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MOONS fibre positioning module: instrument build overview

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ABSTRACT

MOONS (Multi-Object Optical and Near-infrared Spectrograph) is a third-generation visible and near-infrared spectrograph for the ESO Very Large Telescope, currently nearing the end of the assembly phase. The three channel spectrograph is fed via a fibre positioning module (FPM) which configures the location of 1001 fibres. The robotic fibre positioning units (FPUs) have been jointly developed by the UK Astronomy Technology Centre (UKATC) and MPS Microsystems (MPS) and provide a high-performance multiplexed focal plane with excellent transmission characteristics. An overview of the as-built mechanisms and supporting infrastructure is presented, with details on the extensive calibration process carried out. The integration process to date will be described, including a discussion of key lessons learned.

Keywords: MOONS, VLT, MOS, infrared, fiber, positioning, integration, calibration

1. INTRODUCTION

MOONS is a highly efficient multi-object visible and near-infrared spectrograph for the VLT [1], currently nearing completion with first light due in 2023. The MOONS rotating front-end (RFE) [2] centrally comprises a fibre positioning module (FPM) which is made up of ~1000 independently-controlled, dual-arm fibre positioning units (FPUs), enabling up to 1000 spectra per observation. The two key MOONS science cases are surveys of stars in the dust-shrouded galactic centre and distant, red-shifted galaxies. Both cases make use of the multiplexed capability of MOONS over the full wavelength and resolution range. However, the extragalactic case is more onerous on the positioner requirements as it requires optimal light transmission. A consequence of this is the requirement for close alignment of the fibre inlet aperture with the instrument pupil, demanding exceptional control of mechanical tolerances in the fibre positioner. Additionally, signal-to-noise can be improved by sky-subtraction, correcting for the local sky signal by using an adjacent fibre at close separation. This requires the entire 25 arcmin field of view (FoV) to be reachable by a minimum of two fibres at 10 arcseconds separation meaning the positioners must position accurately and have substantial overlap with each other. The combination of these requirements makes the MOONS focal positioning module a significant engineering challenge.

A detailed description of the FPU mechanical and electronic design is presented in [3].

The FPU driver and control software is described in [4].

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2. BUILD STATUS AND PERFORMANCE

As of July 2022, all FPUs have been delivered to the UKATC in Edinburgh by the vendor, MPS Microsystems AG. Of these, 659 FPUs have been fully characterised and installed into the FPM. The installation rate is ~20 per week and completion is expected before September 2022.

The average as-built performance from these FPUs is summarised below:

Table 1. FPU requirements and performance to date

Item	**Goal / Requirement**	**As-installed average**
Optical alignment with the instrument pupil *(worst combined error)*	0.1° / 0.2°	0.12°
Positional repeatability *(RSS of alpha & beta 95th percentile error)*	20 µm / 30 µm	12.0 µm
Positional accuracy *(95th percentile of error magnitude measured at 72 positions, after calibration)*	20 µm / 50 µm	35.8 µm

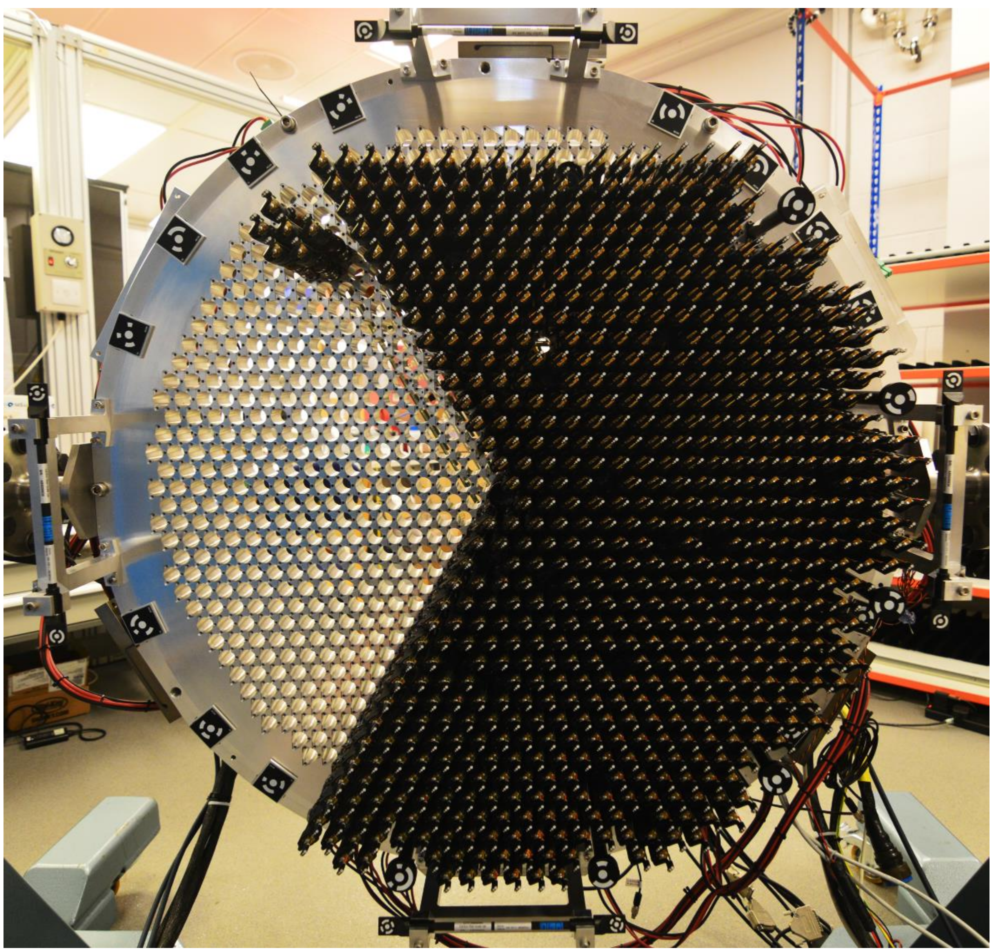

Figure 1. Current FPM build state

3. MECHANISM CHARACTERISATION

3.1 Process overview

Characterisation of the MOONS FPUs is a multi-faceted process that begins in the factory at MPS with end-of-line tests, then continues with goods inwards inspections and an automated performance verification process in Edinburgh, before final in-situ functional tests are carried out after integration. The extensive testing carried out post-delivery is necessary because it is not practical for MPS to use the optical methods required to fully characterise the units.

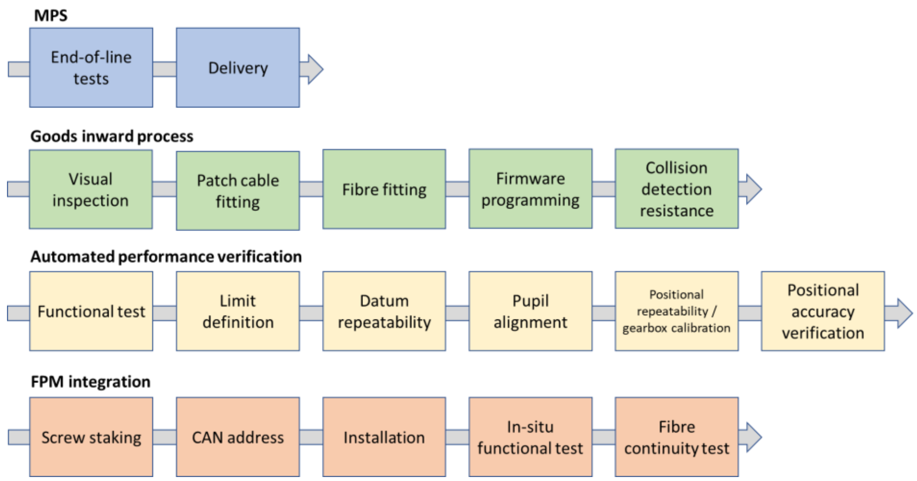

Figure 2. FPU characterisation process

3.2 MPS delivery

FPUs are manufactured at MPS in two sub-assemblies with the motor shafts as interfaces. The motor gearboxes are pre-loaded and tested for positional repeatability and shaft alignment independently, before being assembled together and the beta arm fitted. Repeatability testing is carried out with a temporarily-fitted encoder while alignment testing uses a CMM. The FPUs are then packed into anti-static bags and shipped in segmented polystyrene boxes. These boxes continue to be used until the fibre is fitted, whereby they are stored in a shelving unit in anti-static foam compartments.

