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MOONS – Multi Object spectroscopy for the VLT: Design and testing of the MOONS metrology system

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ABSTRACT

MOONS is the Multi-Object Optical and Near-IR Spectrograph to be mounted at a Nasmyth focus at the Very Large Telescope. The instrument is equipped with 1000 fibres configured over a field of view of ~500 square arcmin using theta-phi fibre positioning units (FPUs). The MOONS metrology system must accurately determine the position of the fibres in the focal plate, providing fast feedback to the instrument control software during operations. The returned fibre positions can be used for calibrations of the FPUs or fast system recovery after a power loss. If required, the system can also be used for calculating fine adjustments of the fibre positions during acquisition. In this paper, a description of the system design, implementation, and testing in the MOONS focal plate are provided. The presented system has high potential for adaptation to a variety of astronomical instrument applications during integration, testing, and operation stages.

Keywords: Metrology, fibre position measurement, multi object spectroscopy, MOONS, VLT, MOS

1. INTRODUCTION

The MOONS metrology module is based on an off-the-shelf photogrammetry system with a single fully calibrated camera and commercial software to perform the measurements. The commercial camera and software are integrated into the MOONS instrument to allow operation using the instrument control software. The sub-system is designed to accurately determine the physical location of the fibre positioning units (FPUs) in the plate reference system at any instance required during operations. An overview of the MOONS instrument, FPUs, and the metrology system in context can be found in [1], [2], and [3].

The most important function of the metrology system is to provide a means of recovery following software or hardware failure which leaves the fibre positioners in an unknown condition. The system will need to determine both the fibre position and angle of the FPU beta-arms to safely unpick the field. In addition, the system provides the option of a quasi-closed loop control of the fibre positioners in case of aging related accuracy problems. Life testing of the FPUs shows that this will not be needed during the instrument lifetime, the implemented system ensures the fibre positioning accuracy to be maintained even in the rare event of wear in the gears-box of FPUs.

Extensive testing of the system has been carried to show compliance with the instrument requirements This paper describes the design of the MOONS metrology system and how it is implemented into the instrument for operations, as well as providing some example applications of the photogrammetry system.

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2. METROLOGY SYSTEM DESCRIPTION

2.1 COTS photogrammetry system

The metrology system uses a Commercial off-the-shelf (COTS) photogrammetry system from Hexagon Manufacturing (https://www.hexagonmi.com/en-GB/products/photogrammetry) named DPA professional, that applies the principle of spatial image triangulation for fully automated 3D coordinate recovery of a set of targets. The system uses a Canon 5Ds camera with a fully calibrated lens to obtain images mapping dedicated targets and references from different viewing angles. These are processed with a dedicated photogrammetry tool (DPA pilot) that employs an integrated simultaneous calibration procedure and produces a 3D cloud of target coordinates. The reference targets are used for orientation of the photogrammetry system analysis. Four small scale bars are used for a fine final adjustment of the measurements.

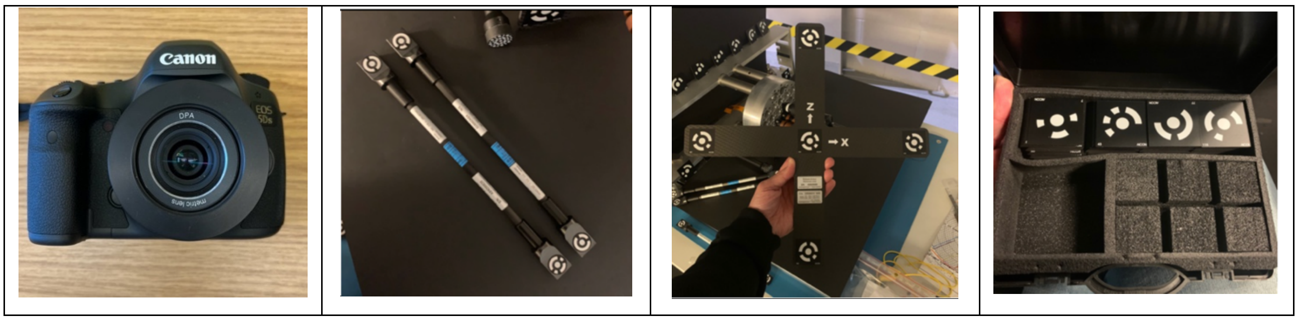

Figure 1. COTS photogrammetry system hardware components (from left to right): Canon 5Ds camera and calibrated lens, small scale-bars, reference cross, and coded targets.

