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Development of the fibre positioner for MOONS

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ABSTRACT

The Multi-Object Optical and Near-Infrared Spectrograph (MOONS) will exploit the full 500 square arcmin field of view offered by the Nasmyth focus of the Very Large Telescope and will be equipped with two identical triple arm cryogenic spectrographs covering the wavelength range 0.64µm-1.8µm, with a multiplex capability of over 1000 fibres. This can be configured to produce spectra for chosen targets and have close proximity sky subtraction if required. The system will have both a medium resolution (R~4000-6000) mode and a high resolution (R~20000) mode.

The fibre positioning units are used to position each fibre independently in order to pick off each sub field of 1.0" within a circular patrol area of ~85" on sky (50mm physical diameter). The nominal physical separation between FPUs is 25mm allowing a 100% overlap in coverage between adjacent units. The design of the fibre positioning units allows parallel and rapid reconfiguration between observations. The kinematic geometry is such that pupil alignment is maintained over the patrol area.

This paper presents the design of the Fibre Positioning Units at the preliminary design review and the results of verification testing of the advanced prototypes.

Keywords: MOONS, VLT, Fibre positioner.

1. INTRODUCTION

MOONS will be a fibre-fed, optical to near-infrared multi-object spectrograph designed to utilise the full 25 arc minute field of view of the VLT Nasmyth focus and with a multiplex capability of over 1000 fibres[1]. The fibres will make the link between the focal plane and the two spectrographs. Each of the fibres will be positioned within a local patrol field by a dedicated Fibre Positioning Unit (FPU). Between observations, the fibres will be allocated to science targets. This paper describes the design and prototype test results of the FPUs at the post preliminary design phase.

2. DESIGN DESCRIPTION

2.1 Specification

Table **1** is a summary of the MOONS requirements that are governing the design of the FPUs.

Table 1. FPU performance requirements

Parameter	**Requirements**	
	Value	**Units**
Number of fibre	≥ 1000	-
X, Y fibre maximum positioning error	≤ 20	µm

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Parameter	Requirements	
	Value	**Units**
Fibre maximum focusing error	≤ 70	µm
Fibre maximum tilt error relative	≤ 9 (FPU allocation)	arcmin
Close packing	≤ 4000	µm
Object allocation efficiency	If in a science field, there is the same number of objects as the number of observation channels in the field of view, it shall be possible to allocate more than 80% of the objects to observation channels for the first pass observation.	
Fibre positioning time	20	seconds
FFPA Orientation	Vertical focal plane, rotation about horizontal central axis	
FFPA range of rotation	-30 to +30	degrees
Orientation	-30 to +30	degrees
Temperature	Nominally ambient	°C
Life-time for 1 x 10^6 deployments	10 Years/1x10^6 deployments	years

2.2 FPU in context of Rotating Front End

The FPUs are mounted on a retractable support plate contained within the Rotating Front End module of the MOONS instrument which mounts on to the VLT Nasmyth de-rotator. The FPUs are closely packed on a support plate such that the patrol fields cover the entire focal plane. Each individual FPU patrol field extends to the centre of the neighboring FPU.

The support plate is isostatically mounted to the retraction ring by means of three tangential flexures. The retraction ring allows the entire assembly to be retracted back for the purpose of optical metrology of the FPU positions.

A representation of the assembly is shown in Figure **1** below.

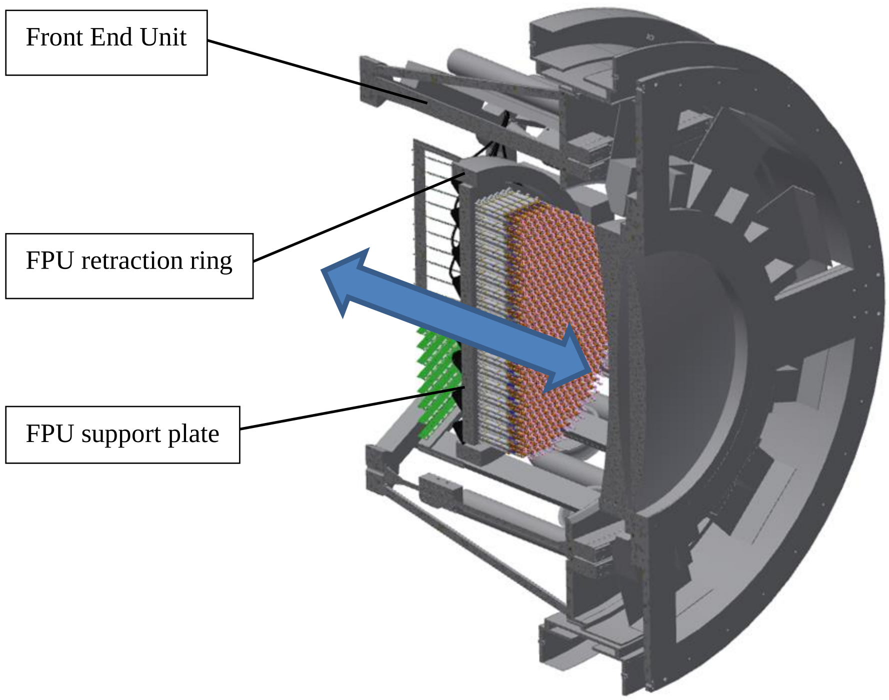

Figure 1. Rotating Front End

2.3 FPU

The purpose of the FPU is to put the fibre in a pre-determined position within an annular patrol field to a specified accuracy and maintain this position during an observation.

The following layout represents the prototype constructed for testing. There are some differences, compared to the final design, reflecting the requirements for testing and some compromises were made to reduce cost and lead times for the prototype.

Table 2 Differences in prototype design to final design

Item	**Note**
Motor gear ratios	Gear ratios are the highest standard ratios for the gear motors. Final ratios are to be chosen.
Encoders	The encoders are useful for diagnostics when testing but will not be implemented in the production units
End stops	Hard end stops will be augmented by switches to avoid damage
Alpha arm PCB and flexi	The flexi and Alpha arm PCB will be replaced with a one-piece custom flexi-rigid board
Beta arm coating	The beta arm is bare aluminium, these will be coated black to avoid stray light interfering with the metrology. The coating needs to be electrically conductive for the collision detection system.

