask or neutral density filter) will need to be introduced. Currently we have not yet included this feature in our conceptual optical design.

4 Optical Layouts

We have investigated a range of possible layouts of optical components which meet the top-level requirements for the FLC.

4.1 Layout constraints

Although the entire Nasmyth table is in principle available to the FLC, there are two practical boundary conditions which have constrained the range of optical layouts that we have been able to explore:

1. The finite size and orientation of the UT Nasmyth table, in particular its shorter dimension which runs parallel to the direction of the exit beam from the telescope tertiary mirror;
2. There is a hard limit to the maximum height that any element of the FLC may present above the table surface.

In order to accommodate the thermal enclosure for the camera within the height restriction, we have had to exclude the possibility of elevating the camera above the table surface. In turn, this has meant that we have needed to use a fold mirror to obtain the specified image scale.

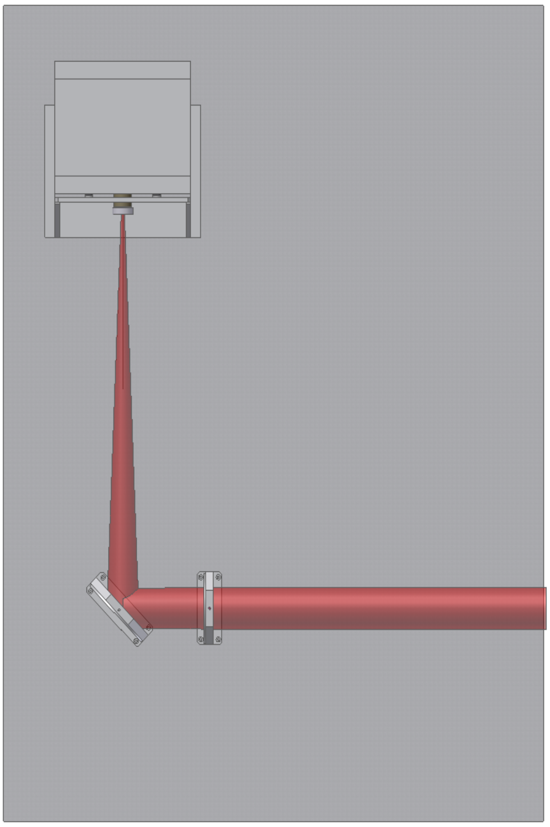
4.2 Conceptual layout

Our conceptual optical design is shown in Figure 1. The collimated beam from the UT tertiary mirror enters from the right and is intercepted by a COTS achromatic doublet (Linos Photonics 332387000). This has a focal length of 1250 mm which gives a pixel scale of 0.18 arcseconds, well within the range allowed by the derived requirements of 0.15″–0.25″. This lens has a diameter of 135 mm and so allows a 20 mm annulus around the perimeter of the lens for mounting. The converging beam is then folded by a plane mirror and sent to the FLC sensor. We intend to optimise the relative distances between the lens, fold mirror and camera so as to optimise the tolerance of the optical system to potential bending of the Nasmyth optical table due to temperature changes.

The waveband-defining filter would be located in the converging beam, close to the camera entrance aperture. For this configuration, the spot-size across the R photometric waveband is roughly 20 µm, which corresponds to ~0.2 seconds of arc, easily within the 1 arcsecond image quality required by the FLC.

This layout can be trivially adjusted to accommodate different locations of the FLC head (to the left or right in the figure) should the MROI Project Office wish to to locate additional opto-mechanical components on the Nasmyth table during commissioning.

Figure 1: Conceptual layout for the FLC optical components. The optical design uses a COTS achromatic doublet with focal length 1250 mm, giving an image scale of 0.18 arcsec/pixel. In this illustration the relative distances between the lens, mirror and camera have not yet been optimised. The wavelength-selecting filter is located close to the camera entrance window and so cannot be clearly seen in this illustration. The location of the FLC camera head can be adjusted to left or right in the figure to accommodate other equipment that the MROI Project Office might wish to install on the Nasmyth optical table during commissioning.



4.2.1 Tolerancing Analysis and Feasibility

A tolerancing analysis was performed for the proposed optical elements using the ZEMAX optical design software. Our main results are presented in Table 1. As will be clear from the entries in the table, the installation and alignment tolerances for the optical elements are all relatively benign, and we envision no problems in meeting these straightforwardly. A discussion of the sensitivity of the design for the purposes of maintaining night-time stability is presented in Sec. 6.

Element	Degree of freedom	Tolerance in position or angle
Sensor head	δz	$\pm$1 mm
Lens	δz	$\pm$1 mm
"	$\delta\theta_x$	$\pm1.5°$
"	$\delta\theta_y$	$\pm1.5°$
Fold mirror	δz	$\pm$1.4 mm

Table 1: Individual element tolerance in position and angle that lead to the top-level image quality requirement being exceeded for the proposed optical layout. For each element the z-coordinate represents the direction normal to its plane (or optical axis), while the x and y axes are orthogonal to this with the x direction perpendicular to the optical table. Tolerances for the degrees of freedom not shown in the table are sufficiently looser that we have not included them here .

5 Camera selection

As has been mentioned earlier, we intend to use the same camera head in the FLC as for the FTT/NAS. This will reduce costs, but more importantly allow the use of common software and electronics. The reader is referred to the FTT/NAS Conceptual Design Report (AD1) for a full discussion of the selection criteria used in our down-select, and so only the conclusions of that analysis are presented here.

5.1 Conclusions from FTT/NAS evaluation

Of the three potential heads under consideration for use in the FTT/NA system, all would be possible for use in the FLC. The most important differences between the three candidate cameras for use in the FLC would be their thermal dissipation, their ability to be controlled under a real-time operating system and, in the case of the Hamamatsu camera, its limited lowest survival temperature.

The Andor iXon^{EM}+897 head is preferred for both the the FTT/NAS application and the FLC. The Princeton Instruments ProEM 512B would be suitable for the FLC, but its high power dissipation would greatly increase the complexity of any heat removal scheme. The Hamamatsu ImagEM C9100-13 would also be suitable but would need additional thermal protection measures in the event of a loss of power during very cold weather.

6 Conceptual Opto-Mechanical Design

6.1 Layout

The layout of the FLC opto-mechanical system is shown in Figure 2. The beam exiting the telescope is focussed onto the camera but, because the Nasmyth table is not wide enough, a fold mirror must be introduced between the lens and the camera. The positions of the lens and fold mirror with respect to the camera will be adjusted so as to optimise the tolerance of the optical system to potential bending of the Nasmyth optical table due to temperature changes.

The position of the camera may be restricted because of cable length but could be placed closer to the fold mirror if the lens moved closer to the telescope. The layout could be further adjusted, according to what other use may be made of the Nasmyth table during telescope commissioning.

6.2 Mechanical analyses

6.2.1 Thermal expansion analyses

For the range of temperatures expected at the MROI site, any expansion or contraction of the Nasmyth optical table will have no significant implications on the focus or on the stability of the centroid position on the FLC sensor.