2.2 FPU target interface

The system hardware interfaces with MOONS with a set of metrology target dots in the beta arms of the FPUs and reference targets distributed across the focal plate. Figure 2 shows an image of the MOONS focal plate with 2/3 of the FPUs installed and the distribution of the different metrology targets.

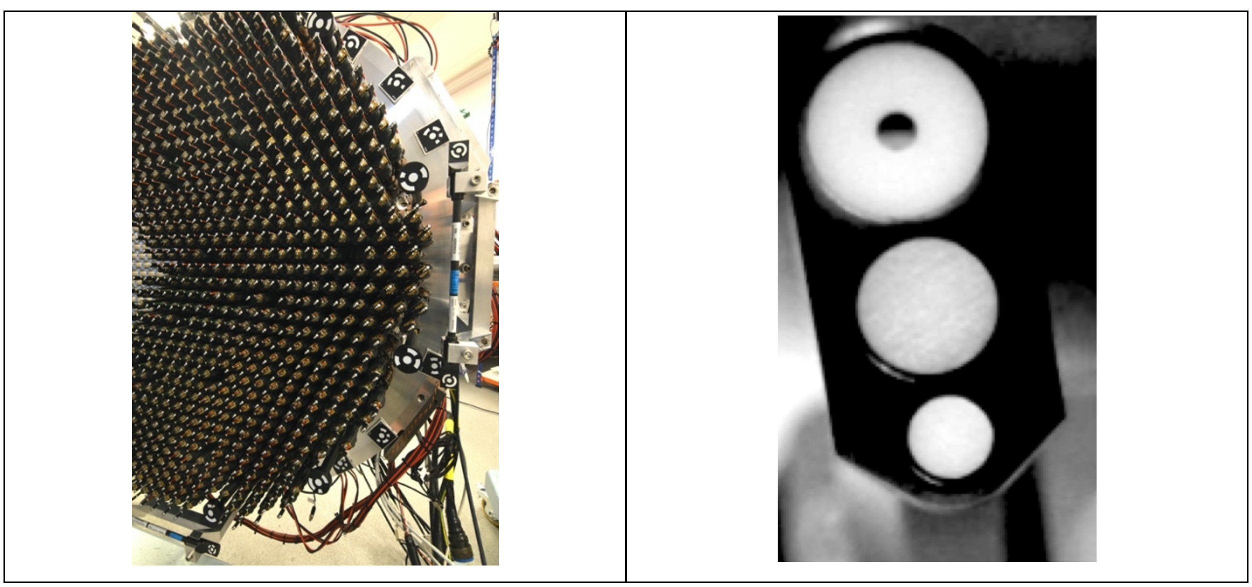

Figure 2. Left: metrology reference targets and scale bars installed in the focal plate. The MACOR targets in the FPUs installed in the plate can be also seen. Right: zoomed in view of the beta arm of an FPU with the metrology target dots of different sizes clearly visible.

Figure 2 also shows a zoomed-in view of the FPU beta-arm targets used for the metrology detection. The different sizes are used to identify the beta-arm orientation and the fibre position determined by the largest target dot.

2.3 Illumination

The COTS system nominally operates with a flash connected to the Canon 5Ds camera. In the MOONS application, the system operates with a set of fixed lamps that provide homogeneous illumination to the plate. The installed illuminators are six adjustable beam angle LED bars from EFFILUX, indicated for machine vision applications (https://www.effilux.com/en/products/led-bar/effi-flex). This illuminator bar equipped with high power LEDs, can be easily configurable with different options to optimize it to the MOONS application. In particular, the illumination angle of the LEDs can be adjusted to ensure optimal illumination to recover the FPUs. The camera exposure time is adjusted during integration to determine the optimal illumination balance for measurements in the shortest possible amount of time. Figure 3 shows the lamp design attached to the MOONS RFE as well as the Canon 5Ds camera attached to the rotation mechanism.