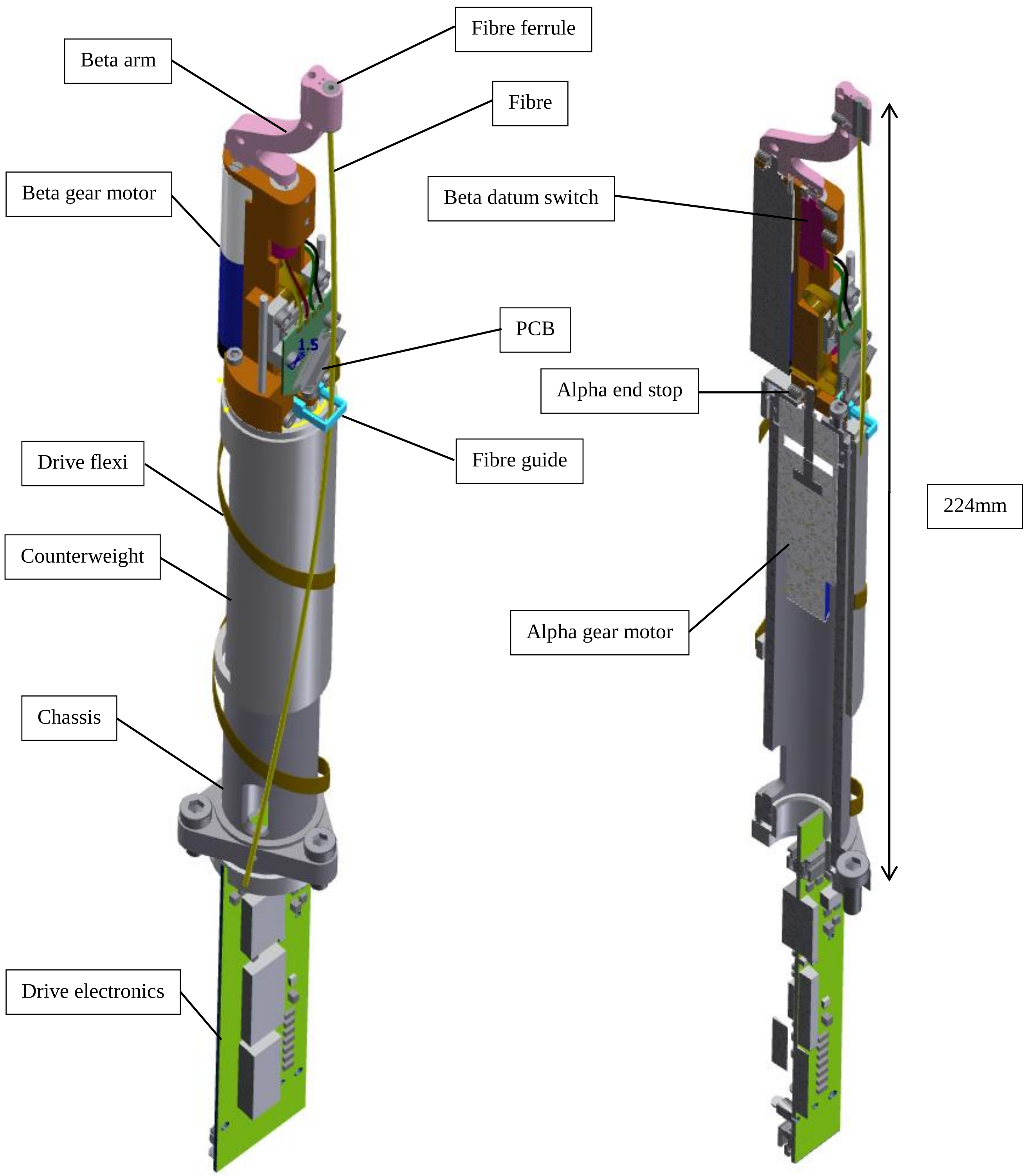

Figure 2. FPU Layout

The FPU consists of three main sub-assemblies: chassis, alpha arm and beta arm assemblies. A brief description of the assemblies is provided below.

2.4 Chassis assembly

The chassis assembly is comprised of a central cylindrical chassis component with a flat triangular base that forms the interface to the FPU support plate. The support plate will have a flat mating face and a locating hole that defines the FPU chassis angle and position respectively. Three captive fasteners are used to attach the FPU to the FPU support plate. Rotation of the FPU is defined by the clearance between the fasteners and the mating holes.

The drive electronics support ring inserts in the base of the chassis and is retained by a set screw.

At the top of the chassis a screw in endcap provides the mount for the Alpha axis gear motor. This component also has features to provide an end-stop for the alpha rotation. This consists of a radial trough that houses a ball bearing. The endcap also provides a bump for actuation of the Alpha rotation datum micro switch.