Figure 3. FPU shipping boxes (left); storage after fibre fitting (right)

3.3 Goods inward process

On arrival at the UKATC, FPUs first undergo a visual inspection against a checklist. Rarely, units can be damaged during packaging/shipping or have minor problems such as suspect solder joints. Having passed inspection, the protective heat shrink is removed to fit a patch cable, then the heat shrink is re-applied.

Fitting fibres [5] to FPUs requires detachment of the rear drive PCB. The fibre is fed behind the spiral interface flexi and through a hole in the bottom of the chassis, exiting the mechanism alongside the alpha motor wires. It is pulled through and inserted into the beta arm, where two grub screws push the ceramic casing of the micro-lens/ferrule assembly against the bore of the arm. Finally, the fibre is inserted into a strain relief clip mounted to the bottom of the alpha arm; this is a Delrin C-clip compressed into a split clamp.

With the FPU mechanically complete, the drive firmware is updated and a serial number is flashed into non-volatile memory. The serial numbers of the FPU, fibre and drive PCBs are also entered into a master spreadsheet which tracks the status of the FPU assembly.

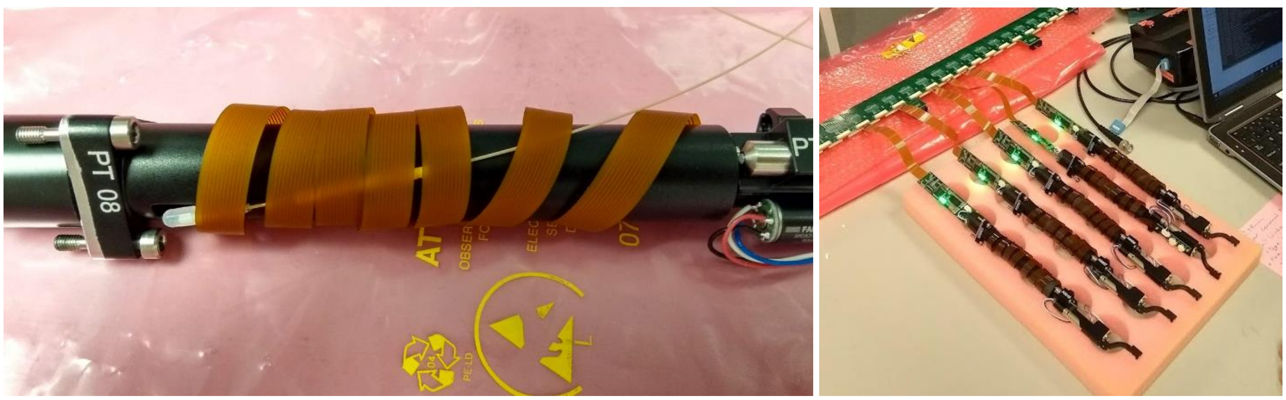

Figure 4. Fibre fitting (left); firmware re-programming (right)

The final manual test is of collision detection resistance – this system uses a pattern of voltages applied to the beta arms so that any contact between FPUs results in a detectable current flow. The voltage is conducted into the FPU via a screw between the PCB and alpha arm, then through the motor bearings into the steel shaft and up to the beta arm. The bearings are lubricated with grease which can interfere with the electrical contact. During the test, a logger measures resistance as the beta arm rotates through its full sweep. Typically, a short run-in mitigates any increased resistance; the system can tolerate a resistance of ~1 kΩ but, above this, the risk of an undetected collision increases. FPUs are classified into 4 categories: pass, borderline, fail and unstable. The first three are installed, with borderline and failed FPUs being selectively located to reduce the risk of problematic collisions. Only unstable FPUs, which are effectively open-circuit, are rejected.

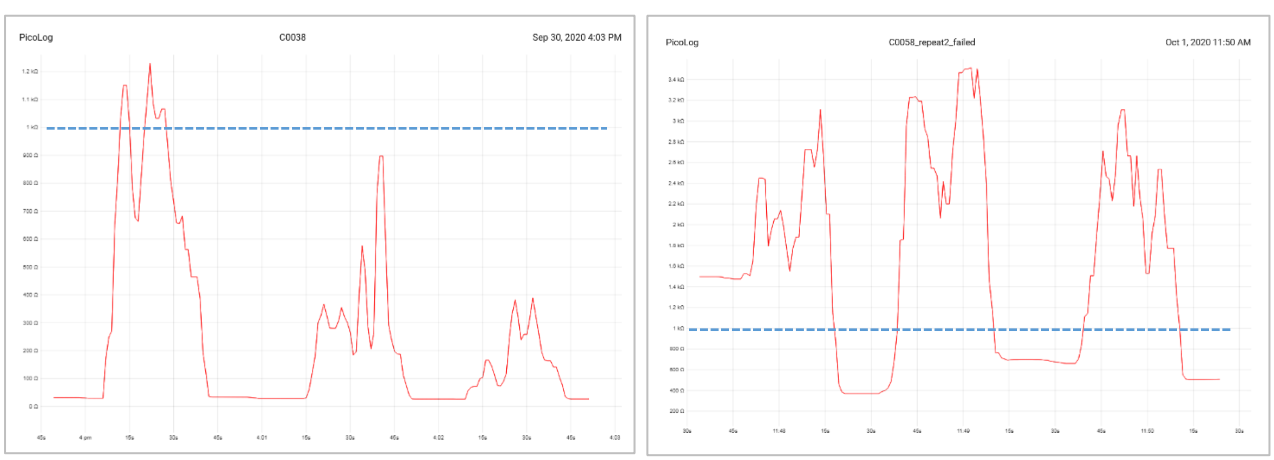

Figure 5. Collision detection resistance measurements: passed (left); failed (right)

3.4 Automated verification

The automated verification process uses a custom-built rig in a light-tight enclosure which can accommodate 5 FPUs and moves sequentially through a series of test stations. This approach allows efficient 24-hour testing of the FPUs at a rate of 8 per day, with characterisation of each FPU taking ~2.5 hours.

There are five test stations within the rig:

- **Collision detection test** – a flexible contact connected to ground.
- **High resolution** – a 4k camera with a narrow FoV telecentric lens which measures metrology target centroids to < 1 µm centroiding precision.
- **Medium resolution** – a 4k camera with a distortion-corrected wide-angle lens which measures metrology target centroids to ~ 2 µm centroiding precision.
- **Metrology target profile** – a 4k camera with a telecentric lens which measures the protrusion of the metrology targets above the beta arm to < 1 µm linear precision.
- **Pupil alignment** – a 2k camera with a distortion-corrected wide-angle lens which centroids of backlit fibre project. A high-power focussed LED backlights the fibres via the patch fibres and projects onto a screen at the pupil distance (4.1 m) via fold mirrors.

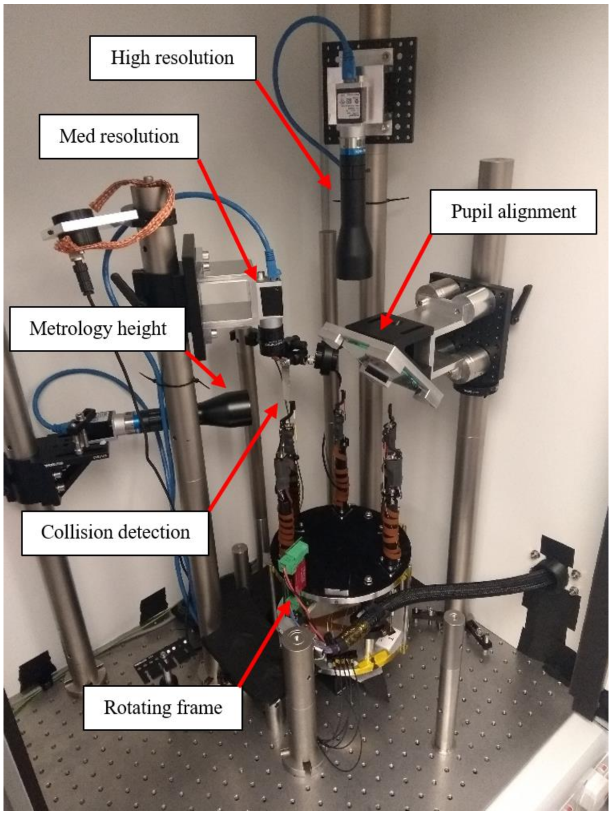

Figure 6. Verification rig hardware

The control software for the system is highly configurable, allowing a great deal of flexibility in debugging and repeat tests alongside the comprehensive default test. The images and results are analysed and logged, with data backed up locally.