However there are two thermally-induced effects which may impact pointing and tracking tests. These are:

- distortion from a plane, of the surface of the Nasmyth optical table;
- a global shift of the Nasmyth table with respect to the output beam from the telescope.

For the optical design proposed the most sensitive component will be the fold mirror. It is likely that the angle at which this intercepts the beam will need to be stable at the sub-arcminute level during the night to meet the centroid stability requirement for the FLC system.

The compensation of image motion arising from instabilities of the optical table is not within the remit of the FLC design, but we feel it is important that the Project Office is appraised of this at the present time. Whether the actual distortions of the Nasmyth optical table will impact the ability of users to successfully undertake and/or analyse the results of any pointing or tracking tests remains to be evaluated.

6.2.2 Earthquake and relocation loads

None of the camera manufacturers specify shock load limits for their cameras. Although we have asked each specifically, only one manufacturer has responded so far and has confirmed that they have no information available. There is no reason to believe that the camera will not survive an earthquake load of 0.3 g but, when mounted to the optical table the actual shock loads will depend on the earthquake spectrum and any magnification introduced by the table mounting structure. We do not expected this to be an issue though.

Shock loading due to relocation, although only quoted to us as 0.4 g, will depend again on the shock spectrum and this is likely to contain higher frequency components than an earthquake. Relocation loading will be assessed during the preliminary design phase and a conclusion reached as to whether to recommend that the camera be dismounted or left in place during relocation.

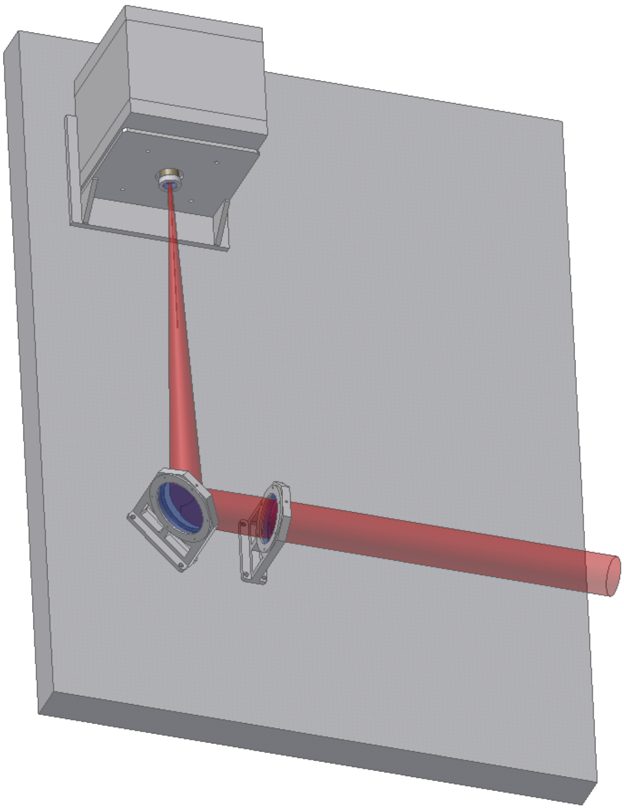
6.3 Optical mount design

6.3.1 Focus lens mount

The lens mount will be of a simple design and is expected to be manufactured in aluminium. It will be designed so that the lens is centred in the mount to within ±0.2 mm and remains centred to within 50 µm. for a 5 °C temperature change. The mount, which is very similar to the mount we intend to use for the folding mirror, is shown schematically in Figure 3. The lens would be held against a reference face in the mount by a compliant ring and backed by a retaining ring which would screw into the mount. The contacting surface of the shoulder machined in the mount will be machined so as to be tangent to the lens surface. The lens is held radially in the mount using two reference surfaces and a compliant pre-load screw. Manufacturing tolerances will be controlled so that the mount should not need to be adjusted in tilt and will be able to be bolted directly to the optical table.

6.3.2 Folding mirror mount

Figure 2: Illustration of the FLC opto-mechanical assemblies, showing the lens mount, folding mirror mount, and camera mount/camera enclosure. In this figure the relative distance between the lens, mirror and camera has not been optimised.



The folding mirror mount has a somewhat higher requirement on stability than the lens mount and will be based on the mount design for the FTT/NAS fold mirrors. The mirror will be pre-loaded against an axial reference face by the retaining ring and held radially by two reference surfaces and a compliant pre-load surface (see Figure 3).

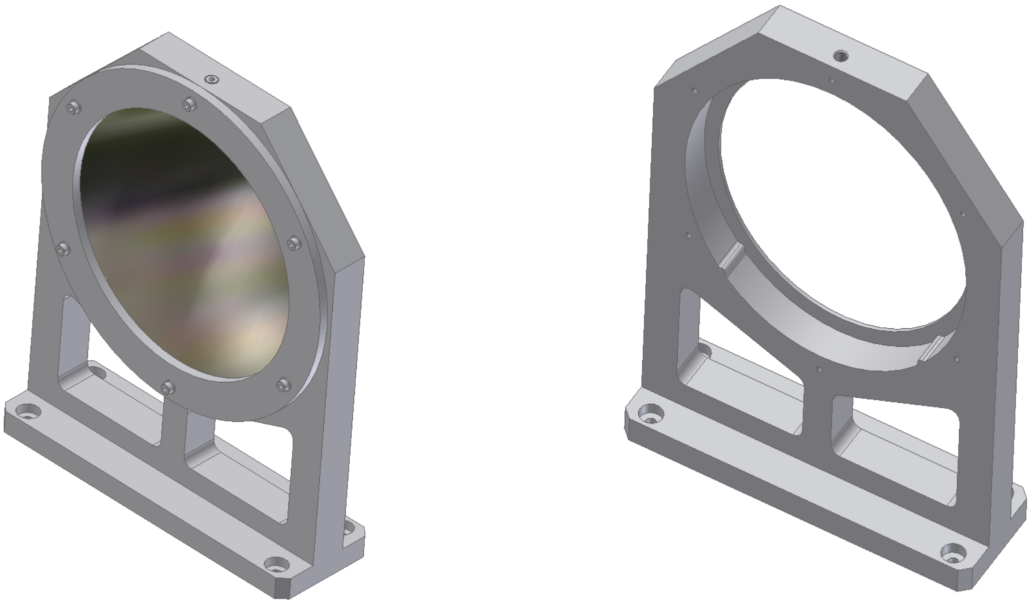
6.3.3 Earthquake and relocation loads

The mounts used to hold the FLC optical components will be sufficiently rigid that their first natural frequencies will be high and they can be regarded as rigid bodies for earthquake loading calculations. This means that loads on the optics will be very low, ~3 N, which is of no safety consequence. Relocation loads should be no more than 50% larger in magnitude and consequently also not a significant concern.