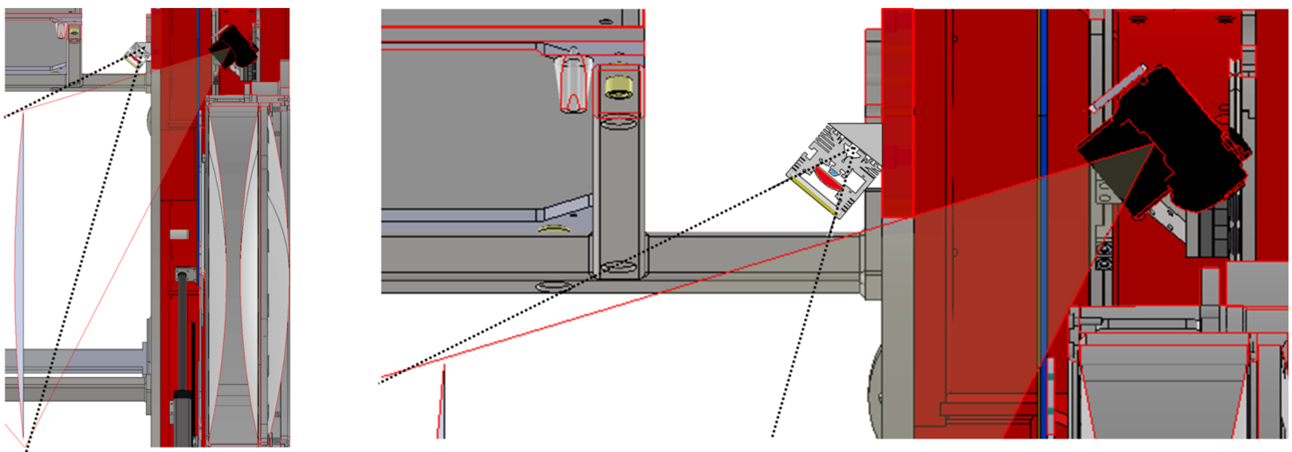

Figure 3. Design of the metrology camera installed in the MOONS RFE together with the illumination solution integrated.

The lamps are powered from a Beckoff ES2535. These modules provide PWM control of the power at 24 V. Control of the cameras on/off setup is done from the instrument control software via the MOONS RFE cabinet. A description and update of the MOONS RFE can be found in [4].

2.4 Metrology rotation mechanism

The COTS photogrammetry system requires several images to be obtained from different angles to compute the 3D cloud of the targets. Similarly, all the FPUs need to be visible in all images (or as many as possible) to ensure a 3D coordinate recovery with high precision. To achieve this, the camera is attached to a rotation mechanism which was integrated into the RFE at the IA in Lisbon [4]. The metrology rotation mechanism allows for control of the camera to obtain the necessary number of images around a full rotation around the plate. The mechanism that provides the rotation capability to the metrology camera is composed of a fixed part attached to the RFE Mounting Structure and a moving part supporting the camera, connected to the fixed part via a rail and a slide (Figure 4).

The rotation mechanism is controlled one of the 6 controllers offered by 3 Beckhoff AX5203 units (dual modules) available in the MOONS sub-cabinet (3 are used for the retraction mechanism and 2 for the calibration screen).