Positional measurements use thresholded images of the tops of the beta arms. The two metrology targets are found using an OpenCV blob detection algorithm, then filtering against size, circularity and relative separation. A mass weighted average of the two targets gives the “FPU coordinate”.

The default test process runs as follows:

- **Functional test** – the FPUs are datumed on each arm separately, verifying functionality of the motors/switches.
- **Collision detection test** – the beta arms are driven into a grounded contact testing the collision detection circuit.
- **Limit test** – the FPUs are driven close to their expected positive and negative limit angles on both arms, then moved at minimum speed until the limit detection triggers. The angle of detection is stored in the database.
- **Metrology target height** – using the metrology target profile camera, a silhouette of the beta arm profile is generated and lines fitted to the profile of the beta arm surface and metrology targets to derive target protrusion.
- **Datum repeatability** – the high resolution camera measures the position of the FPUs after 10x datum operations, then again after being cycled through 10x +30° movement / -30° movement / datum sequence. From the positions, the 95th percentile datum position repeatability is determined.
- **Metrology target calibration** – the high resolution camera images the FPU with ambient lighting, then again with the fibre backlit and a shortened exposure time. The relative centroids allow a relationship between the targets and fibre location to be determined, which is used by the instrument metrology system.
- **Pupil alignment** – the fibre is backlit and the FPU moves through four 90° beta arm increments at each of four 90° alpha arm increments, effectively four "beta circles", for a total of 16 positions. The fibre axis error (intrinsic to the beta arm) is equal to the average radius of the four transcribed "beta circles", and the beta axis error (intrinsic to the alpha arm) is equal to the radius of the circle transcribed by the centres of the four "beta circles".

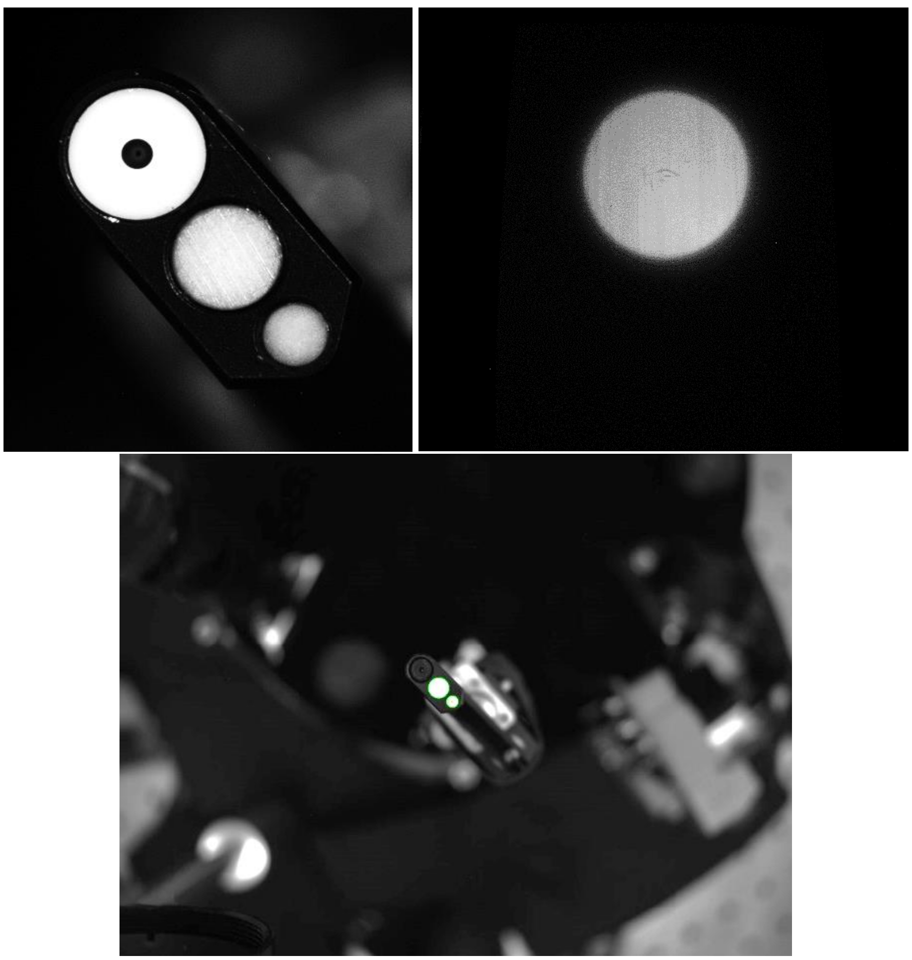

Figure 7. Verification rig images: high resolution (top left); pupil alignment (top right); medium resolution (bottom)

- **Positional repeatability** – the medium resolution camera measures the target positions as the individual arms are moved as follows:
    - Coarse measurement - 20° movements, back and forth between limits three times
    - Fine measurement – 360 movements (approx 0.9°), back and forth between limits once

  The fine measurement typically shows up most manifestations of hysteresis but some FPUs demonstrate inconsistent hysteresis which might only show on one of the repeated coarse sweeps.

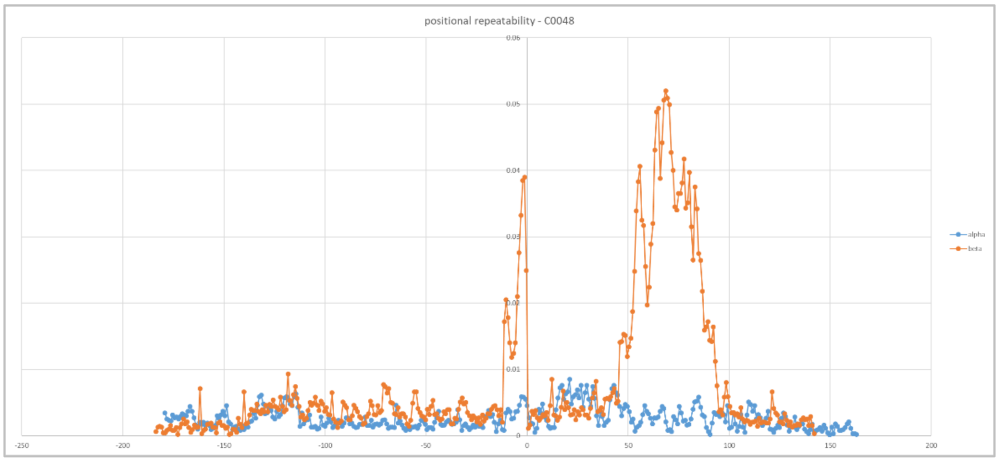

Figure 8. Example of fine positional repeatability measurement, showing localized hysteresis in beta arm

- **Gearbox calibration and positional accuracy** – from the fine positional repeatability data, the average real position of the arm is calculated at each pair of out and back points. From this, the coordinate of the centre of rotation and the radius of each arm is derived, along with the datum coordinate. These allow a local coordinate system to be created and a relationship between demanded FPU angles and predicted position in the camera frame to be determined. When a plot of the real v predicted position is made, it shows a complex non-linear response deriving from mechanical tolerances in the gearbox. The peak magnitude of the non-linearities can be up to 150 µm, making correction of this effect critical. The data are turned into a look-up table which corrects demanded positions to improve positioning accuracy of the FPUs. The FPUs are moved through a series of ~80 positions at varying alpha and beta angles with this correction applied and the real position compared against predicted position again. The 95th percentile of all absolute errors is calculated as the headline FPU accuracy.