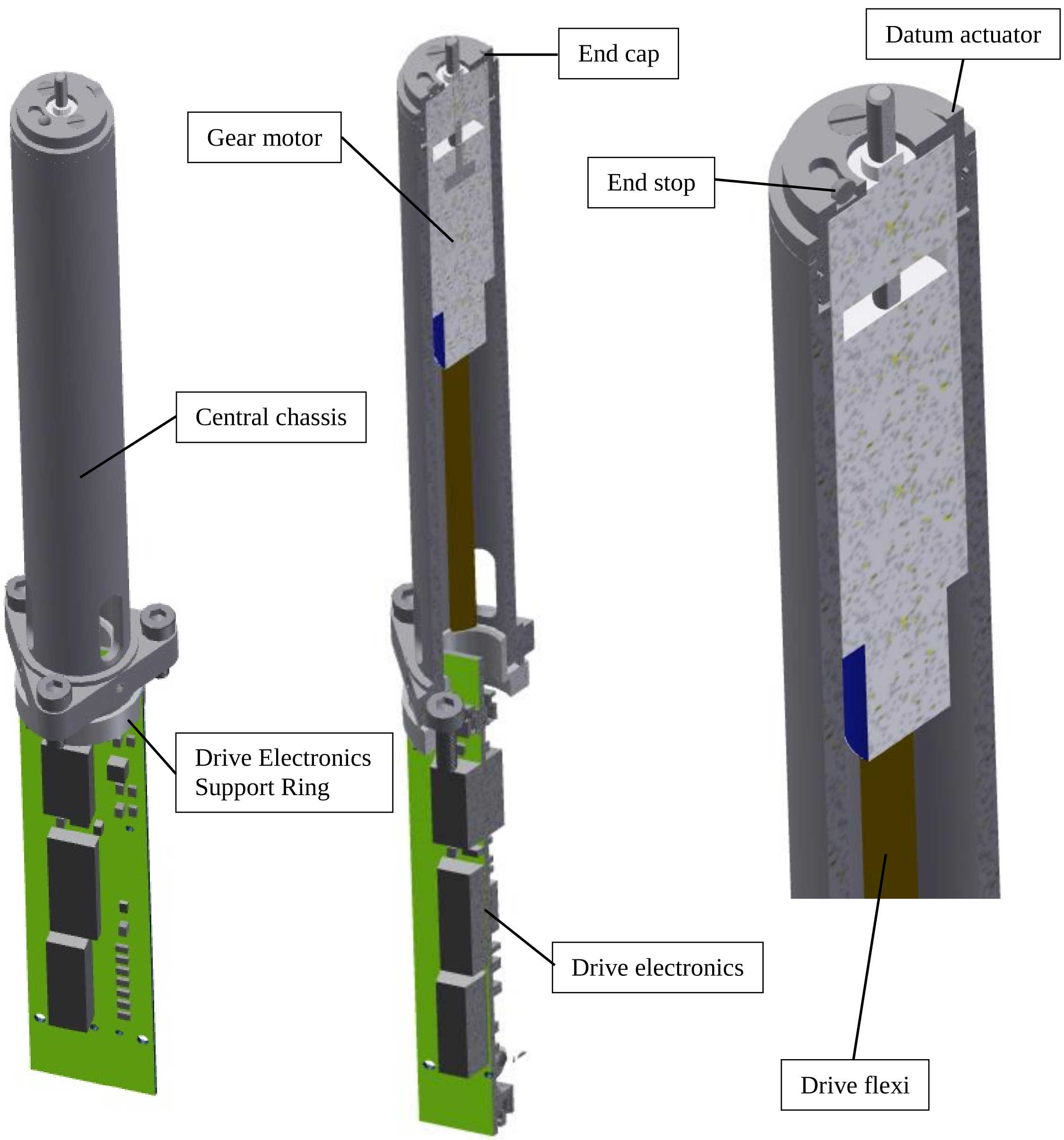

Figure 3. FPU Chassis Assembly

2.5 Alpha arm assembly

The Alpha arm attaches directly to the output shaft of the Alpha gear motor and is secured by a set screw. Attached to the bottom of this component with three fasteners is a mount for the cylindrical counterbalance weight that in turn screws onto this. This component also provides a feature for the Alpha axis end-stop that strikes the ball bearing on the chassis assembly. There is a hole for a second ball bearing that actuates the Alpha end stop micro switch.

A U-shaped fibre guide is attached to the lower part of the Alpha arm by two fasteners. There are also holes for two rods that guide fibres as they wrap around the arm during rotation. These are bonded in place.

The Alpha rotation datum switch is mounted in a hole in the base of the Alpha arm and secured by a set screw.

About the middle of the arm, there are mounting features for a connecting PCB which is fastened by two screws. This PCB accepts the connection for the Beta axis motor and Alpha and Beta datum switches and provides a connector for the flexi that spirals down the FPU and goes through a slot in the chassis to the drive electronics board.

The top of the arm provides a mount for the Beta axis gear motor. This is a flat surface with a location hole. There are two countersunk fasteners for the gear motor. The flat surface is angled such that the motor axis intersects the chassis axis at the focal surface centre of curvature.

The top of the arm provides interfaces to the Beta datum switch and ball catch. These are both secured by set screws. The ball catch is a small assembly consisting of a cylindrical housing, ball retainers and ball bearing. There is also a pin that acts as the Beta rotation end stop.

