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# INTRODUCTION

This document analyses the “FPU Verification Process Flow Chart”, below, and breaks it into smaller tasks, which are described in detail.

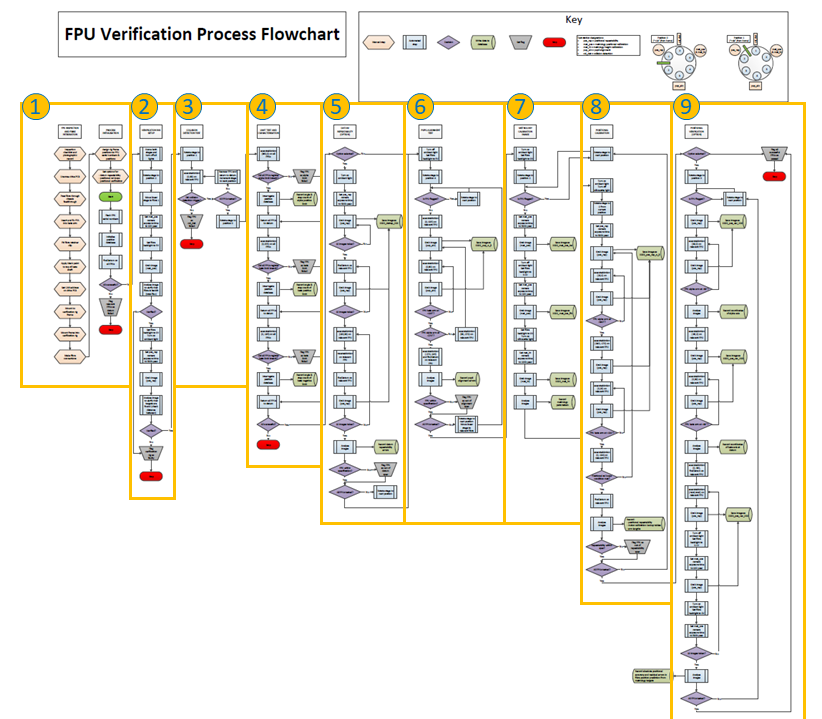


Figure 1: FPU Verification Process Flowchart

# PREREQUISITES

The following things need to be completed before the tests can be carried out.

* Software to control each camera, take exposures and save the images to a file.
* Metrology camera distortion calibrated using a rectangular pattern of dots. This process generates a set of distortion coefficients which can be used to rectify each camera image.
  + Primary plan: calibration the cameras with Holger’s software
  + Backup plan: calibrate the cameras with openCV library functions.
* Software to control the Thorlabs turntable.
* Software to control the linear stage.
* Software to control the lamps.
* FPU control parameters (minimum and maximum speed and acceleration) agreed.
* The turntable, linear stage, lights and cameras have all been tested and verified to work.  
  There should a self-test procedure which verifies all the components are responding.

# Verification process specification

## Initialisation

For each fibre positioner received

Assign a unique serial number to that fibre positioner.

For each of 6 positions on the verification rig turntable.

Assign a unique CAN ID and address to that position.

For each group of 6 fibre positioners

For each positioner in that group

Assign the positioner to a turntable position

Associate the FPU serial number with the CAN ID and address of that position.

Flash the FPU PCB with the serial number.

Initialise the FPU verification database.

Find datum for all FPUs simultaneously.

If all FPUs successful

Start the automated verification tests (as below) 🡪

Else

For each failed FPU.

Flag FPU as “datum failed”.

Stop with an error – FPU or electronics failure ●.

# Error recovery – see below.

If any FPUs have failed.

# Manually check the cause of the error.

If datum is confirmed non-functional.

Remove FPU from verification rig.

Choose a new FPU to fill this slot.

Update the serial number to turntable slot to CAN bus mapping.

Else

# Manually correct the non-datum issue.

Flag FPU for retest and leave it on the rig.

Restart the initialisation process until all FPUs can be datumed and the automated tests can begin.

## Verification Rig Setup

Home the turntable and the linear stage.

Turn off all lights.

Rotate turntable to position 2.

Move linear stage to fibre 1.

If all above operations successful then

Configure met\_pos camera.

Configure lighting for fibre backlight measurement.

Take a metrology image and calibrate it.

If successful then

Analyse metrology image

If fibre backlight detected then

Configure pos\_rep camera.

Configure lighting for position measurement.

Take a position repeatability image and calibrate it.

If successful then

Filter and analyse image to detect metrology targets.

# This next step requires that we analyse some metrology images and determine

# what constitutes a successful detection.

If targets detected and their relative size and distance are within expected limits then

Move to the next stage 🡪.