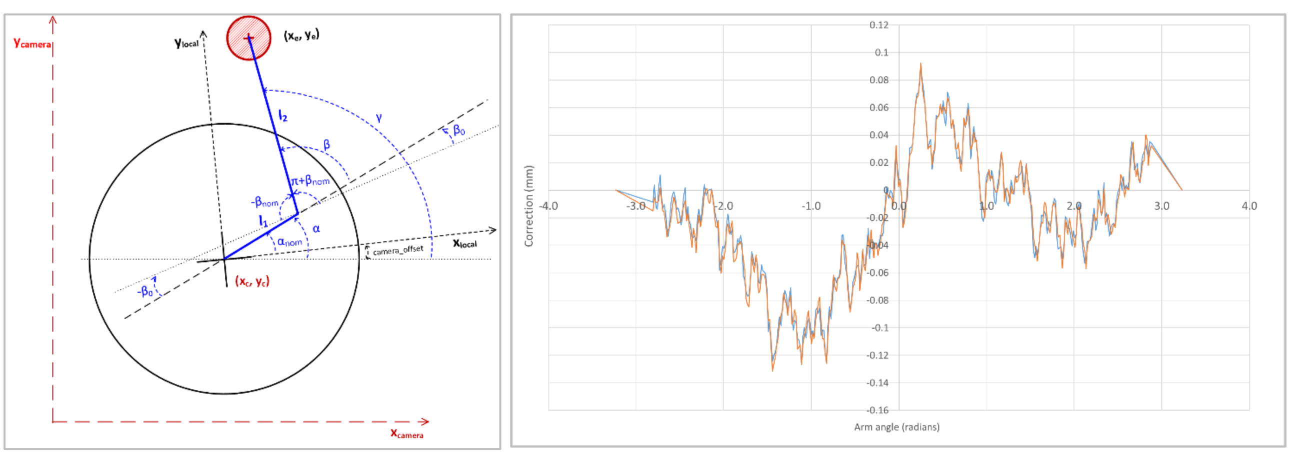

Figure 9. FPU coordinate system and offsets (left); example gearbox look-up table (right)

4. INTEGRATION PROCESS

4.1 Traceability and planning

FPUs are categorised in two ways that affects installation; performance and collision detection resistance. Most FPUs are 'A' class but those which perform only marginally within specification are classified as 'B' and installed at sky coordinates greater than 650 arcsec where there is more probability of obscuration by the VLT guide star probe.

FPUs which have 'borderline' or 'failed' collision detection resistance values (see Section 3.3) are installed such that the risk of problematic collisions is reduced. Practically, this typically means locations at the outer edge, where FPUs have fewer neighbours or only have neighbours with a voltage difference greater than the minimum, partially mitigating the increased resistance in the circuit. There is a concern that these FPUs might be at risk of premature failure and so this installation strategy additionally means access is easier once integrated into the MOONS Rotating Front End.

All of this information is captured in a master spreadsheet, which records all the serial numbers, locations, performance data, categories and a current status. At any given time, this can be filtered on FPUs which are "READY" for installation, giving input to another spreadsheet which represents the as-installed focal plate. Each position has an entry with its sky and physical coordinates, the installed component details, collision detection voltage, connection ID and CAN address.