6.4 Camera mount

We intend to contain the FLC camera in the same way as the FTT/NAS camera, i.e. within an enclosure in order to control its environment. The camera mount will therefore be outside the camera enclosure with

Figure 3: Illustration of the mechanical design of the FLC lens and folding mirror mounts. A recess in the mount accepts the optic which is held radially on two raised surfaces and preloaded from the top. A retaining ring with a compliant interface pre-loads the optic axially against the reference surface of the mount.



the camera connected by stiff rods which pass through the enclosure insulation. To prevent heat transferring from the camera to the mount, the rods must also provide thermal isolation. Our proposed camera mounting arrangement is shown in Figure 4. The camera body will be clamped onto a small interface plate via the mounting holes provided in the stainless steel chassis at the front of the camera. This plate is connected to the camera mount using carbon fibre reinforced tubes which pass through holes in the front wall of the camera enclosure. These tubes are good thermal isolators and are very stiff. Thermal FEA shows that the carbon fibre tubes are very effective in reducing heat transfer from the camera to the support.

Since it is important that dry air be retained within the enclosure, adequate seals will be produced where the tubes pass through the insulation. Another tube forms a barrel so that the incoming light beam can pass through the insulation to the CCD window.

The camera mount will be made of aluminium and must interface to the Nasmyth table which has a stainless steel skin. This needs to be realised without introducing any over-constraints when the temperature changes. To prevent over-constraining the camera mount, we intend to bolt it down firmly at the centre of the base flange but clamp it with pre-loading springs and screws at the outer edges of the flange. The "wings" at either side of the mount which project behind are primarily provided to prevent the camera from tilting backwards when the hold-down bolts are removed from the base flange but can be used to help position the camera using adjuster blocks.

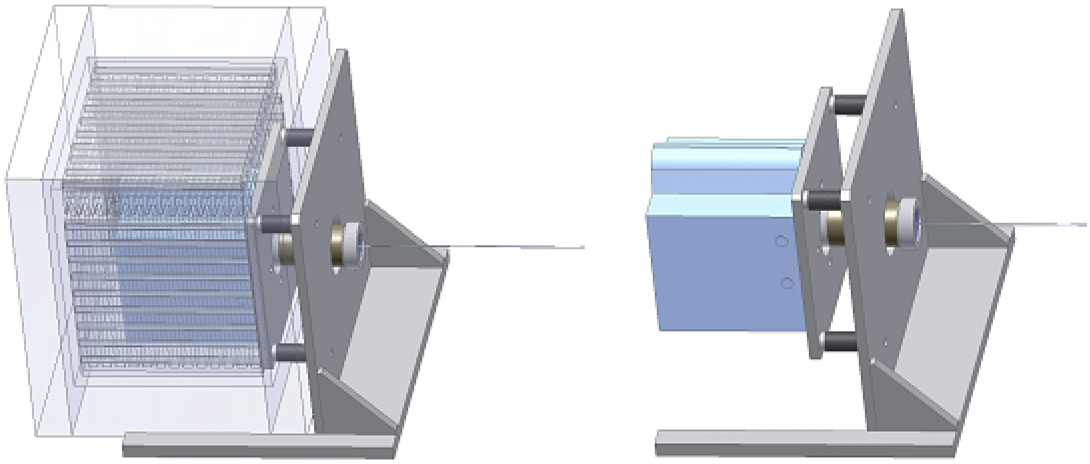
6.4.1 Earthquake load

A discussion of the expected earthquake loading on the camera head has been presented earlier and can be found in Sec. 6.2.2.

6.5 Focal adjustment

Once the camera position has been adjusted to produce the correct focus it should not be necessary to refocus with a change in temperature over the operating range. The focus tolerance is ±1 mm and the CTE of the table is ~17×10^{-6} leading to a change of only 0.5 mm over a 30 °C temperature range.

Figure 4: Design of the FTT camera mount (a) showing the temperature control enclosure, and (b) with the enclosure removed.



6.6 Beam alignment

As has been described in Sec. 4.2.1 the installation and alignment of the FLC optical elements is not very critical. We envision that the hole-pattern of the optical table will be sufficient to ensure correct relative alignment of the optics.

7 Conceptual Thermal Design

7.1 Thermal control

The vendor-specified minimum guaranteed operating temperature for all the candidate EMCCD cameras is 0 °C, in a non-condensing environment. The minimum survival temperature for the Andor and Princeton cameras is minus 25 °C but for the Hamamatsu camera it is only -10 °C. Therefore for operational and camera safety reasons the FTT/NAS camera will be placed within an enclosure in which the air will be maintained above 0 °C. To prevent overheating of the camera and to meet the maximum surface temperature constraints for hardware that is located in the telescope dome, the camera enclosure must be insulated and heat will need to be removed from it. This concept requires that some further design constraints be applied:

1. When operating at night the camera enclosure temperature must be controlled to protect the camera and to minimize heat dissipation to the environment. There is no requirement to ensure that the exterior surface temperature of the camera enclosure is within 2 °C of ambient;
2. The camera environment should be controlled at all times, even though the camera may not be switched on. This will ensure that the camera can be switched on without first having to warm up or dry the enclosure;
3. The camera enclosure should contain a heating element so that the enclosure can be warmed up after a long power break during cold weather;
4. The air in the camera enclosure should be maintained above the dew point whenever the camera is powered on (and preferably at all times so as to reduce the risk of condensation on the internal electronics);

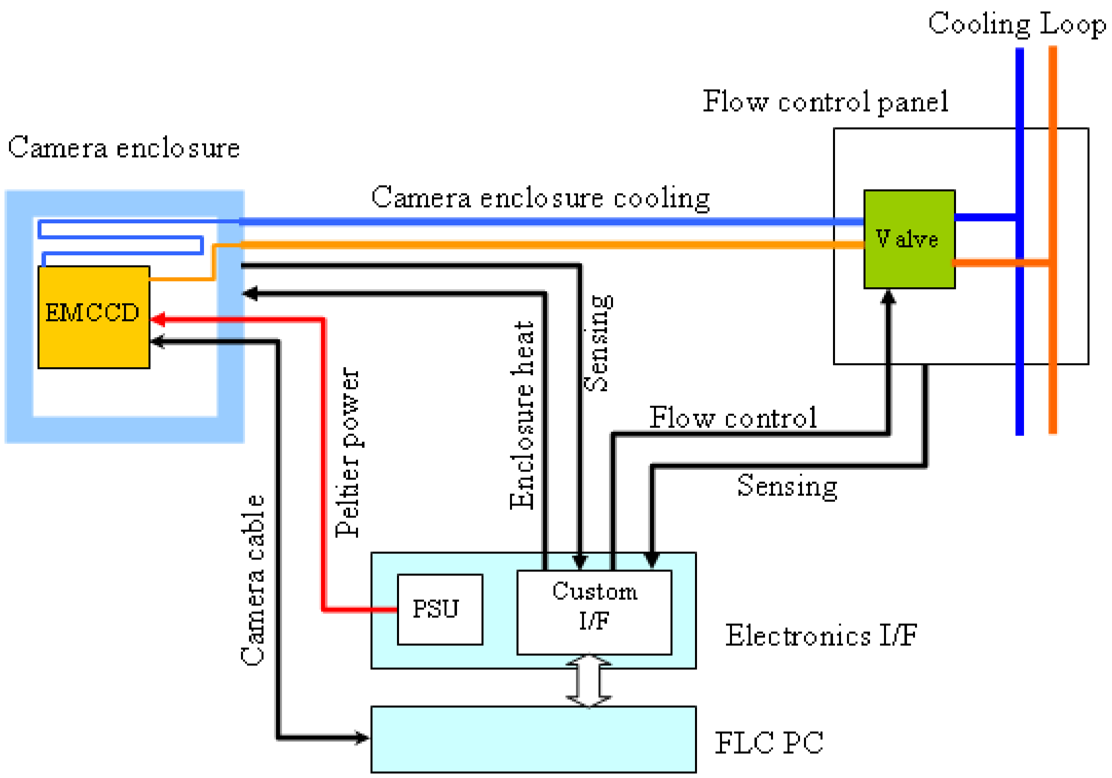
5. Heat will need to be removed from the camera Peltier heat exchanger and the enclosure. We intend to exchange this to a liquid flowing at a controlled temperature and flow rate.