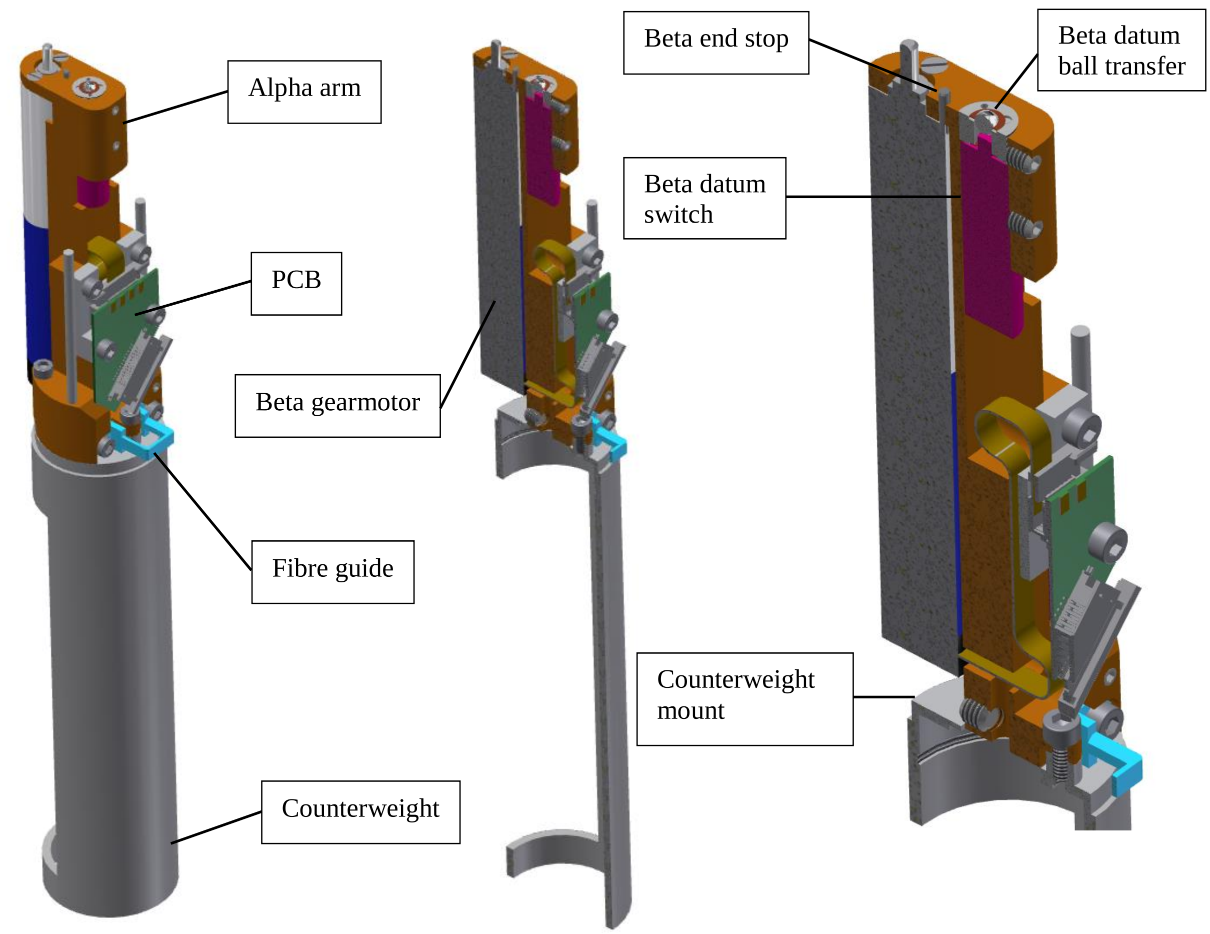

Figure 4. Alpha Arm Assembly

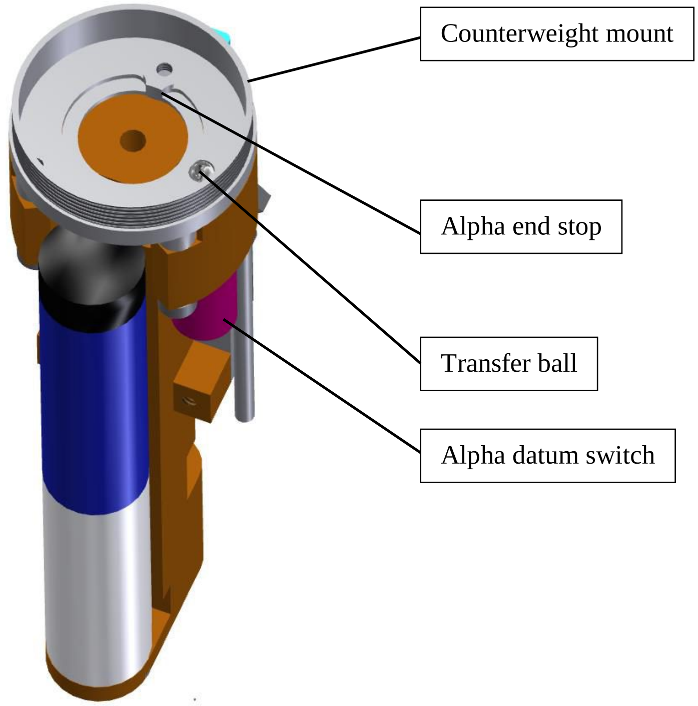

Figure 5. Alpha Datum and End stop

2.6 Beta arm assembly

The Beta arm is a curved component that mounts directly to the Beta axis gear motor. It is retained by a set screw. The lower part of the arm provides a tab that acts as a rotation stop. There is also a mount for a ball bearing that actuates the Beta datum switch. The ball bearing is bonded in place.

The top of the arm provides a cylindrical clamp interface for the fibre ferrule which is retained by a set screw. This cylinder is angled such that it points towards the focal surface centre of curvature.

The top of the arm provides a flat area for mounting metrology targets which will be bonded in place.

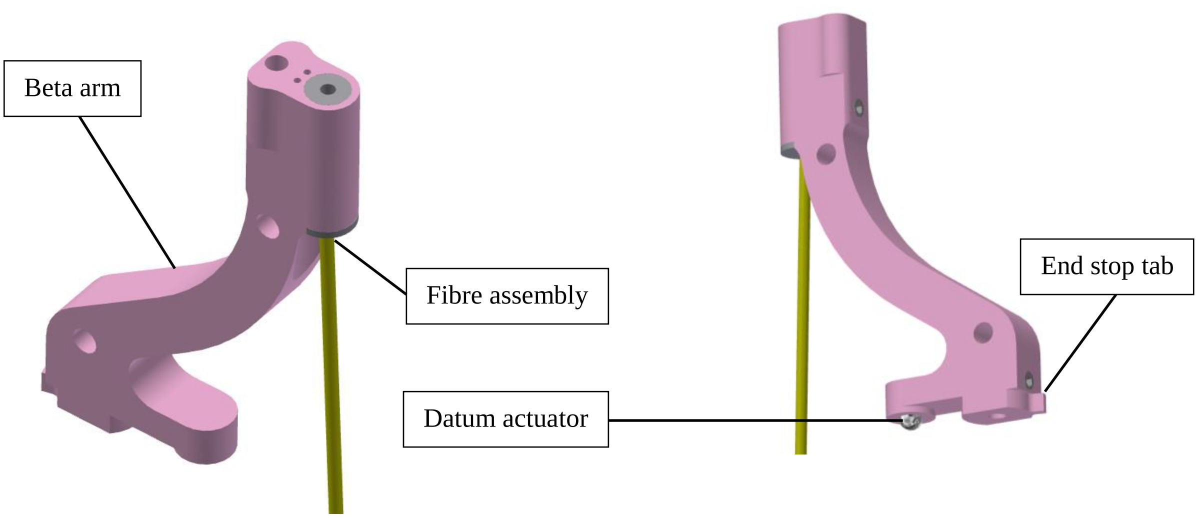

Figure 6. Beta arm assembly

2.7 Custom parts

The custom parts for the baseline FPU are shown below.