Baseline

FPU ID	Batch	Box	Delivered	Fibre SN	Fibre sup	Fibre note	PCB SN	Gearbox calibration	Patch cable fitted	Location	Alignment - rig						Datum repeatability					Positional repeatability								Target height		Posver	Posver_	Collision voltage test	Performance classification	Ready	91
vfrig report commands											tion_ -fmt long | egrep "(pupil alignment."er						./vfrig report -f "/batch_configs/productic					./vfrig report -f "/batch_configs/production_test_batch -fmt long | e								./vfrig report -f "/b		./vfrig report -f "/bat				Fail	74
											vfrig	Alpha m	Beta m	Alpha sec	Beta sec	Total, sec	vfrig	Datum only, m	Datum only	Datum and move, me	Datum and move	vfrig	Alpha, 50%	Alpha, 95%	Alpha max	Beta, 50%	Beta, 95%	Beta max	RSS, 95%	Small	Large	95%	95%		9.31707 7	TBD	57
C0678	16	18	1	1026-	SQS		760	Done	YES	0204	0	1.94	4.38	1.62	3.67	5.30	0	0.0008	0.0017	0.0008	0.0014	0	0.0027	0.0052	0.007	0.0102	0.0147	0.0197	0.0156	0.0264	0.016	0.0365	0.0365	Pass	A	Installed	
C0679	16	18	1	1112	SQS		876	Done	YES	RETURN1	0	1.31	7.83	1.10	6.56	7.66	0	0.0006	0.0011	0.0026	0.0058	2	0.0021	0.0049	0.0068	0.0071	0.0304	0.0569	0.0308	0.0257	0.0168	0.0267	0.0267	Pass		RETURN	Failed beta posrep
C0680	16	18	1	1058	SQS		080	Done	YES	0205	1	2.52	5.85	2.12	4.90	7.02	1	0.0011	0.0027	0.001	0.0018	0	0.0024	0.0054	0.0077	0.0087	0.015	0.0248	0.0159	0.0107	0.0284	0.0456	0.0456	Pass	A	Installed	
C0681	16	18	1	1091	SQS		805	Done	YES	0206	0	3.62	3.19	3.03	2.67	5.70	0	0.0009	0.0013	0.0008	0.0013	0	0.0025	0.0051	0.0061	0.0059	0.0106	0.0149	0.0118	0.0385	0.0274	0.0334	0.0334	Pass	A	Installed	
C0682	16	18	1	1213	SQS		806	Done	YES	0207	0	1.79	2.00	1.50	1.67	3.17	0	0.0005	0.001	0.001	0.002	0	0.0017	0.0045	0.0063	0.0053	0.0097	0.0144	0.0107	0.0279	0.0279	0.0437	0.0437	Pass	A	Installed	
C0683	16	20	1	1170	SQS		801	Done	YES	T5	0	4.09	5.60	3.43	4.69	8.12	0	0.0012	0.0015	0.0007	0.0017	1	0.0108	0.0174	0.0195	0.0082	0.0114	0.0143	0.0208	0.0202	0.0136	0.0411	0.0411	Pass		TBD	Check plots
C0684	16	20	1							CD RETEST																										Fail	Unstable collision detection circuit
C0685	16	20	1	0218	SQS		802	Done	YES	0208	0	1.08	9.39	0.90	7.87	8.77	0	0.0014	0.0034	0.0018	0.0031	0	0.0028	0.0065	0.0087	0.0082	0.0125	0.0175	0.0141	0.0193	0.0178	0.0404	0.0404	Pass	A	Installed	
C0686	16	19	1	1047	SQS		807	Done	YES	0209	0	1.41	1.49	1.18	1.25	2.44	0	0.0005	0.001	0.0009	0.0022	1	0.0025	0.0045	0.0061	0.0051	0.0096	0.014	0.0106	0.0275	0.0218	0.0344	0.0344	Pass	A	Installed	
C0687	16	19	1	1210	SQS		586	Done	YES	0210	0	0.23	7.02	0.20	5.89	6.08	0	0.0006	0.001	0.0006	0.001	1	0.0025	0.0064	0.0089	0.0074	0.0124	0.0211	0.0140	0.0219	0.016	0.0319	0.0319	Pass	A	Installed	
C0688	16	19	1	1101	SQS		553	Done	YES	0211	0	3.64	2.52	3.05	2.11	5.16	0	0.0003	0.0006	0.0003	0.0006	0	0.0031	0.0068	0.0091	0.0062	0.0107	0.0162	0.0127	0.0407	0.0341	0.0353	0.0353	Pass	A	Installed	
C0689	16	28	1	1218	SQS		585	Done	YES	0167	0	2.46	2.96	2.06	2.48	4.54	0	0.0005	0.001	0.0004	0.0009	0	0.0021	0.0053	0.0082	0.0062	0.0108	0.0159	0.0120	0.0275	0.0329	0.0435	0.0435	Pass	A	Installed	
C0690	16	28	1	1196	SQS		603	Done	YES	RETURN16	0	3.37	2.80	2.82	2.35	5.17	0	0.0008	0.0012	0.0008	0.0014	1	0.0092	0.0401	0.0543	0.0045	0.0173	0.0333	0.0437	0.0123	0.019			Pass		RETURN	Failed alpha posrep
C0691	16	28	1	1021	SQS		604	Done	YES	0168	0	2.83	1.71	2.37	1.43	3.80	0	0.0015	0.0029	0.0007	0.0013	0	0.0024	0.0053	0.008	0.0068	0.0111	0.0161	0.0123	0.0301	0.0301	0.0244	0.0244	Pass	A	Installed	
C0692																																					
C0693	16	28	1	1181	SQS		772	Done	YES	0169	0	2.91	3.13	2.44	2.62	5.06	0	0.002	0.0032	0.0024	0.0027	0	0.0034	0.0071	0.0108	0.0063	0.0103	0.0174	0.0125	0.0248	0.0347	0.0345	0.0345	Pass	A	Installed	
C0694	16	28	1	1221	SQS		804	Done	YES	B BOX	0	3.02	3.14	2.53	2.63	5.16	0	0.0009	0.002	0.0009	0.0016	0	0.0024	0.0052	0.0081	0.0048	0.009	0.0133	0.0104	0.0295	0.0319	0.05	0.05	Pass	B	Ready	
C0695	16	27	1	0909	SQS		778		YES	INVEST	1	0.03	3.55	0.03	2.97	3.00	1	0.0009	0.0023	0.0014	0.0028									0.004	0.0084			Pass		Fail	Beta limit collision during posrep
C0696	16	26	1	0897	SQS		803	Done	YES	0170	0	1.08	6.44	0.90	5.40	6.30	0	0.0022	0.0032	0.0012	0.0024	0	0.0026	0.0047	0.0074	0.0055	0.0113	0.0192	0.0122	0.0326	0.0245	0.0337	0.0337	Pass	A	Installed	
C0697	16	26	1	0852	SQS		776	Done	YES	0171	0	3.92	3.49	3.29	2.92	6.21	0	0.0005	0.001	0.0014	0.0038	0	0.004	0.0088	0.0129	0.0085	0.0137	0.0179	0.0163	0.0266	0.0104	0.0311	0.0311	Pass	A	Installed	
C0698	16	26	1	0774	SQS		777	Done	YES	0172	0	0.49	6.56	0.41	5.50	5.91	0	0.0011	0.0019	0.0009	0.0016	0	0.0025	0.0054	0.008	0.0073	0.0153	0.0242	0.0162	0.0311	0.0247	0.0307	0.0307	Pass	A	Installed	
C0699	16	26	1	1009	SQS		773	Done	YES	0173	0	1.42	5.36	1.19	4.49	5.68	0	0.0006	0.0009	0.0017	0.0021	0	0.0021	0.0047	0.0073	0.0071	0.0104	0.0156	0.0114	0.0303	0.0292	0.0332	0.0332	Pass	A	Installed	
C0700	16	26	1	0849	SQS		774	Done	YES	0174	0	3.33	8.66	2.79	7.26	10.05	0	0.0005	0.001	0.0016	0.0025	0	0.0028	0.0049	0.006	0.0075	0.0134	0.018	0.0143	0.0117	0.0281	0.042	0.042	Pass	A	Installed	
C0701	16	19	1	1030	SQS		779	Done	YES	0175	0	2.99	3.36	2.51	2.82	5.33	0	0.0007	0.0013	0.0006	0.001	1	0.0086	0.0145	0.019	0.007	0.012	0.0153	0.0188	0.014	0.0252	0.0304	0.0304	Pass	A	Installed	
C0702	16	19	1	1145	SQS		810	Done	YES	T5	0	2.26	1.91	1.90	1.60	3.50	0	0.0029	0.0091	0.0006	0.0014	3	0.0135	0.0199	0.0231	0.0068	0.0108	0.0155	0.0226	0.0186	0.0307	0.0474	0.0474	Pass		TBD	Check plots
C0703	16	27	1	0912	SQS		775	Done	YES	T6	1	3.83	9.45	3.21	7.92	11.14	1	0.0005	0.0008	0.001	0.0024	0	0.0036	0.0068	0.0091	0.0075	0.016	0.0377	0.0174	0.0187	0.0348	0.0342	0.0342	Pass	A	Ready	
C0704																																					
C0705	16	27	1	0924	SQS		809	Done	YES	RETURN16	1	1.16	5.78	0.97	4.85	5.82	1	0.0004	0.0009	0.0006	0.0011	1	0.0024	0.0876	0.0891	0.1819	0.9067	0.9838	0.9109	0.0317	0.0287			Pass		RETURN	Failed alpha and beta posrep
C0706	16	36	1	0749	SQS		557	Done	YES	T6	0	3.30	6.37	2.76	5.34	8.10	0	0.0028	0.0064	0.0012	0.0028	0	0.004	0.0077	0.0107	0.006	0.0108	0.0151	0.0133	0.0282	0.0232	0.0357	0.0357	Pass	A	Ready	
C0707	16	36	1	0755	SQS		558	Done	YES	T6	0	3.77	6.70	3.16	5.62	8.77	0	0.0004	0.0007	0.001	0.0027	0	0.0043	0.0076	0.0091	0.0071	0.0129	0.0397	0.0150	0.0259	0.0178	0.0448	0.0448	Pass	A	Ready	
C0708	16	17	1							INVEST																										Fail	Beta arm not moving
C0709	16	17	1							INVEST																										Fail	Beta arm not moving
C0710	16	17	1							INVEST																										Fail	Alpha arm not moving
C0711	16	17	1	0418	SQS		559	Done	YES	RETURN1	0	3.78	3.19	3.17	2.68	5.84	0	0.0012	0.0021	0.0008	0.0015	2	0.0102	0.028	0.0401	0.0051	0.0084	0.0108	0.0292	0.0075	0.0129	0.0446	0.0446	Pass		RETURN	Failed alpha posrep
C0712	16	17	1	0394	SQS		624	Done	YES	T5	0	0.78	12.01	0.66	10.07	10.72	0	0.0004	0.0009	0.0015	0.0036	1	0.0038	0.0063	0.008	0.0096	0.0194	0.0296	0.0204	0.0113	0.027	0.0304	0.0304	Pass		TBD	Check plots
C0713	16	30	1				623		YES	RETURN1																								Pass		RETURN	Beta arm fibre hole undersized near top surface
C0714	16	30	1							INVEST																										Fail	Beta arm not moving
C0715	16	30	1	0365	SQS		621	Done	YES	0176	0	3.98	3.52	3.33	2.95	6.29	0	0.0048	0.0092	0.001	0.0029	0	0.0029	0.0075	0.0102	0.0071	0.0118	0.0169	0.0140	0.0395	0.0229	0.0344	0.0344	Pass	A	Installed	
C0716	16	30	1							INVEST																										Fail	Beta arm not moving
C0717	16	30	1	1230	SQS		634	Done	YES	0177	0	2.49	3.13	2.09	2.62	4.71	0	0.002	0.0055	0.0045	0.0095	0	0.0029	0.0064	0.0084	0.0086	0.0133	0.0224	0.0148	0.0322	0.0273	0.0373	0.0373	Pass	A	Installed	