Note that the requirement to operate without a chilled water supply is to be waived.

These constraints will be satisfied by a thermal control system, managed by the FLC computer. The major components of this system are illustrated in Figure 5. The camera enclosure will be fitted with temperature and dew-point sensors connected to a custom interface board in the FLC electronics interface rack mounted in the EIE electronics housing designated Q5. A thermal control panel or enclosure, to be located on the telescope enclosure wall beneath the Nasmyth optical table, will supply fluid at a controlled flow rate (and possibly temperature) to the camera enclosure. The FLC electronics will then interface these monitor and control signals to the FLC computer which will control the operation of the thermal system to ensure camera safety.

7.1.1 Conceptual design of thermal control

Figure 5: Block diagram of FLC camera thermal control system. The camera enclosure is located on the Nasmyth optical table; the electronics interface and FLC PC would be located in the EIE electronics housing designated "Q5"; and the flow control panel (or enclosure if necessary) would be located beneath the optical table.



Baseline design The preferred approach to cooling of the camera enclosure and the camera itself is to use the EIE electronics housing cooling loop (referred to as Loop 1). Connections to this loop will be brought to an interface at the south edge of the Nasmyth optical table. Here a flow valve, controlled by the FLC computer in the Q5 electronics housing, will provide an appropriate flow through the camera enclosure and camera.

Temperature sensors and a dew-point sensor within the camera enclosure will be monitored by the FLC computer so that conditions can be evaluated and the camera protected as necessary.

A temperature sensor will also be placed on the external enclosure surface to monitor its temperature and another will monitor the air temperature in close proximity. The telescope enclosure temperature and dew point will be supplied to to the FLC by the ISS except when the FLC is in its standalone role.

A small heating element will be placed within the enclosure so that it can be warmed (more quickly than the cooling loop could achieve) in the event that the system had been shut down for some time during the winter and the enclosure temperature and camera fall below 0 °C.

Finally, the camera enclosure would be reasonably sealed and fed by a constant stream of dry air at < 1 litre per minute so that the dew point should always remain at least 5 °C below the enclosure temperature.

Alternative design In the event that a greater temperature difference is required between ambient and the cooling fluid supplied, a subsidiary cooling loop will be designed. This cooling loop would exchange heat to the telescope motor/enclosure cooling loop in a separate housing mounted to the UT enclosure structure underneath the Nasmyth optical table. The components of this system would be:

1. Insulated enclosure;
2. Peltier liquid-liquid heat exchanger;
3. Circulating pump;
4. Expansion tank;
5. Flow control;
6. Thermal controller;
7. Interface to FLC computer.

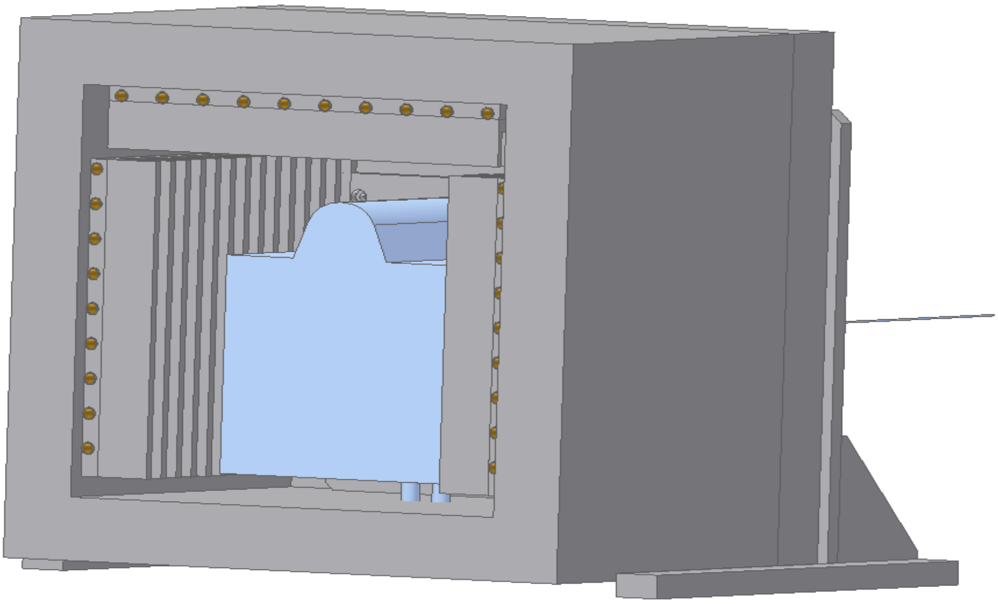
7.2 Enclosure thermal design

7.2.1 Camera enclosure design

Our proposed camera enclosure is constructed on an aluminium framework which is faced with thermal insulation panels and an outer skin. The insulation properties must be very good if the enclosure size is not to become too large. It is proposed that "aerogel" insulation sheets be used as these can provide a thermal conductivity of 0.02 W/mK or lower. The overall dimensions are expected to be about 350 mm high (including a 10 mm high foot to space the body of the enclosure from the Nasmyth optical table) by 340 mm wide by 300 mm depth. The thickness of insulation would be approximately 40 mm. These dimensions leave a clear space about the camera at the sides and the top for cold plates with finned heat sinks to be fitted. The thermal enclosure is shown schematically in Figure 6. The camera is located inside the enclosure with its front mounting plate close to the front wall where it is supported by insulating supports that pass through the wall to the camera mounting bracket outside. Thus the camera is not mounted to the enclosure and the enclosure is fixed independently to the optical table. This reduces the influence on the camera of forces acting on its enclosure. The enclosure is fitted with three cold plates which are coupled in series so that cooling fluid flows through them in turn and then into the camera. Each cold plate has an integral continuous looped cooling tube and is commercially available. The finned heat-sinks will be chosen so that the total area is sufficient to produce the desired cooling capacity. The fins would be arranged so that they support natural convection from the top and sides of the camera, creating circulation of the air as far as possible.