Figure 7. FPU Custom mechanical parts

2.8 Gearmotors

The gear motors consist of a stepper motor with encoder, mated to an anti-backlash speed reducing gearbox. The motors selected in the baseline design are from Faulhaber. The gearboxes have pre-loaded ball bearings at the output shaft and have been modified to improve the angular runout and flexure of the output shaft. The motor shaft also has ball bearings (normally a plain bush).

A 12mm gearbox is used on the Alpha axis and an 8mm gearbox is used on the Beta axis. Both motors are 8mm diameter with 20steps/rev. The nominal Alpha and Beta motor gear ratios are 2050:1 and 1518:1 respectively.

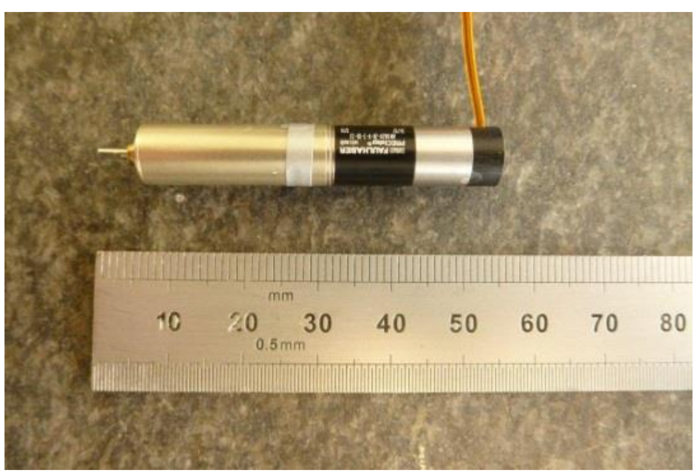

Figure 8. Faulhaber gear motor – 8mm

2.9 Datum switches

The datum switches are Metrol PT5M1WB. These switches have stated repeatability of 1 micron and an actuation of 0.5N with a lifetime of $1x10^6$ operations. They are normally closed configuration.

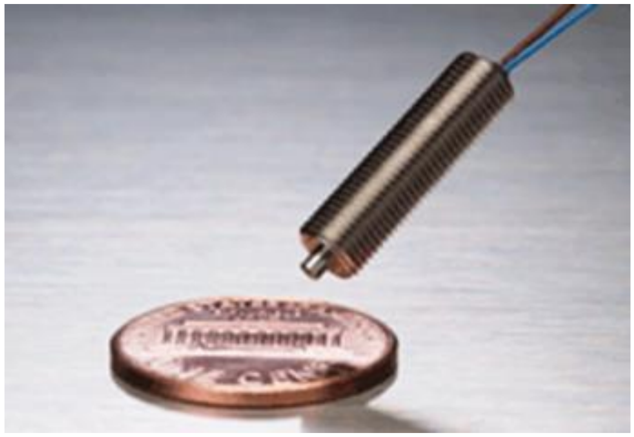

Figure 9. Metrol datum switch

3. ELECTRONICS DESIGN

5.1.1 Introduction

An important feature of the MOONS instrument is that each FPU can access targets in their neighbour's patrol field. As such adjacent FPUs can collide if their movement is not carefully calculated and executed. To reach their allocated targets the local FPU electronics executes travel profiles which have been calculated in advance by path analysis software (a collision avoidance algorithm which implements a de-centralised navigation function[2]). This software runs on the positioner workstation and generates travel profiles for each FPU prior to an observation. The travel profiles are in turn converted to low level commands by the positioner software and downloaded to each FPU to be stored in local memory. They are stored in tables containing discrete information on number of steps, step frequency and direction for both motors. Once all waveforms are downloaded the FPUs are instructed to start executing their stored profiles concurrently.

5.1.2 FPU Local Drive Electronics

Each FPU includes local electronics which communicate with the positioner workstation over CAN Bus. They are responsible for receiving and executing travel profiles. This requires the ability to drive the two stepper motors concurrently at different and varying speeds. Commercially available ICs are used to implement the required functionality (such as local drive electronic bipolar stepper drive and quadrature counter chips). Figure 10 presents a block diagram of the demonstrator drive electronics which include the following main components:

1. PIC18F458: microcontroller (MCU) which includes a fully implemented CAN module and In-Chip Serial Programming interface (ICSP). Amongst other functions this manages communications with the positioner workstation, generates clocking to execute motor waveforms, datums the motors, and reads the quadrature counters.
2. MCP2551: CAN Bus transceiver to interface the MCU CAN module to the CAN Bus.
3. A3967 (x2): full/micro-stepping bipolar stepper motor drive chips with controller and built in translator. They are driven with various control lines from the MCU including clock and direction signals. Its outputs can be disabled between movements (motor windings depowered). It supports current limiting by appropriate choice of external components (set to 150mA for this application)

4. HCTL-2032: dual quadrature counter to monitor the motors' incremental rotary encoders.
5. Address module: provides a unique address/ID to each FPU on the bus. Currently implemented as a 7-bit DIP switch for addresses 1→127 to be selectable (0 reserved).