No	ID	Sky coordinate		Focal plane coordinate		Component type	86.21%	Component ID	Fibre serial number	Drive PCB serial number	DIP switch CAN ID	Baseplate point			Focal plane point			Fiducial			Collision	Sector	Backplane ID	Backplane connector ID
		ρ (rad/FOV)	ϕ (orient'n)	r (radius)	ϕ (orient'n)		2.30%					X	Y	Z	X	Y	Z	X	Y	Z				
		arcsec	degrees	mm	degrees		10.89%					mm	mm	mm	mm	mm	mm	mm	mm	mm	V			
959	0959	733.90	-44.70	426.47	-44.70	Fiducial_A		FID_A_09			01001100	186.666	-314.571	317.831	-22.152	-299.460	302.563	12.659	-302.015	305.145	6	A	A_10	A_10_12 (not used)
960	0960	704.68	-42.22	409.27	-42.22	Empty					10001100	188.492	-288.465	317.950	-20.403	-274.544	302.606	14.423	-276.887	305.188	5	A	A_10	A_10_11 (not used)
961	0961	676.83	-39.52	392.91	-39.52	FPU	Fail	C0169	1599	413	00110000	190.162	-262.330	318.058	-18.805	-249.618	302.645	16.034	-251.748	305.228	4	A	A_09	A_09_12
962	0962	650.57	-36.59	377.49	-36.59	FPU	Pass	C0369	0710	267	11010000	191.674	-236.169	318.156	-17.360	-224.682	302.681	17.492	-226.600	305.264	3	A	A_09	A_09_11
963	0963	626.09	-33.42	363.15	-33.42	FPU	Pass	C0303	0254	539	01001100	193.028	-209.985	318.242	-16.066	-199.739	302.713	18.797	-201.443	305.296	2	A	A_08	A_08_12
964	0964	603.64	-30.00	350.00	-30.00	FPU	Pass	C0291	0512	474	10001100	194.223	-183.781	318.317	-14.925	-174.788	302.741	19.948	-176.279	305.325	1	A	A_08	A_08_11
965	0965	583.45	-26.33	338.19	-26.33	FPU	Pass	C0360	0095	333	00110000	195.260	-157.558	318.382	-13.936	-149.830	302.766	20.946	-151.109	305.349	7	A	A_07	A_07_12
966	0966	565.79	-22.41	327.87	-22.41	FPU	Pass	C0357	0551	336	11010000	196.138	-131.321	318.437	-13.098	-124.867	302.786	21.790	-125.932	305.370	6	A	A_07	A_07_11
967	0967	550.91	-18.26	319.18	-18.26	Camera		AC_16			01001100	196.856	-105.072	318.482	-12.413	-99.899	302.803	22.481	-100.752	305.387	5	A	A_06	A_06_12 (not used)
968	0968	539.04	-13.90	312.25	-13.90	FPU	Pass	C0264	0438	546	10001100	197.416	-78.812	318.516	-11.880	-74.928	302.816	23.018	-75.567	305.400	4	A	A_06	A_06_11
969	0969	530.39	-9.37	307.21	-9.37	FPU	Pass	C0248	0553	286	00110000	197.815	-52.546	318.541	-11.500	-49.953	302.826	23.402	-50.380	305.410	3	A	A_05	A_05_12
970	0970	525.13	-4.72	304.14	-4.72	FPU	Pass	C0209	1544	421	11010000	198.055	-26.274	318.556	-11.271	-24.977	302.831	23.632	-25.190	305.415	2	A	A_05	A_05_11
971	0971	523.37	0.00	303.11	0.00	FPU	Pass	C0186	1152	492	01001100	198.135	0.000	318.561	-11.195	0.000	302.833	23.709	0.000	305.417	1	A	A_04	A_04_12
972	0972	525.13	4.72	304.14	4.72	FPU	Pass	C0317	1321	350	10001100	198.055	26.274	318.556	-11.271	24.977	302.831	23.632	25.190	305.415	7	A	A_04	A_04_11
973	0973	530.39	9.37	307.21	9.37	FPU	Pass	C0177	1447-	419	00110000	197.815	52.546	318.541	-11.500	49.953	302.826	23.402	50.380	305.410	6	A	A_03	A_03_12
974	0974	539.04	13.90	312.25	13.90	FPU	Pass	C0179	1512	486	11010000	197.416	78.812	318.516	-11.880	74.928	302.816	23.018	75.567	305.400	5	A	A_03	A_03_11
975	0975	550.91	18.26	319.18	18.26	FPU	Pass	C0144	1479	406	01001100	196.856	105.072	318.482	-12.413	99.899	302.803	22.481	100.752	305.387	4	A	A_02	A_02_12
976	0976	565.79	22.41	327.87	22.41	FPU	Pass	C0145	1470	404	10001100	196.138	131.321	318.437	-13.098	124.867	302.786	21.790	125.932	305.370	3	A	A_02	A_02_11
977	0977	583.45	26.33	338.19	26.33	FPU	Pass	C0071	1407	209	00110000	195.260	157.558	318.382	-13.936	149.830	302.766	20.946	151.109	305.349	2	A	A_01	A_01_12
978	0978	603.64	30.00	350.00	30.00	FPU	Pass	C0073	1522	251	11010000	194.223	183.781	318.317	-14.925	174.788	302.741	19.948	176.279	305.325	1	A	A_01	A_01_11

Figure 10. Master FPU spreadsheet (top); FPM as-installed spreadsheet (bottom)

4.2 Preparation

FPUs installed in rows according to the respective backplane PCB. This keeps the electrical/fibre management in the backplane neater and simplifies functional testing. The spreadsheets described above are used to assign FPUs to each position in the row. The FPUs are collected and laid out on anti-static foam. The drive PCB of each FPU is rotated to the appropriate orientation - all FPUs are installed in the same orientation but the respective backplane PCBs are angled at 120° from each other in three segments. Instead of twisting the flexi running from the drive PCB to the backplane connector, the drive PCB itself is rotated using a Delrin interface ring at the back of the FPU chassis. The setscrews holding the fibre ferrule in the beta arm are staked, using a spot of Scotch-Weld 2216 Gray epoxy. Finally, the CAN address is assigned by setting an 8-bit DIP switch on the drive PCB.

4.3 Installation

A special tool with a carrier for the fibre is passed through the baseplate by one person. A second person holds the FPU at the front, loads the fibre into the tool and then inserts it into the hole while the fibre is pulled simultaneously. Once flush with its respective baseplate facet, the three captive screws are tightened. In the backplane, the fibre ferrule is placed in the connector holder and the drive PCB flexi is looped back on itself and inserted into the respective backplane connector. A small clip made up of two interlocking PTFE cable ties is used to keep the flexi loop tidy.

Once the row is complete, the relevant entries are made into the CAN configuration file and the segment is powered up. If all drive PCB LEDs are lit, a datum command is passed. If this is successful, a small (10°, 10°) movement is executed, then reversed and the FPUs datumed again as the in-situ functional test. Finally, a visual transmission check is made of the fibres to ensure no damage has been sustained during installation. If this is successful, the captive screws are staked, again using 2216-Gray and the row is complete.