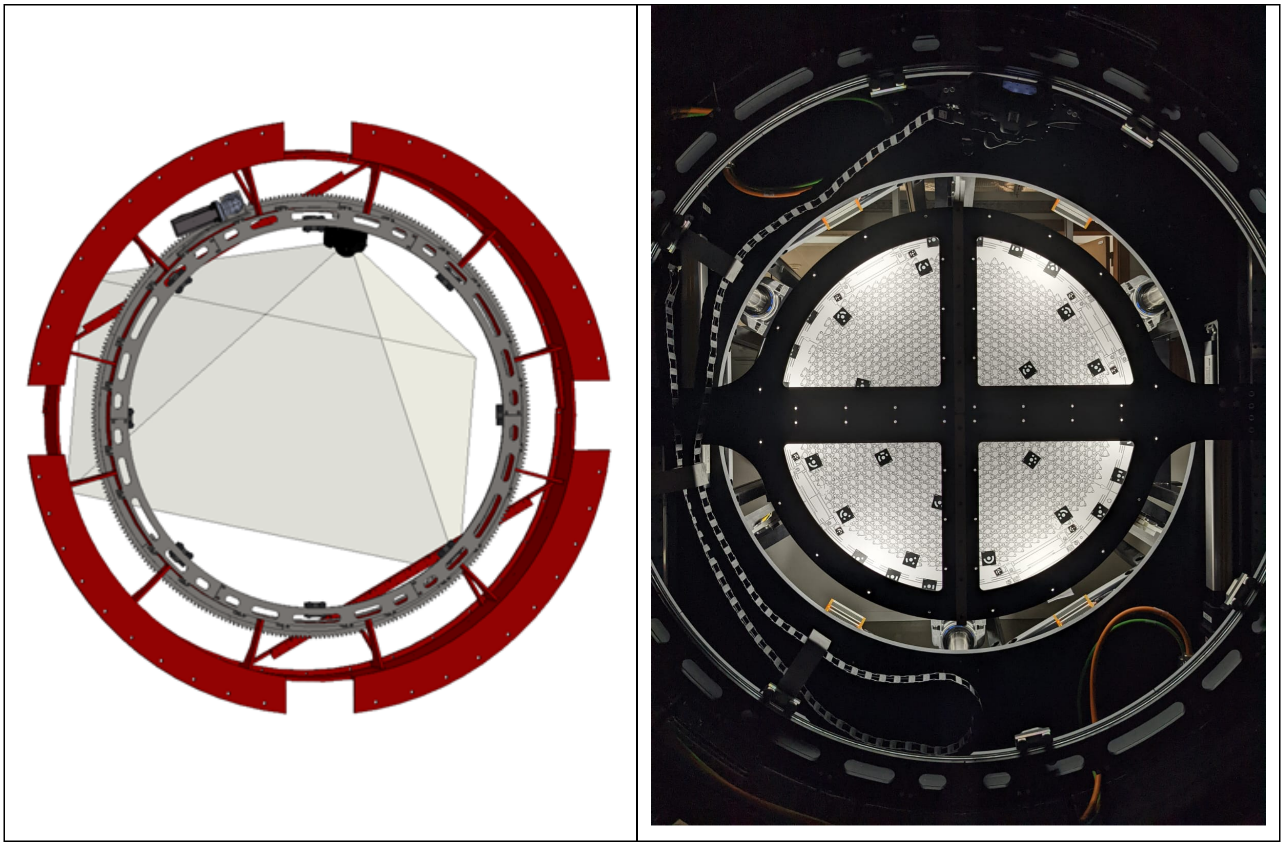

Figure 4. Left: MOONS RFE diagram with the viewing angle of the metrology camera in the rotation mechanism, covering the focal plane. Right: Metrology camera installed in the RFE rotation mechanism (visible at the top). A drawing of the plate with metrology coded target can be seen in the back.

2.5 Focal plate reference system

The coordinate system of the COTS system is normally determined by a reference cross provided by Hexagon. In MOONS, this reference cross is not available in the system and the coordinate reference should follow the MOONS plate coordinate system in which the FPUs operate. This is necessary so that the feedback provided by the metrology system is correctly used by the FPU control software [5] for positional recovery. This coordinate system is pre-defined in the focal plate assembly, and it will be referenced to sky using the acquisition camera system. The acquisition cameras have masks that can be installed at the focal plane level, containing a set of target dots detectable by the metrology system as well as being visible in the images taken with the acquisition cameras themselves. This provides a transformation between the pixel coordinates of each acquisition camera (which will be calibrated to sky coordinates during commissioning) and the plate coordinate system. In particular, the central acquisition camera marks the origin reference of the plate coordinate system.

To obtain the focal plate coordinate system during instrument integration, a large number of images are obtained using the COTS system *in hand-held* mode (i.e. not linked to the MOONS metrology interface) and the COTS reference cross placed on the plate and visible in the images. A first measurement is obtained to retrieve the position of the coded targets installed (fixed) at the edge of the plate and the central acquisition camera mask. The coordinates of the coded targets are then transformed from the COTS reference cross to the MOONS plate coordinate system. These coded targets are then used as the reference object for the COTS software and thus all measurements of the metrology system will be in this reference system.

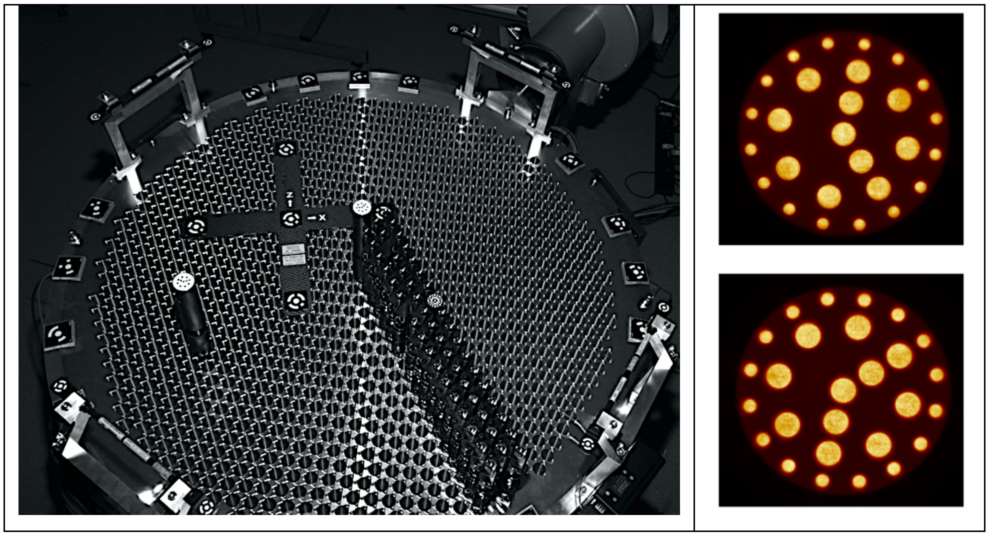

Figure 5. Left: example of metrology image of the focal plate with a set of FPUs, scale bars, reference targets and the reference cross. Two acquisition cameras and their masks are installed at the center and lower left quadrant. Right: Image of the masks taken with the acquisition cameras in the plate.