The rear face of the enclosure would be removable for access to the camera electrical connections. The enclosure chassis will support an interface manifold in such a way that the connections for the cooling circuit are on the outside, projecting through a cutaway in the rear panel. A dry air supply and connectors for enclosure sensors will also be provided to this interface. It should only be necessary to remove the rear panel if it

Figure 6: View of the camera enclosure with the rear insulation panel removed. The overall size of the enclosure is 340 mm tall by 340 mm wide and 300 mm deep and has insulation panel thickness of 40 mm. The camera is surrounded on three sides by finned cold plates which are connected in series with the camera Peltier cooling connections. The loops of the cold pipes running through the cold plates are shown in section. The camera is mounted to a bracket outside the enclosure using insulated studs which pass through the insulation. The enclosure fixes to the Nasmyth optical table.



is intended that the camera cable should be unplugged for some reason. Otherwise all connections would be available outside the enclosure.

To minimize the increase in outer surface temperature (due to residual heat within the enclosure not being removed by the cooling system) the camera enclosure outer surface will be designed with a relatively high emissivity. Also, the cover placed over the Nasmyth table (for physical protection and to shield the table from the cold night sky) should have a similar emissivity towards the camera enclosure.

7.2.2 Camera enclosure sensors

Apart from providing temperature and humidity measurements within the enclosure for safety reasons there are sensors for monitoring the thermal performance of the enclosure. The minimum set of sensors within and external to the camera enclosure will be:

- Camera case temperature sensor;
- Enclosure air temperature sensor;
- Cold plate temperature sensor;
- Internal dew point sensor;

- External surface temperature;
- External air temperature.

7.2.3 Electronics Housing thermal design

For the designs presented here there are no thermal design implications for the electronics housing.

7.2.4 Additional heat exchange enclosure design

If it becomes necessary to incorporate an additional heat exchanger as described in Sec. 7.1.1 then the design of this will be addressed during the preliminary design and test phase. A location has been identified for such a heat exchanger and it is likely to be placed in an insulated housing. Most of the heat generated within this enclosure will be cooled by the cooling system to which it connects and so no thermal issues are likely to arise.

7.2.5 Power consumption

The power consumed by the Andor iXon^{EM}+897 camera should just meet the power consumption requirement when combined with the other components of the FLC system in the EIE electronics housing. However, if an additional thermal heat exchanger is required to cool the camera and enclosure an increase in power consumption will be necessary, though it should meet the enhanced power consumption allowance proposed in the derived requirements.

7.3 Interfaces

Interfaces to the camera enclosure have been described already and interfaces to the FLC computer are discussed in Sec. 8. The only other interface proposed for this concept is concerned with the supply of dry air. The telescope enclosure air supply is not guaranteed to be dry and so an air drying facility will be designed and fitted within the enclosure near to the Nasmyth optical table.

8 Conceptual Electronics Design

The FLC system computer, the interface or controller for the EMCCD camera and the interface for monitoring and control of the FTTA are to be mounted in the equipment rack designated Q5 in the EIE UTE interface document. In addition to these functions, interface electronics will also be provided to control the thermal environment of the FTT/NAS sensor and the heat exchange mechanism which removes heat from the camera enclosure and exchanges it into the liquid cooling circuit provided within the UT enclosure. The flow valve regulating the flow of coolant to the camera will not be mounted in the Q5 electronics housing but will be located in a special housing mounted to the UTE wall beneath the Nasmyth optical table.

Each candidate EMCCD camera has different interface and power supply arrangements which take up differing amounts of space in Q5 and this conceptual design allows flexibility for any of the cameras to be incorporated.

The electronics interface will be contained in two racks mounted in Q5. A 2U rack will be used to house the computer and a 3U rack will house all other necessary interfaces and power supplies.

8.1 Computer interface

The computer is a commercial off-the shelf 2U rack-mounted Intel-style PC, to be placed within the 5U-high space allocated in equipment rack Q5. It has space for at least three interface cards, which communicate with the computer via the PCI bus as shown in Figure 7. These three cards will be :

1. An analogue to digital conversion card with digital input/output lines. This will provide a route for digitising the analogue environmental sensor quantities prior to computer processing;
2. A digital to analogue conversion card with additional digital input/output lines. This will provide a mechanism for computer control of analogue thermal management devices and possibly digitally controlled actuators;
3. A camera interface card, to interface with the EMCCD camera. This would be a custom card, a dedicated gigabit ethernet card, or a Camera Link card depending on which camera is chosen.

There are many cards on the market that combine analogue and digital input and output functions onto a single board, however, splitting these functions between the two units minimises the rework involved should one board or the other become obsolete during development.

The PCI cards will be connected to the 3U interface rack via whatever multi-core cables are dictated by the PCI card external interfaces. For added flexibility, USB, RS232 and ethernet interfaces will also be available for direct connection to the hardware if necessary.

8.2 Electronics Interface

The electronics interface will be a 3U rack containing a custom electronics interface board, interface modules, as necessary, and the FLC sensor controller or power supply, depending on the camera selected. This is shown schematically in Figure 7 and has the following features:

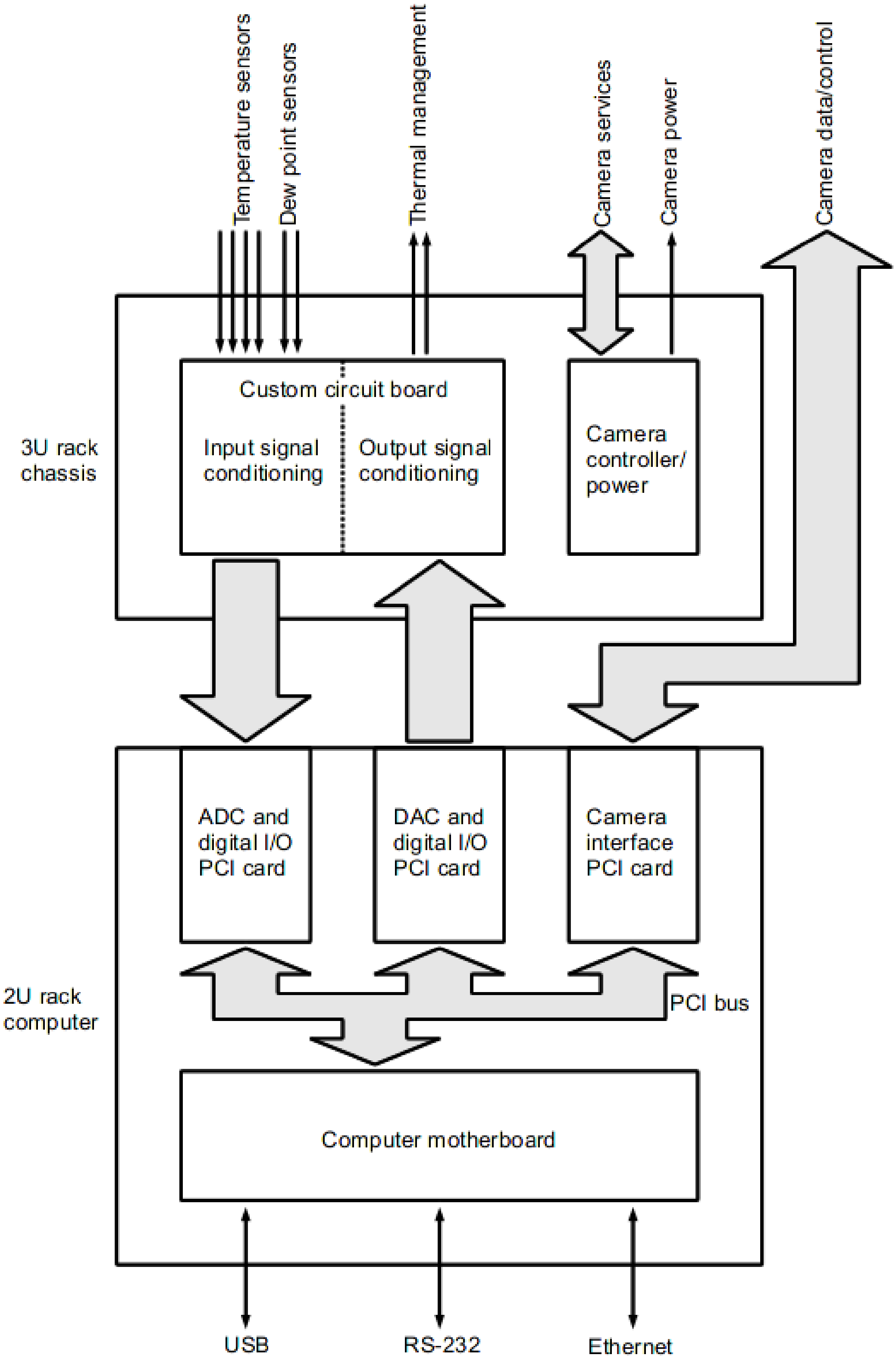
- Camera control and data from the camera are connected directly to the computer. This would be to a PCI board in the case of an Andor camera, via Gbit Ethernet in the case of a Princeton camera, or to a Camera-link PCI board in the case of a Hamamatsu camera;
- Camera control and/or power would be mounted in the 3U rack for convenience. These would be simple power supplies in the case of Andor or Princeton cameras or a special camera controller box in the case of a Hamamatsu camera;
- Input and output signal conditioning would be provided on a custom designed board mounted in the rack with connections to individual connectors on a back-panel for ease of interfacing to the various sensors or systems. A space would also be available in the rack to mount signal conditioning modules for some sensors if they are needed to deliver better performance.

8.2.1 Custom electronics interface

The custom electronics interface contains signal conditioning circuits to handle sensor inputs and control outputs. A provisional list of functions it would need to handle is as follows:

1. Interface and signal conditioning requirements for all thermal control sensors and signals connected to the camera enclosure including:
   (a) Camera case temperature sensor;
   (b) Enclosure air temperature sensor;
   (c) Cold plate temperature sensor;
   (d) Dew point sensor;
   (e) Heating element to warm up the camera enclosure following a long power-off condition in winter.

Figure 7: Schematic of the FLC electronics.



2. Interface and signal conditioning requirements for all thermal control sensors, signals and actuators connected to the camera heat exchange enclosure. This will likely include the following (according to the heat exchange system adopted):
   (a) Coolant inlet and outlet temperature sensors;
   (b) Flow control valve set point;
   (c) Flow rate sensor;
   (d) Temperature set point;
   (e) Enclosure air temperature.
3. Temperature monitoring signals from the Nasmyth optical table. These channels will be available to connect other temperature sensors to for monitoring purposes but are not required for FLC operation purposes. The following locations are proposed but might be extended if further, more accurate, temperature monitoring of the Nasmyth optical table is desired:
   (a) Nasmyth optical table temperature (in vicinity of camera);
   (b) Temperature of overhead shield.

It is possible that some of the sensors may be interfaced using USB or some other interface standard that would reduce the number of connections to the custom electronics interface. This would probably involve increased heat dissipation on or near the Nasmyth optical table and so would only be used if circumstances demanded and permitted it.

8.3 Camera Enclosure

The camera enclosure will be fitted with several temperature sensors and a dew point sensor. A heating element will be fitted within the enclosure so that the enclosure can be warmed in the event that it is too cold to switch on the camera. Cables associated with these functions will be routed along with the camera cable to Q5, a distance of ~6 m.

8.4 Heat Exchange Enclosure

This enclosure will house the components which are necessary to transfer heat from the camera Peltier cooler and camera enclosure to the EIE-provided cooling circuit. In our conceptual design we expect only a flow valve would be needed to divert the flow of coolant at a suitable flow rate but the nature and amount of electronic control and sensing housed in this enclosure will depend on the amount of heat to be transferred. It is expected that at least one set-point will be sent to this enclosure to control a flow valve or provide a set-point temperature, and that several temperature sensor signals and a flow sensor signal will be returned to the electronics interface.

9 Conceptual Software Design

9.1 Software requirements

The FLC software must allow the system to be operated in both its intended roles:

- A standalone role, independent of the MRO ISS, which will primarily be used for commissioning and acceptance testing of the UTM. In this role the FLC will be used for manual target acquisition and to develop pointing models and perform open-loop tracking tests;

- A role where it operates under the control of the ISS and performs the NAS functions (for example automatic target acquisition and tracking) that are anticipated for the FTT/NAS system. This role will be used when integrating the UT with the ISS.

The MRO software framework for interfacing to the ISS (AD3) has been architected to facilitate the testing of interferometer systems without requiring the ISS to be running centrally. An important aspect of this support for "standalone" operations is the ability to run the minimal set of ISS services required by the system (such as the Data Collector) locally. We expect to be able to take advantage of these capabilities in implementing the standalone role of the FLC. In other words, we interpret "independent of the MRO ISS" to mean independent of a centrally running ISS, rather than not requiring any ISS code.

In order to save resources, the FLC software will be as far as possible a strict subset of the FTT/NAS code. One consequence of this choice that we wish to draw attention to is that the FLC PC (but not any separate laptop or control-room computer running the GUI component of the software) will run the Xenomai real-time variant of Linux,rather than a vanilla Linux operating system.

The FLC software requirements differ from those for FTT/NAS in a few minor respects:

- The FLC must be capable of 10 Hz frame rate (rather than ~1 Hz) in Acquisition Mode;
- The FLC must be able to log centroids to a CSV-format file (rather than an unspecified format);
- "Zoom" image display: the FLC must provide an enlarged display of a user-selected region of the full frame images;
- Display of centroid values: the FLC must provide a live numerical display of the average and rms centroid.

9.2 Definition of software tasks

The FLC software will be required to accomplish the following tasks, to which we have given the following names (these are a subset of the FTT/NAS tasks defined in AD1):

1. SystemController: Start up the FLC system, and communicate with the ISS (not in standalone role) and/or GUI to receive commands, coordinate their execution, and return status;
2. CameraController: Set up the camera and change its modes;
3. NasController: Implement the acquisition mode which takes raw full frames from the camera and sends appropriate offsets to the telescope mount (via the ISS);
4. TempController: Provide (slow) real-time control of the camera enclosure temperature (note that real-time control of the CCD temperature is performed by the camera itself) by adjusting chiller parameters;
5. MonPublisher: Send monitor data to the ISS (not in standalone role) and/or GUI;
6. LocalDataCollector: Optionally record monitor data to a local file for later retrieval;
7. GraphicalInterface: Provide an engineering GUI which allows control of the system and display of status and monitor data. This will be slightly different from the FTT/NAS GUI in that it must support display of zoomed images and numerical centroids.