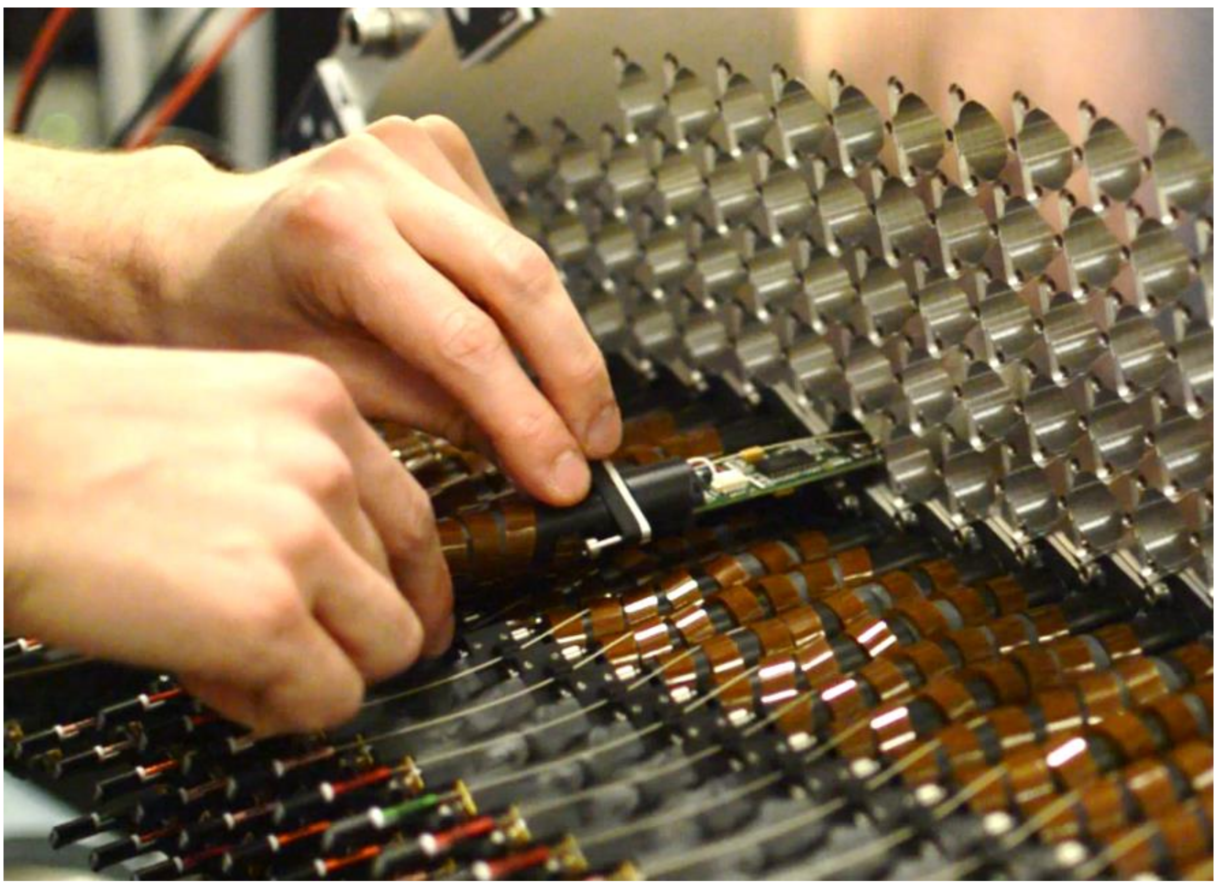

Figure 11. FPU installation from the baseplate front

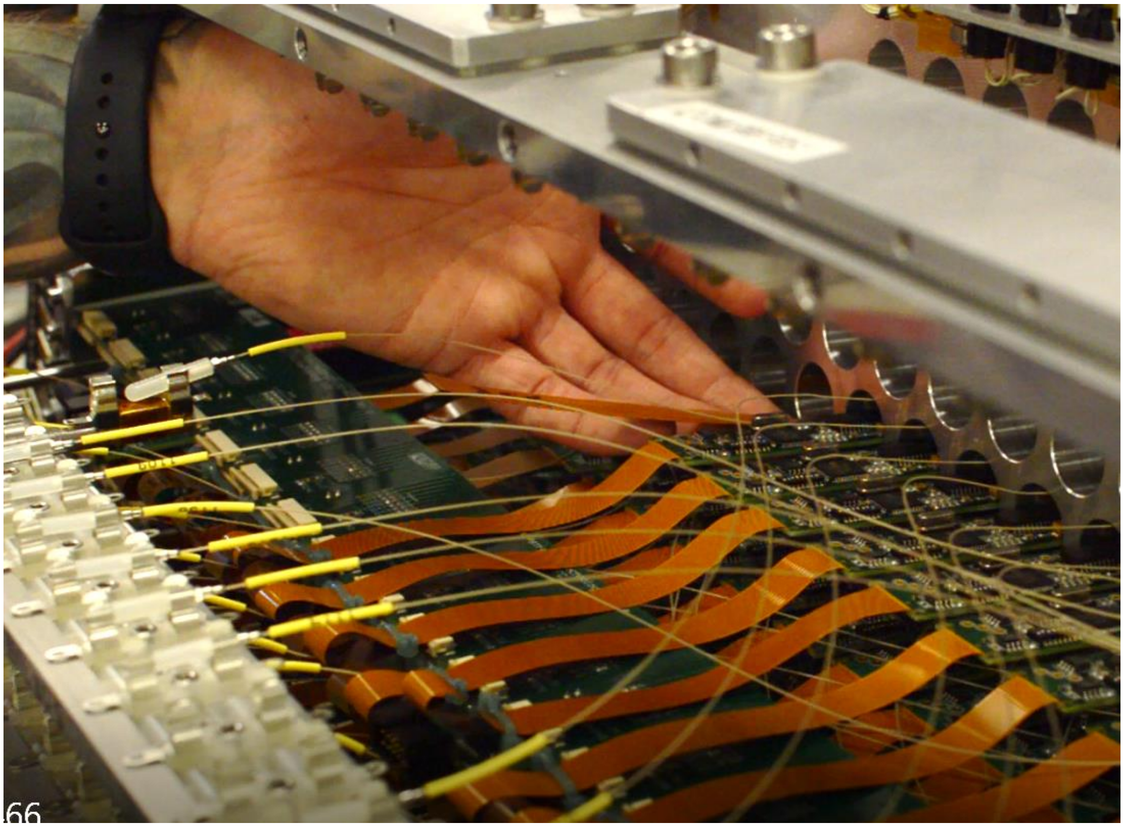

Figure 12. FPU installation from the backplane

4.4 Integration with the RFE

The completed FPM is mounted into its interface ring on a integration plate. This process ensures co-planarity between the baseplate front surface, the titanium flexures and the ring. The whole assembly is then lifted into the dismantled RFE and rests on precise spacers which define the science position with respect to the rotator flange. The retractor is then constructed around the FPM, the calibration system is installed and subcabinets are mounted.

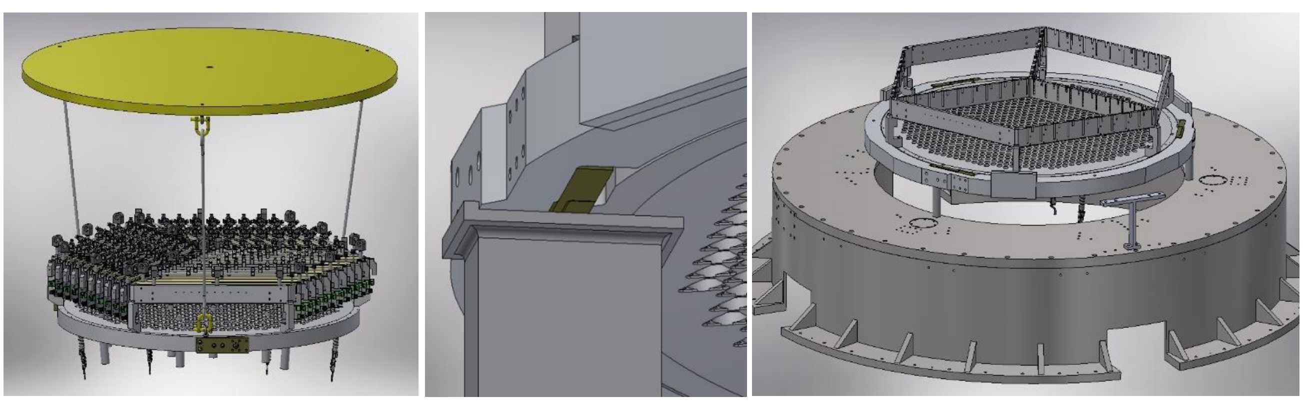

Figure 13. Various stages of FPM-RFE integration

4.5 Integration at the VLT

The primary task at the VLT is to make the connections between the front-end fibre tails and the rear fibres running into the spectrograph slit. The connection is made in the FPM backplane. The rear fibres enter the FPM via the RFE rotator wrap then a retractor box, before entering into the backplane in bundles of 16 fibres. A metal sheath at the termination of the bundle is fixed using rotating clamps, then the 16 fibres are routed to a fibre connector panel. This panel consists of fuse holders mounted on aluminium plates into which the Molex SnapMate connector is inserted. Although these connections are easily made in the lab, carrying out the process at the VLT will not be straightforward; limited space is available between the MOONS spectrograph and the front-end, the focal plane is at an awkward height and making the connection requires concentration and dexterity.

Mapping of the rear fibres to the front-end fibres must be done carefully to ensure that, wherever possible, adjacent FPUs are close to each other on the slit and the number of fibre pairs which cross the two halves of the spectrograph is minimized. This mapping will be finalized on completion of RFE integration ahead of delivery to the VLT.