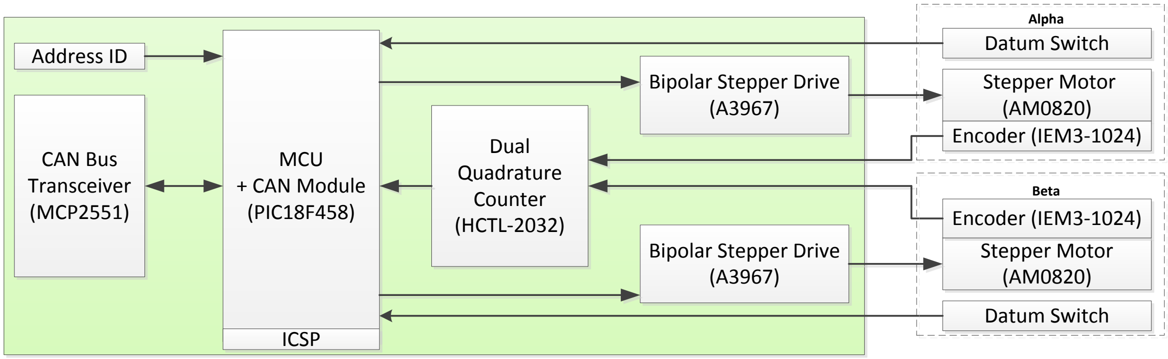

Figure 10: Local Drive Electronics Block Diagram

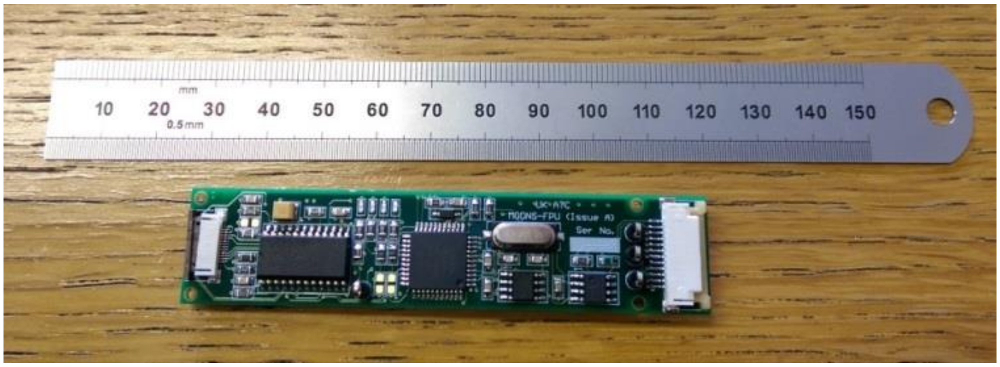

Figure 11: FPU Demonstrator Local Drive Electronics

The FPU electronics receive commands from the positioner software over CAN Bus and the CAN Bus protocol is locally implemented in the MCU's CAN module. This includes all message arbitration, error checking and packet filtering. The CAN Bus protocol includes an 11-bit identifier field allowing module targeted messaging. During initialisation the MCU reads the local address module and configures the CAN module packet filter and mask registers to ensure that only commands intended for it are passed through the CAN module to interrupt the MCU. Broadcast messages with an ID=0 are received by all modules on the bus and have the highest priority. These are used to instruct all FPUs on the bus to start executing their stored travel profiles at the same time. The MCU executes the travel profiles by generating clock patterns for both the stepper drive chips (A3967).

5.1.3 Collision Detection

The path analysis software reduces the likelihood of collisions but cannot fully eliminate it due to potential error conditions. As such a secondary system is required to detect collisions and in doing so cut power to the motors. Using the encoders to realise this function was considered; whereby they would be read between each step to check that motors were moving as expected and had not stalled. However, the incremental encoders are located on the output shaft of the motor drive, whereas potential collisions would impart force on the output shaft of the motor's gearbox. Since such high ratio gearboxes are being used the instantaneous output torque of the gearbox can exceed its rating before a stall can be detected due to wind up in the gear box. As such this option was ruled out.

A second option has been considered which applies a unique voltage to the case of each FPUs which can collide. When two FPUs collide it is detected by measuring current flowing from one FPU to the other. The current sensing circuit shown in Figure **12** has been successfully prototyped. The circuit includes a full wave rectifier diode network and a voltage comparator (open collector output). The full wave rectifier circuit ensures that current can be detected in either direction (flowing to or from the colliding FPU). In the circuit shown the FPU has its case voltage set to 3V. In a normal no-collision state no current flows through R1 and the pull up and pull down resistors (R3 and R4) ensure the comparator outputs a logic low on the control signal “collide”. If a collision occurs (with an FPU with a different case voltage) then current flows inducing a voltage across R1 which is detected by the circuit and the control signal “collide” is pulled high. FPU case voltages will have to be spaced >2.8V apart as both of the full wave rectifiers (one each colliding FPU) will require ~1.4V to conduct. If two FPUs with the same voltage were to collide then no current would flow and would go undetected. This can be avoided by adopting the 7-node tessellation pattern shown in Figure **13**. Here FPU nodes of the same number are separated far enough to ensure that they cannot physically reach each other to collide. Each of the seven nodes would have a different voltage separated by 3V. It is proposed that the required voltage be pulled off the backplane PCB and as such be made location dependent.

A prototype system was implemented and integrated with a cluster of five FPUs. When a collision is detected the control signal is used to interrupt the local drive electronics’ MCU. It subsequently cuts power to the motors, switches the case voltage to ground and issues a warning message over CAN Bus. This prototype system successfully demonstrated that it could detect single collision events and multiple “pile-up” collisions.

The collision detection circuity will be added to the local drive electronics in the next revision of the board.

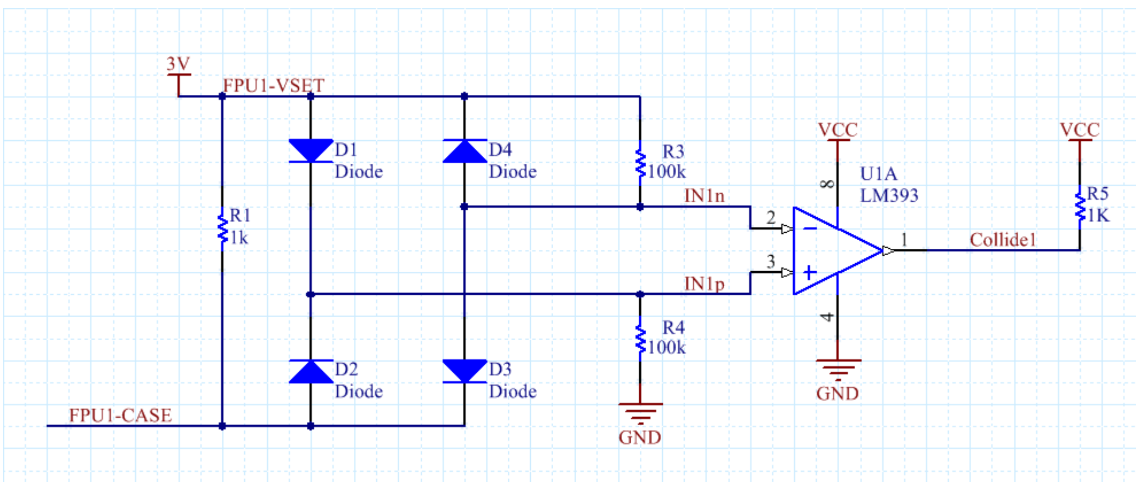

Figure 12: FPU Current Sensing Circuit (Collision Detection)