Else

Stop with an error – metrology targets not detectable or not as expected.

# Error recovery: Examine the images, adjust the lighting or camera settings,

# debug the metrology software or repaint the FPU.

Else

Stop with an error – pos\_rep equipment failure ●.

# Error recovery: Rerun the verification rig self-test and correct fault.

Else

Stop with an error – fibre backlight not detectable ●.

# Error recovery: Examine the images, adjust the lighting or camera settings,

# debug the metrology software or adjust the fibre.

Else

Stop with an error – met pos equipment failure ●.

# Error recovery: Rerun the verification rig self-test and correct fault.

Else

Stop with an error – equipment failure ●.

# Error recovery: Rerun the verification rig self-test and correct fault.

## Collision Detection Test

## Limit Test and Characterisation

## Datum Repeatability Test

Configurable constants

* DATUM\_REP\_PASS
* DATUM\_REP\_EXPOSURE
* POS\_REP\_POSN\_N

Configure pos\_rep camera for DATUM\_REP\_EXPOSURE *(4.4)*

Configure lighting for positional repeatability test (silhouette/backlight off, ambient on) *(4.3)*

For each of 6 FPUs

Move rotary stage to POS\_REP\_POSN\_N *(4.1)*

For 10 iterations (baseline)

Take image with pos\_rep camera *(4.4)*

Pass image to positional repeatability image analysis script *(5.1)*

For 10 iterations (datum)

Run findDatum on FPU

Take image with pos\_rep camera *(4.4)*

Pass image to positional repeatability image analysis script *(5.1)*

For 10 iterations (move-then-datum)

Configure and execute waveform (+30,+30)

ReverseMotion

Run findDatum on FPU

Take image with pos\_rep camera *(4.4)*

Pass image to positional repeatability image analysis script *(5.1)*

Pass coordinates to datum repeatability parameter script *(6.6)*

If returned value is below DATUM\_REP\_PASS then

Flag FPU as DATUM\_REP\_OK

Return average and maximum values to output file

Else

Flag FPU as DATUM\_REP\_FAIL

Return all measured coordinates to output file

## Pupil Alignment Test

Configurable constants

* PUPIL\_ALN\_POSN\_N
* PUPIL\_ALN\_PASS
* PUPIL\_ALN\_EXPOSURE

Configure pup\_aln camera with PUPIL\_ALN\_EXPOSURE *(4.4)*

Configure lighting for pupil alignment test (ambient/silhouette off, backlight 5V) *(4.3)*

For each of 6 FPUs

Move rotary stage to PUPIL\_ALN\_POSN\_N *(4.1)*

Configure and execute waveform (+10, -170)

For 4 iterations

Take image with pup\_aln camera *(4.4)*

For 3 iterations

Configure and execute waveform (0,90)

Take image with pup\_aln camera *(4.4)*

If Not the final iteration Then configure and execute waveform (90,-270)

Configure and execute waveform (-279,-279)

Run findDatum

For 16 saved images

Pass image to pupil alignment image analysis script *(5.5)*

Pass coordinates to pupil alignment parameter script *(6.4)*

If returned value is below PUPIL\_ALN\_PASS then

Flag FPU as PUPIL\_ALN\_OK

Return axis errors to output file

Else

Flag FPU as PUPIL\_ALN\_FAIL

Return axis errors to output file

## Metrology Calibration Image

Configurable constants

* METROLOGY\_CAL\_POSN\_N
* METROLOGY\_CAL\_TARGET\_EXPOSURE
* METROLOGY\_CAL\_FIBRE\_EXPOSURE

For each of 6 FPUs

Move rotary stage to METROLOGY\_CAL\_POSN\_N *(4.1)*

Configure met\_cal camera with METROLOGY\_CAL\_TARGET\_EXPOSURE *(4.4)*

Configure lighting for metrology calibration target image (backlight/silhouette off, ambient on) *(4.3)*

Take image with met\_cal camera *(4.4)*

Pass image to metrology calibration target image analysis script *(5.2)*

Configure met\_cal camera with METROLOGY\_CAL\_FIBRE\_EXPOSURE *(4.4)*

Configure lighting for metrology calibration fibre image (ambient/silhouette off, backlight 0.1V) *(4.3)*