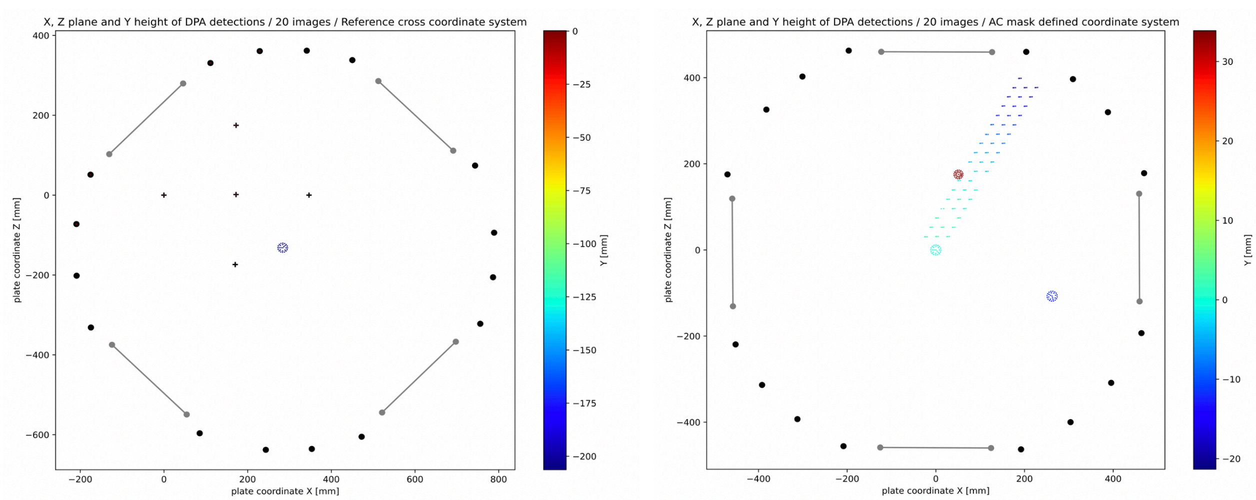

Figure 6. Coordinates of the reference targets and acquisition cameras recovered with the metrology system in the reference coordinates provided by the cross. Right: Metrology measurement of the FPUs and acquisition cameras in the plate coordinate system after transformation of the reference target coordinates.

2.6 Software

2.7 Metrology software sub-system

The Metrology Software sub-system handles, in a coordinated way, several functions to measure the position and orientation of all 1000 fibres within a given time. The subsystem is divided into four parts grouped in similar software functionalities:

1. A first module comprises the low-level software drivers to control the power of devices, move the camera, and illuminate the focal plate. These functions are operated through a Beckhoff PLC (industrial computer) which controls those diverse hardware elements (lamps, camera, moving party).
2. Another functionality is the image acquisition operation. In this part, after the camera has been commanded to some position, a specialized process (TDCS) within this second module controls the image acquisition and

subsequent transfer. Additionally, an Odroid1 SBC board is configured as an image server to receive the expositions from the camera, and transfer acquired images to the instrument control server (ICS). The resulting images will be published and saved under a shared directory of the ICS server.

3. The measurement module, based on the COTS photogrammetry system proprietary software installed in a Windows 10 operating system, computes the FPUs and reference target positions. The outcome of this measurement process is a cloud of points with the 3D positions of every FPU metrology target on the plate.
4. The cloud of points is processed to perform a metrology analysis. The objective is to identify the beta-arm associated to each FPU and feedback the fibre position and angle of the beta-arm.

2.8 Metrology measurement

The metrology measurement subsystem is composed of an OPC UA server to interface with the Hexagon library. This library is an API that provides C functions to manage and perform measurements. The functions of this API calculate the 3D coordinates of all target points in the plate using a spatial image triangulation. The API analyses a set of FPU images, taken at different positions around the plate, into a 3D cloud file with the position of FPUs deployed across the plate. The OPC UA server receives a command to execute methods in the ctrl folder to start a metrology measurement with the images saved in the shared folder. The execution takes around a minute to process all images and produce a file with a cloud of 3D points. The resulting measurements are saved in a file on the shared folder.