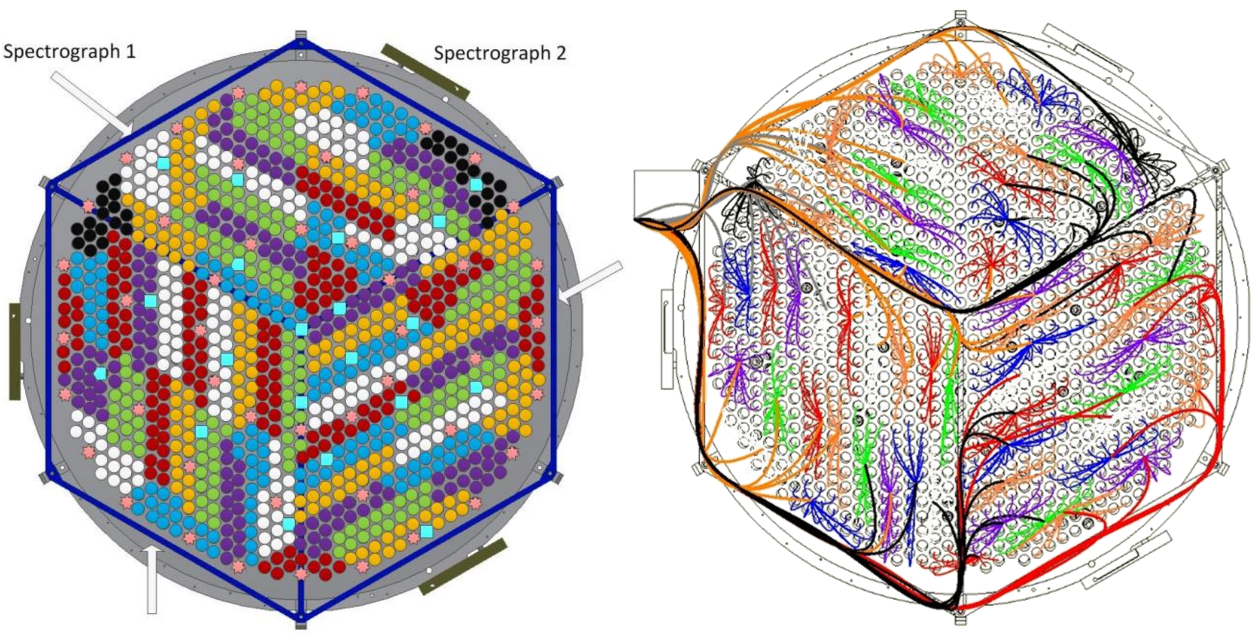

Figure 14. Fibre mapping strategy

4.6 Maintenance

The baseline operational strategy for the MOONS FPM is zero maintenance, a consequence of high reliability mechanisms but also difficult access leading to a risk of collateral damage when making interventions. However, it is anticipated that a single major intervention may be made at some point during the life of the instrument, to replace any failed fibres, electronics and FPUs. To remove an FPU is not difficult from the front but unmaking/remaking the fibre and electrical connections at the rear is challenging at full population density, so a cost-benefit analysis will need to be made for each individual intervention on the basis of the potential performance improvement, FPU location and surrounding environment.

5. CHALLENGES OVERCOME AND LESSONS LEARNED

5.1 Achieving positional requirements

The choice to use geared and zero-backlash stepper motors was made early, primarily because the determinism allows a discretized mode of path planning and imparts no constraints on direction of target approach, considered necessary given the algorithmic difficulty associated with the high level of FPU overlap.

Given the space constraints, the gearboxes necessary to achieve the positional resolution are at the extreme end of the Faulhaber product range. The antibacklash functionality in these gearboxes is achieved with a secondary geartrain, torsionally loaded against the primary drivetrain. However, this option is not routinely selected for such small units and successful application of the preload was a major challenge for the MPS-Faulhaber team, requiring an extensive development period and a complete overhaul of the preload tooling.

Although the achieved performance of installed FPUs is exceptional, the initial failure rate against the positional repeatability rate is between 10% and 20% for most batches and has added a considerable testing and returns overhead to the project. In hindsight, given the constraints, the antibacklash function may have been more effectively achieved via the use of torsion springs.

An additional issue is the testing overhead required by the gearbox calibration. During the design phase, it was assumed that achieving the accuracy requirement would not be onerous if the repeatability requirement could be met. However, the complexity of the testing regime and software to generate the look-up tables was not anticipated. The verification rig could have been more effectively designed to make the calibration software tasks easier and the whole calibration process should have been incorporated into the project plan much earlier.

5.2 Collision detection system

As described previously, the collision detection system has caused technical challenges throughout the entire development phase.

- Isolating FPUs from each other requires creating an electrical break somewhere which does not compromise the alignment tolerances. Anodization of the chassis flange or a similar conversion process to the baseplate were investigated. The problem was eventually solved by using a centreless ground silicon nitride alpha motor shaft and ceramic balls to actuate the datum switch.
- Achieving a matte black finish on the beta arm for metrology purposes while maintaining electrical conductivity required development of a black chromate process applied onto a micro-shot peened aluminium substrate.
- The unpredictable electrical resistance of the lubricated bearings is managed by testing, running-in and selective installation but might have been avoided by use of a brush or coil contact between the alpha and beta arms.

5.3 Design for wiring and fibres

A number of issues have required resolution during integration which can be attributed to the treatment of ‘flexible’ components during the mechanical design process:

- A clash between compressed beta motor wires, resolved by the patch cable installation described in Section 3.3
- Fibre management in the backplane, requiring a complex crossover pattern and an awkward installation process
- Potential fibre snags due to external fibre routing, partially mitigated by software choices

All of these problems originate in the difficulty of accurately modelling the behaviour of unconstrained or partially-constrained wires/fibres during the CAD design phase.

The beta motor wire clash occurred due to the wires being routed around the beta gearbox, then compressed by protective heat shrink, resulting in a bump which violated the space envelope. This routing was selected due to the cable being a standard item of a fixed length and the path being the most obvious one. However, the CAD did not accurately model the as-built path and the heat shrink was also not modelled, so the envelope violation did not show during CAD assembly analysis. The resolution of adding a patch cable, allowing an alternative routing path, is very effective and not an onerous modification but the situation should have been avoided by better scrutiny during design reviews and the prototype phase.

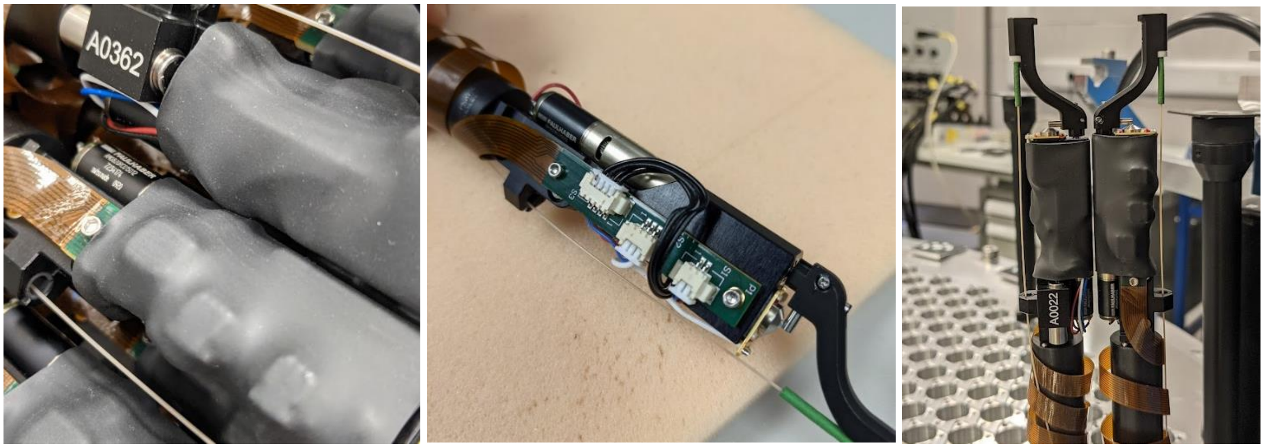

Figure 15. Clash due to compressed beta wires (left); patch cable installation (middle); clash resolved (right)

The fibre management issues derive from MOONS being a very large instrument and space being unavailable for more robust fibre management strategies, as seen on other instruments – as such the fibres on both sides of the baseplate are partially unconstrained.

The main concern is that fibre slack drawn through the plate by FPU movement remains at the front when the movement is reversed, resulting in a bulge which could snag on adjacent FPUs. The extreme component density in the fibre feedthrough holes and within the backplane can result in higher fibre friction, which can exacerbate the issue. Given the space constraints, a retrofitted hardware solution isn't possible so the primary means of mitigation is to move the FPUs slowly, giving more time for fibre movement.

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