In the standalone role the NasController will be responsible for capturing frames from the camera and computing centroids but will not transmit offsets to the UTM.

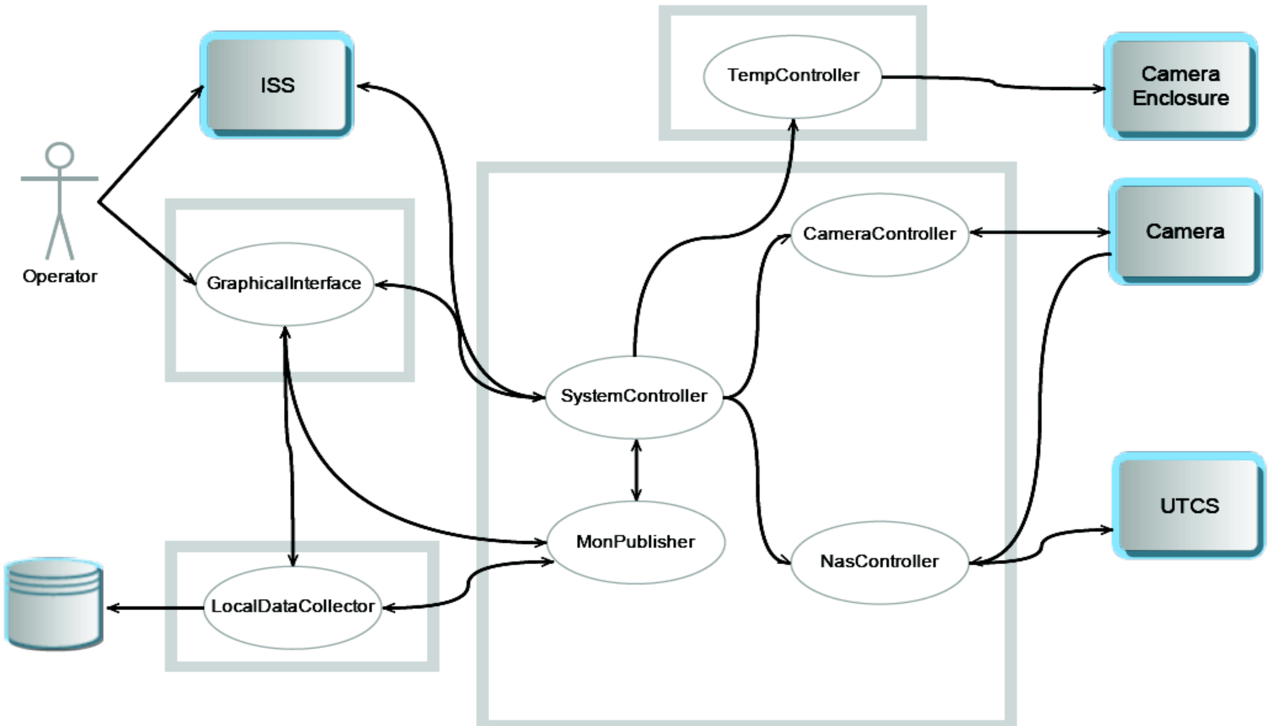
9.3 Software architecture

The list of tasks above provides a natural partitioning of the software. It has the desirable property that the coupling between partitions is relatively loose, thereby improving the modularity of the code. All of these tasks can in principle run on the same machine, but it would be desirable to have the GUI running on a machine which is directly connected to the console at which it is desired to display the diagnostics, thereby maximising the display bandwidth for real-time video display of the camera frames. Therefore we have adopted a distributed architecture where all the tasks except for GraphicalInterface are executed on the dedicated FLC computer and GraphicalInterface resides, at least potentially, on a different machine, be it a laptop in the telescope enclosure or the main console in the MROI control room.

Many of the tasks above must be accomplished at roughly the same time and so it is natural to partition them into tasks which can execute in parallel either by sharing a single CPU or through using multiple CPUs, for example in a multi-core processor. A discussion of the advantages and disadvantages of various methods for achieving this parallel operation is included in AD1, leading to a conclusion about how best to split the FTT/NAS software tasks. We have adopted the same architecture, using a subset of the tasks, for the FLC – this architecture is shown in Figure 8.

The FLC application would thus be divided into the following processes:

Figure 8: A diagram showing the tasks and dataflows within and external to the FLC software. Items inside ellipses are tasks while the rectangles indicate process boundaries. The NasController may be implemented as a kernel thread but is shown as a user-space thread in this diagram. Flows of monitor data from the tasks generating the data to the MonPublisher are not shown in order to not clutter the diagram. We understand that MRO would prefer to route communications between the FLC software and the AMOS-provided UTCS via the ISS (not directly as shown in the diagram), and we are happy to comply with this.



1. A GUI process (task GraphicalInterface): this needs to be able to reside on a different machine, and when the system is running under the control of the ISS the GUI is not required;

2. The temperature controller process (task TempController): a long-running task which will likely need to operate during the daytime in order to maintain the camera enclosure temperature. It is relatively weakly coupled to the rest of the tasks and needs to share very little common state;

3. A local data collector (task LocalDataCollector): this task is likely to be a copy of the ISS data collector software: it has very similar functionality to the latter, but use of the identical software will require understanding the ISS software in more detail;

4. A Xenomai real-time thread (task NasController): this task may be a Xenomai kernel thread, but it may also be a Xenomai user-space thread, in which case it would be part of the process enumerated below. This thread handles frames arriving from the camera and is scheduled by a real-time interrupt when the camera frame arrives. This is a real-time thread to maximise the commonality with the FTT/NAS software;

5. A master process (all remaining tasks): this collects together tasks which have relatively tight coupling or do not merit a separate process.

The non-Xenomai tasks in the master process could be executed either as threads or as an event-loop. The decision as to which of these to use has not been taken, and depends to some extent on the ISS command API which has both threads and non-threads versions: the final details of this API were not known at the time of writing.

For the purpose of describing at least one candidate architecture, we assume that all the remaining tasks are implemented as threads. To avoid problems with conflicting access to shared state, the threads are designed to use as little shared state as possible, making use of information hiding techniques such as private variables. Instead the threads use the "actor model", where each thread communicates with other threads using a message-passing paradigm. A possible implementation for this is the in-process message queue system provided by "ZeroMQ", an open-source messaging stack (www.zeromq.org).

For communicating with tasks in different processes within the FLC system, the ZeroMQ software can also be used, making use of TCP/IP or Unix sockets. Once the connection has been set up, ZeroMQ makes communication to intra-process tasks look identical to communicating to extra-process tasks. This means that threads can be moved to different processes quite easily, so that the assignment of tasks to threads and processes need not be frozen in stone at an early stage.