The above measurement process can be controlled by the OPC UA server through services exposed in the form of methods, state variables, and configuration parameters. The OPC UA server provides high-level interfaces to start and stop a measure, monitor the state of a processing measurement, and configure the input/output filesystems to get input images and save output files with the obtained 3D measurements. The API libraries are installed in a Windows10 virtual server machine, see Figure 7. The input images and the output file with 3D cloud point are configured to use the same shared folder.

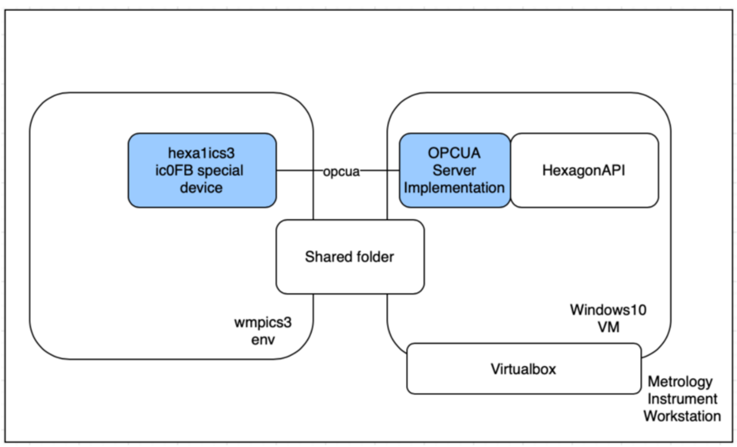

Figure 7. Diagram that depicts a Windows10 workstation with OPC UA server and Hexagon API. This Windows 10 virtual server is a Virtualbox operating system client hosted by the main Linux instrument server. The operation of any metrology measurement is commanded by the methods exposed on the OPC UA server. A shared folder between host and client is defined to read the input images and save that output file.

Once the 3D cloud is available, a notification is sent back to the MOONS software, which instead triggers the fiber positioner identification routines and saves the results in the OLDB for further usage.

3. TESTING

3.1 FPU target detection

The system has been tested taking a representative number of images around a complete rotation from the RFE. The 3D cloud of targets and filtering of detections was performed, resulting in the coordinates of targets shown in Figure 8. The curvature of the plate can be clearly seen in the recovered measurements. The results from these tests were used to define the baseline of 15 images needed to achieve sufficient accuracy of 15 micron in the fibre target coordinates. This translates into a total duration of 2 minutes for performing a complete metrology measurement, including movement and capture of images, analysis, and returning FPU positioning information to the instrument control software.

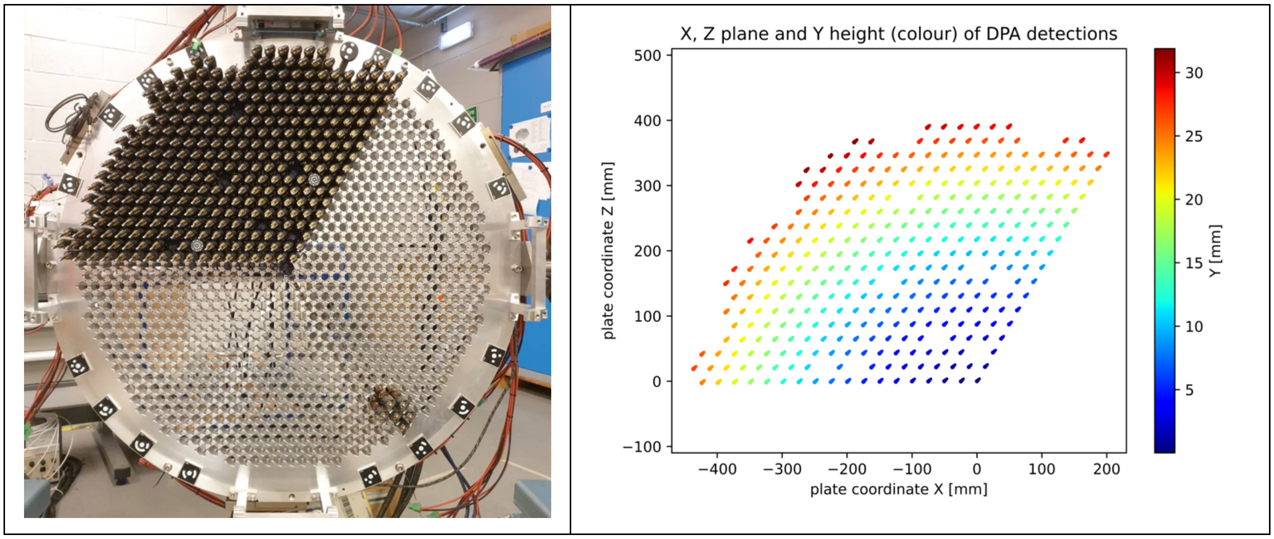

Figure 8. Image of the plate during integration of FPUs (left) and 3D cloud results of the metrology measurement (right).