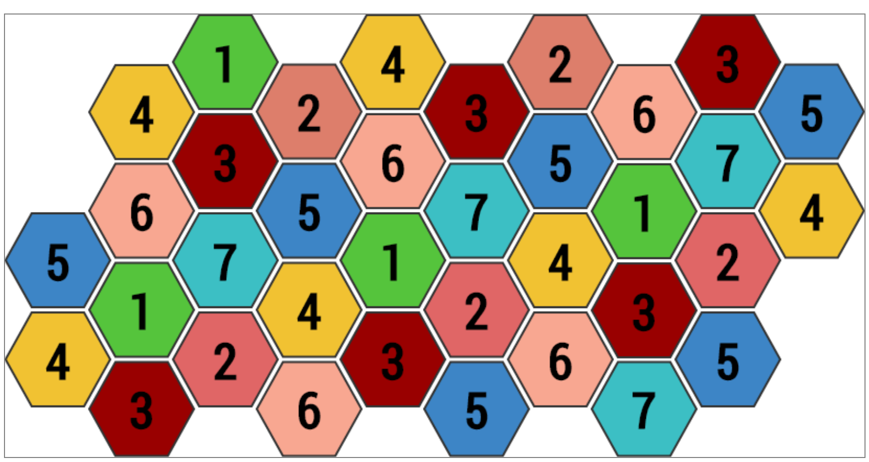

Figure 13: FPU Collision Voltage Tessellation

4. PROTOTYPE TESTING

Five prototype FPUs were manufactured for testing (Figure **14**). These have undergone a series of tests to measure performance against requirements. The tests are summarised with the current status in

Table **3**.

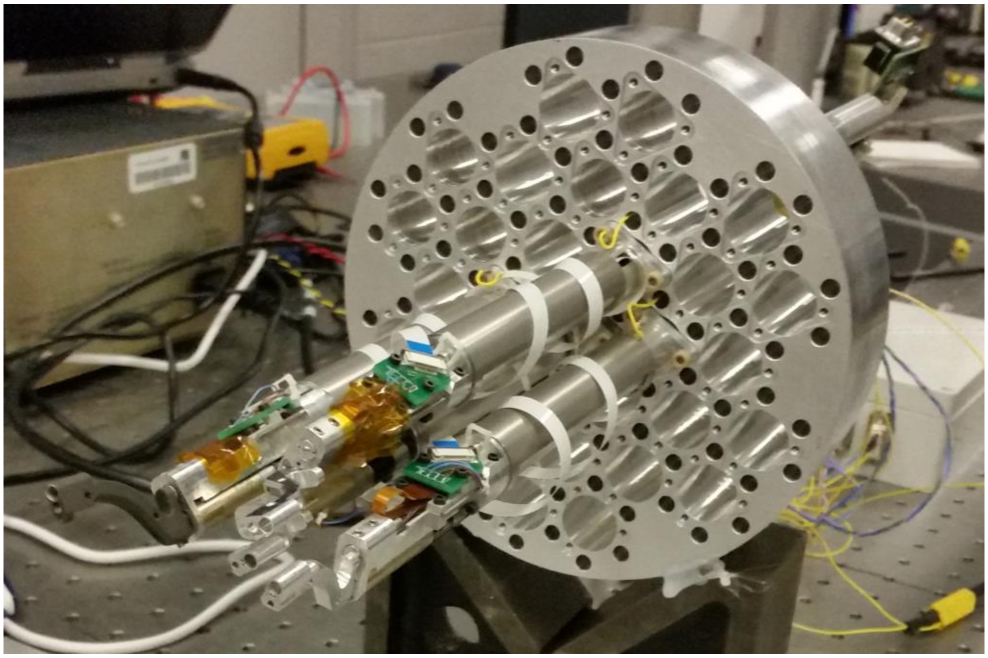

Figure 14. Prototype FPUs

Table 3 Demonstrator test goals

Test goals	**Status and Comments**
Confirm the functionality of the FPU with various options	Completed
Measure performance of the FPU with various options	Completed for the baseline design
To measure the placement repeatability in three dimensional space of each positioner fibre tip for various movements	Largely completed, focus yet to do
To characterise the stability of each fibre tip once in position over typical observation periods (gravity change).	Completed
Determine best option for fibre cladding material and diameter from samples (current baseline 0.5mm PEEK)	The 0.5mm Peek fibre has been used in the tests to date and is satisfactory
Confirm FRD is acceptable over full range	Completed for full range and over life testing
Confirm that fibre management scheme does not harm fibre	Results to date show no physical signs of damage or fibre breakage.
Develop fibre and services distribution scheme	Completed
Demonstrate positioning with clash protection	Completed
Demonstrate practicality of concept is scalable	This has been largely verified by the manufacture and assembly of the 5 FPUs in the demonstrator.
Generate report & fault log to improve design, identify further testing	Fault log in use
Generate assembly processes and tools	Largely complete, single FPU removal tool in development
Life testing	Completed on one FPU

Position and flexure tests were carried out using a coordinate measuring machine and a camera metrology system (Figure **15** & 11).