9.3.1 Programming language

There are a number of factors influencing the choice of programming language. Since the source code is a deliverable of the work package, then using a language which is well supported at MRO is a key factor. The API to the ISS is available in Java and C, so these two languages are to be preferred. The Xenomai real-time programming interfaces are available in C, and the Cambridge group has experience of delivering software to MRO in C, so C is an obvious choice for programming most if not all of the system. There may be some advantage in using Java for the GUI, if MRO develops a generic display interface for the monitor data, otherwise a C or C++ graphical toolkit such as Gtk or Qt could be used.

10 Interfaces

The FLC system interfaces to four major subsystems. These interfaces will be controlled using Interface Control Documents developed by the Cambridge team. Two provisional ICDs already exist as parts of documentation supplied by other vendors (see Table 2). We propose to separate and detail these interfaces in the set of ICDs we develop for the FTT/NA and FLC systems, referring to the source documentation as necessary. Where the content of an ICD is expected to be identical or overlapping for the FTT/NAS and FLC, a single ICD will cover both systems. We have defined separate FTT/NAS and FLC ICDs to the ISS since the FLC is expected to implement only a small subset of the FTT/NAS commands and data streams.

The proposed set of interface documents are listed in Table 2. The expected contents of each ICD are given in RD5.

ICD reference number	Owner	Description
MRO-ICD-CAM-1000-0109 FTT/NAS,FLC-UTE MRO-ICD-EIE-0032 UTE-FTT	CAM EIE	FTT/NAS & FLC to Enclosure ICD Enclosure to FTT system ICD
MRO-ICD-CAM-1000-0110 FTT/NAS,FLC-NOT	CAM	FTT/NAS & FLC to optical table ICD
MRO-ICD-CAM-1000-0111 FTT/NAS,FLC-UT	CAM	FTT/NAS & FLC to UT optical ICD
MRO-ICD-CAM-1200-0113 FLC-ISS	CAM	FLC to ISS ICD

Table 2: List of FLC interface documents

10.1 Specific Interface issues

Here we have identified a number of critical or urgent interface issues that we believe require assessment in the near term:

- Cooling: we request that cooling loop 1 (EIE electronics housing) rather than loop 2 be routed to Nasmyth optical table [TBC];
- Dry air: we request that air be supplied to the Nasmyth optical table and understand that we should include suitable drying equipment as part of our system;
- The cable route from the FLC sensor on the optical table to controller in electronics housing: The camera cable is 6 m maximum and the latest calculation of the route it must take is approximately 5.3 m. This should be sufficient margin;
- Power consumption: we request an increase in FLC power consumption allowance and a potential increase in power dissipation if an alternative candidate camera must be chosen.

11 CoDR Summary

We have presented our outline of the conceptual design of the MROI FLC system as it currently stands. We believe that a system that meets all of the requirements enumerated in the Technical Requirements Document RD1 can be delivered and we are confident that the risk of our proposed system being non-compliant with the full set of technical requirements is low, save for a small number of issues (see below).

In the following sections we review in brief our assessment of the technical sufficiency of our concept design under six main areas, and finally summarise how we intend to proceed.

11.1 Optical layout

The optical layout for the FLC system can be realised straightforwardly on almost any part of the UT Nasmyth optical table. The layout we have chosen requires a fold mirror in addition to the focus optics and we intend to optimise the relative distance between the lens, mirror and camera very soon.

11.2 Camera selection

We intend to use the same camera for the FLC system as is considered for the FTT/NA system. Of the three potential candidates for the FTT/NAS sensor, the Andor iXon$^{\mathrm{EM}}$+897 camera appears to be the lowest risk choice. Our one remaining concern is that the vendor has yet to come back to us to confirm that a custom 23 $\times$[A0?]23 pixel fast readout mode can be guaranteed. We intend to expedite closing this uncertainty by paying for the necessary custom software development in the near future. Of the remaining cameras both have their pros and cons. The use of the Princeton Instruments ProEM 512B camera is a possible fallback strategy, but there are real uncertainties associated with the time-line for real-time Linux support becoming available and a concern about how much heat it may dissipate. The Hamamatsu ImagEM C9100-13 camera – which we did not test in the lab – is the least well characterised possibility. It appears to have the poorest low-temperature survival capability but in other areas, e.g. software support, appears suitable.

It seems clear that the sooner we can confirm the suitability of the Andor iXon^{EM}+ 897 head, the better. This will be a high priority task for us in the near term.

11.3 Opto-mechanical design

There are no challenging derived requirements on the stability of the optical components for the FLC design. However, there are two issues (see Sec. 6.2.1) related to the stability of the Nasmyth table that may impact the night-time stability of centroid measurements made with the FLC. We shall optimise our design to minimise the impact of these table distortions.

11.4 Thermal design

If we are able to utilise the Andor iXon^{EM}+ 897 camera head, we are confident that all thermal issues will be relatively straightforward to address. We will tap into the EIE-provided coolant loop used for the electronic enclosures and this will be sufficient to meet the system needs. We also expect that meeting the 250 W total power dissipation requirement will not be a problem.

If one of the other camera systems is utilised, then this could be problematic. Not only will the additional heat from the head need to be dissipated, but the power required for the heads and ancillary electronics will be higher by roughly 100 W. These are unlikely to be show-stoppers, but will require additional design work and implementation effort.

11.5 Electronics design

We have no reason to believe that the electronics needed for the FLC will be a problem to deliver. We have assessed that there is sufficient rack space for these and that the total power budget is compliant with what can be realised. The electronics will be identical to those to be designed for the FTT/NA system.

11.6 Software design

As for the electronics hardware above, we do not see any critical issues related to providing any elements of the software needed for the FLC system. Unless we are forced to use the ProEM 512B camera head, we do not assess this to be a high risk area, and will aim to capitalise on our experience with the MROI Delay Line software and our initial tests and investigation of various open-source software components. If the ProEM 512B camera must be used, the associated risk will be one of time and possible schedule delays rather than software technical non-compliance.

11.7 Conclusions and route forward

In conclusion, we believe that our initial investigations, studies and analyses suggest that we have a viable concept for delivering the MROI FLC system which is compliant with the technical requirements. However, we have identified a number of key risk areas that will need to be quantified, assessed, and, if necessary, mitigated as a matter of urgency. These can be summarised as follows:

- **Camera selection:** As has been made clear above, the final down-selection for the FTT/NAS sensor head has still to be made. We believe that the Andor iXon$^{\text{EM}}$+897 camera is the preferred choice but until we have confirmed that a custom 23×23 pixel fast readout mode can be guaranteed an uncertainty remains. If either of the other two possible cameras must be used, there will likely be a greater amount of design, prototyping and test work involved in the project;

- **Nasmyth optical table stability:** We have raised issues regarding the stability of the Nasmyth table in conjunction with the FTT/NA system and we believe these may impact the use of the FLC system for the purposes of developing a pointing model or for assessing UTM tracking accuracy (if the magnitude is sufficiently large).

Closing down on the first of these issues will be the next major element of our design work and we will endeavour to optimise our opto-mechanical design to mitigate the effects of the second.