3.2 FPU identification and measurement uncertainties

Testing of metrology measurement on a partially populated plate was carried moving the alpha arms of the FPUs in 4 positions across a full rotation. A measurement in each of the 4 positions was performed and FPUs identified. A central coordinate of the FPUs was determined using the central axis of this full rotation (left panel of Figure 9). This measurement will be done for the fully populated plate and the "as built" central coordinate of the FPUs will be updated in the configuration file.

The performance of the metrology system can be verified by measuring the distance between the small target and the fibre position target of the beta arms. The measurement of this separation was computed for each detected FPU and it is shown in Figure 9 as a function of the distance of the FPU from the centre of the plate. The RMS of the measurements is confirmed to be 15 micron. However, the uncertainty is dominated by the measurement error of the small dot which is detected in less images. The error in the fibre position is measured to be <15 micron across the entire focal plate.

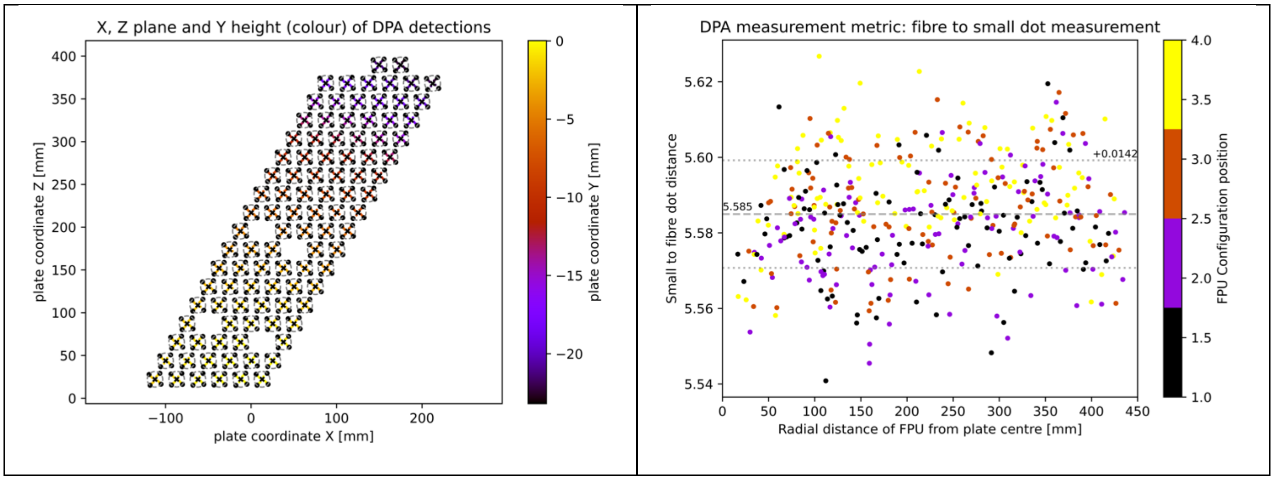

Figure 9. Recovery of 4 positions of a full beta arm rotation for 100 FPUs in the MOONS plate using the metrology system. The central position is determined by the centre of the fitted ellipse. Right: Measured separation of the small dot and fibre position recovered by the metrology system.

4. OTHER INSTRUMENT APPLICATIONS

The metrology system installed in the MOONS instrument described in the previous sections has several applications during integration of astronomical instruments. Two examples used during the MOONS integration are described in this section.

The MOONS FPUs are verified and calibrated using a dedicated verification rig (see [3]). While the FPUs have an excellent repeatability, a gearbox calibration of the FPUs is necessary to ensure that each FPU can reach the correct angle. Once integrated on the plate, the gearbox calibration determined in the verification rig is applied. The metrology system was used to independently verify the functionality of the gearbox calibration in the plate. Figure 10 shows the results of the metrology measurements for alpha and beta arms with and without the gearbox calibration being applied. The measurements show the effectiveness of the gearbox calibration at least to within the uncertainty of the metrology system.