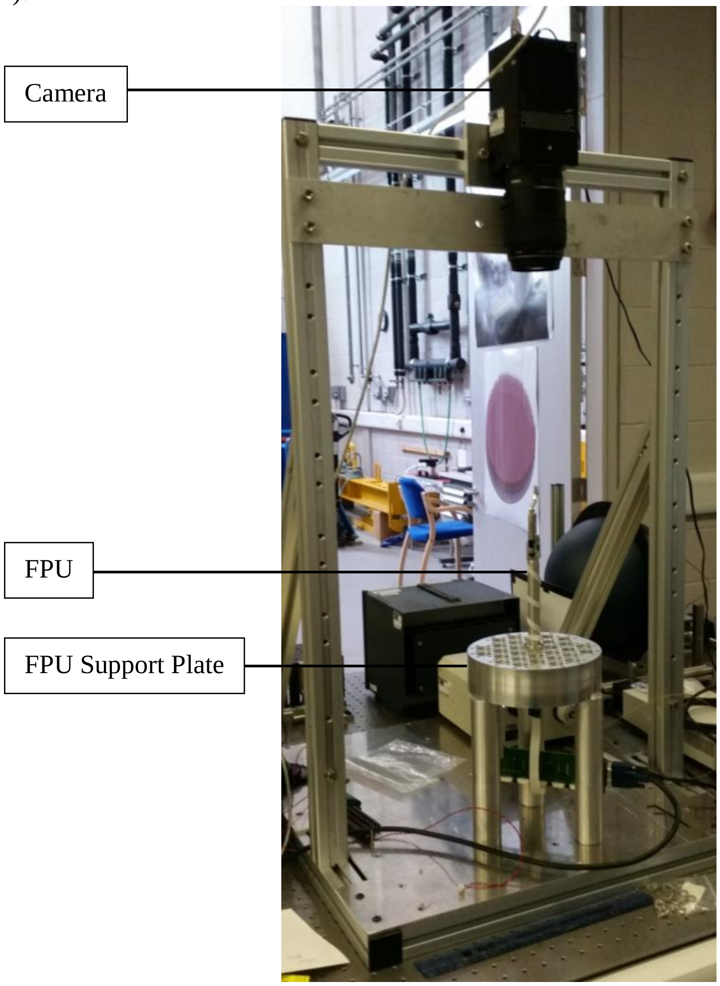

Figure 15. FPU camera metrology test setup

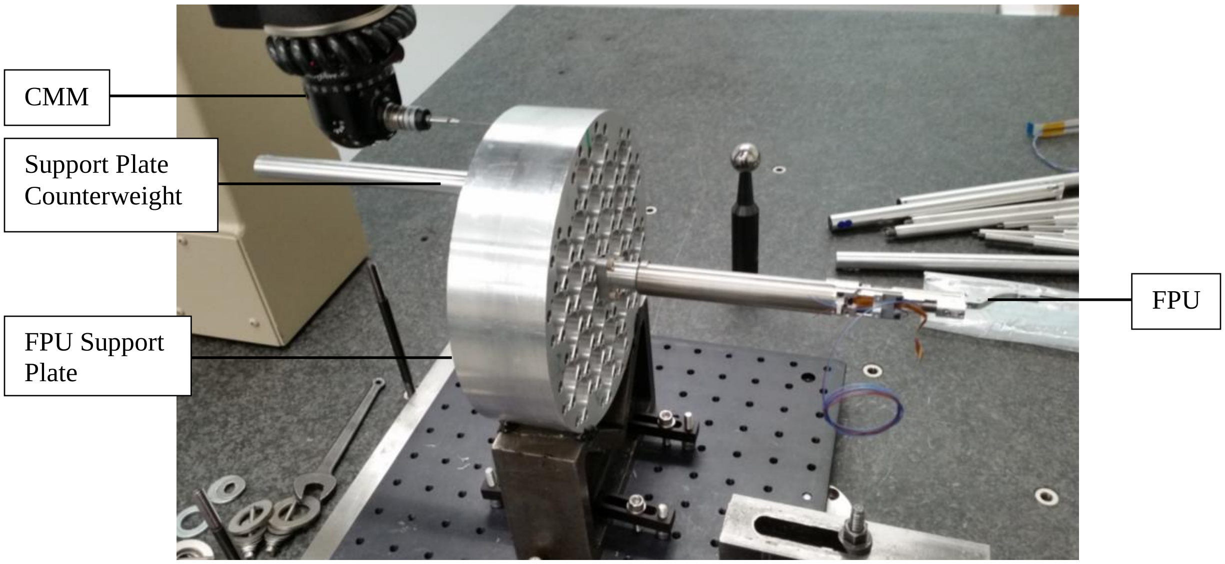

Figure 16. FPU CMM test setup

4.1 Test results FPU assembly

The main test results obtained to date are listed below in Table **4**.

Table 4. Test Results Summary

Test	**Result summary**		**Comments**
	Alpha	**Beta**	
Datum repeatability	2 microns (1 step)	2 microns (1step)	Vertical orientation, 20 movements
Positioning accuracy without look-up table	34 microns r.m.s.	34 microns r.m.s.	Vertical orientation, 20 movements
Positioning accuracy with look-up table correction	3.1 microns (1 step)	3.1 microns (1 step)	Vertical orientation, after LUT correction 20 movements.
Pupil alignment	8 arcminutes		The pupil alignment was well out of spec for the other measurements. This is attributed to interface surface damage on multiple assemblies.
Focus position	Not directly measured		Low pupil tilt errors imply acceptable systematic focus error
Position flexure	< 20 microns		For a full 360 orientation change w.r.t. gravity
Deployment	< 30 seconds		Potential is confirmed but is also affected by collision avoidance path
Assembly/Removal of single FPU	TBD		Not demonstrated to date

4.2 Design improvements suggested from testing

The pupil alignment has proved the hardest requirement to meet. This has been attributed to the non- repeatability of angular alignment in the clamped joints at the motor shafts. Reasons for this non-repeatability are damage to the shafts and mating parts on repeated assembly. Design improvements considered for the next iteration include shafts of increased diameter, length and hardness. Through the integration process, a fault log has been maintained to inform the design improvement exercise.

5. CONCLUSIONS

The MOONS FPU module has been designed and prototypes constructed and tested to demonstrate the technology, de-risk the design and characterise components. The prototypes performed well, except in the area of pupil alignment. Investigation of the causes has led to improvements in the design which will be implemented in an advanced prototype for further testing.

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