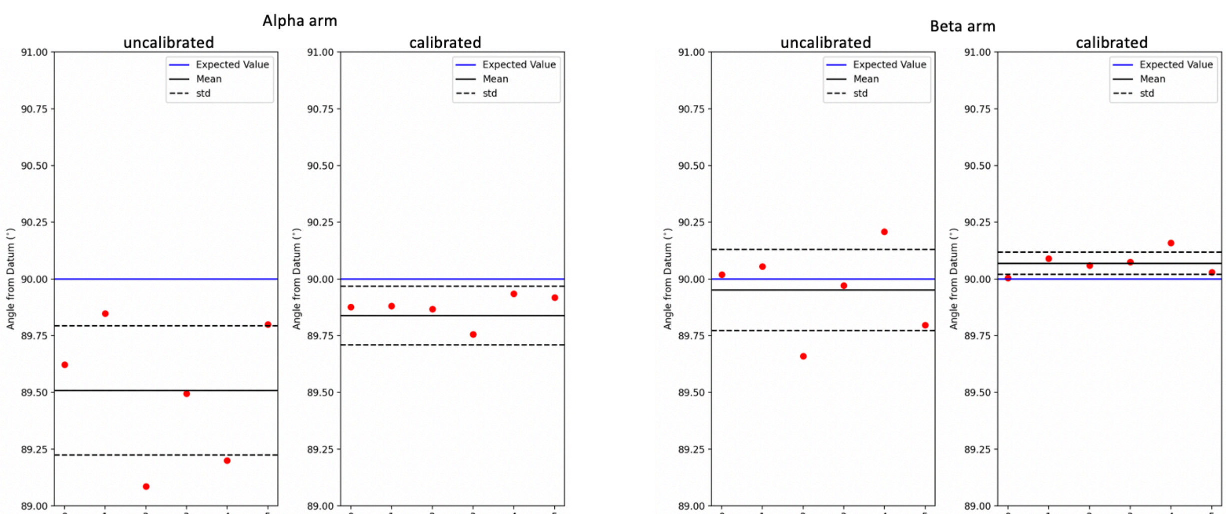

Figure 10. Metrology measurement of alpha (left) and beta arm (right) movements in 5 FPUs installed on the plate before and after applying their gearbox calibration.

The Hexagon COTS photogrammetry system was also used independently of the MOONS software subsystem in *hand-held* operation to measure the repeatability of the RFE retraction mechanism. Figure 11 shows two of the images taken at each retractor position. The reference cross, coded targets and scale bar are visible. The coordinates of the detected targets in each retractor position were recovered after multiple iterations of the retractor movement and the repeatability confirmed to be well within the requirements [4].

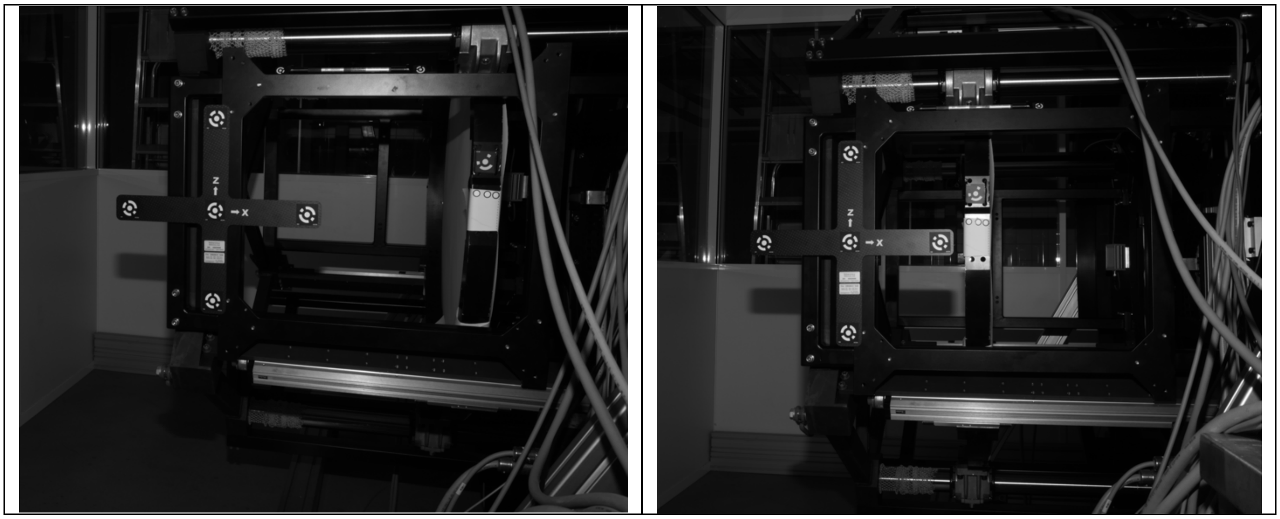

Figure 11. MOONS retractor mechanism being verified with the Hexagon COTS photogrammetry system

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