Take image with met\_cal camera *(4.4)*

Pass image to metrology calibration fibre image analysis script *(5.3)*

Pass coordinates to metrology target calibration parameter script *(6.1)*

Return metrology calibration distances to output file

## Positional Repeatability and Gearbox Calibration

## Positional Verification

# Hardware control specification

## FPU control

* See FPU protocol 2 documentation

## Rotary stage

* Function – the rotary stage rotates the verification frame such that FPUs can be positioned under various test stations.
* Rotary stage - Thorlabs NR360S/M - <https://www.thorlabs.de/thorproduct.cfm?partnumber=NR360S/M>
* Controller - Thorlabs BSC201 – <https://www.thorlabs.de/thorproduct.cfm?partnumber=BSC201>
* Required operations
  + Home
  + Forward absolute movement
  + Reverse absolute movement
* Adjustable parameters
  + Speed

## Linear stage

* Function – the linear stage moves a backlight LED and focussing lens assembly such that light is shone into one of the 6 fibre patch cables coupled with the FPU fibres. This allows imaging of the fibre centre and back projection of the fibre aperture such that pupil alignment can be measured.
* Linear stage - Thorlabs MTS50/M-Z8 - <https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=3002&pn=MTS50/M-Z8#3006>
* Controller - Thorlabs BSC201 – <https://www.thorlabs.de/thorproduct.cfm?partnumber=BSC201>
* Required operations
  + Home
  + Forward absolute movement
  + Reverse absolute movement
* Adjustable parameters
  + Speed

## Lamps and control DAQ

* Function – three LED lamps allow different setups of ambient and directional illumination within the verification enclosure, as well as backlighting of the fibres.
* Ambient illumination - Thorlabs LED cluster LIU365A - <https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=2853>
* Metrology target silhouetting - Thorlabs LED cluster LIU365A - <https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=2853>
* Fibre backlight - Thorlabs mounted LED MCWHLP1 - <https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2692>
* LED driver – Thorlabs LEDD1B - <https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=2616>
* DAQ - RedLab1208LS - <https://www.meilhaus.org/downloadserver/redlab/manual/RedLab%201208LS_en.pdf>
* Required operations
  + On-off for ambient illumination and target silhouetting lamps
  + Voltage control (0-5V) for fibre backlight

## Camera control

* Function – four cameras take images of the FPU and fibre projection during the various tests
* Positional repeatability – Basler ace acA3800-10gm GigE - <https://www.edmundoptics.com/p/Basler-ace-acA3800-10gm-Monochrome-GigE-Camera/32412/>
* Metrology calibration – Basler ace acA3800-10gm GigE - <https://www.edmundoptics.com/p/Basler-ace-acA3800-10gm-Monochrome-GigE-Camera/32412/>
* Metrology height – Basler ace acA3800-10gm GigE - <https://www.edmundoptics.com/p/Basler-ace-acA3800-10gm-Monochrome-GigE-Camera/32412/>
* Pupil alignment – Basler ace acA1920-40gm GigE - <https://www.edmundoptics.com/p/basler-ace-aca1920-40gm-monochrome-gige-camera/3429/>
* Required operations
  + Connect to camera and load configuration using given parameters
  + Save image from a single camera given its IP address
* Adjustable parameters
  + Exposure time

# Image analysis specification

## Find metrology targets from pos-rep camera

* Function – to find coordinates for the metrology targets in real space using the pos-rep camera. Used in the following tests:
  + Datum repeatability
  + Positional repeatability
* Inputs
  + 8bit bitmap image from pos-rep camera
* Return
  + XY coordinates in real space of centres of large target and small target
  + Quality metric of target detection
* Configurable constants
  + POSREP\_SMALL\_TARGET\_DIA\_LOWER\_THRESH
  + POSREP\_SMALL\_TARGET\_DIA\_UPPER\_THRESH
  + POSREP\_LARGE\_TARGET\_DIA\_LOWER\_THRESH
  + POSREP\_LARGE\_TARGET\_DIA\_UPPER\_THRESH
  + POSREP\_TARGET\_CIRCULARITY\_THRESH
  + POSREP\_THRESHOLD\_VAL
  + POSREP\_PLATESCALE
  + POSREP\_DISTORTION\_MATRIX
* Potential errors
  + Contaminated image from stray reflections leading to false positive detections
  + Unable to find one or both targets due to shadows/noise/contamination
* Algorithm
  + Process image (distortion correction and threshold)
  + Find contours
  + Filter contours on size and circularity to detect targets and reject contamination
  + Find centre of targeted contours using Centre of Mass

## Find metrology targets from met-cal camera

* Function – to find coordinates for the metrology targets in real space using the met-cal camera. Used in the following tests:
  + Metrology calibration
* Inputs
  + 8bit bitmap image from met-cal camera
* Return
  + XY coordinates in real space of centres of large target and small target
  + Quality metric of target detection
* Configurable constants
  + METCAL\_SMALL\_TARGET\_DIA\_LOWER\_THRESH
  + METCAL\_SMALL\_TARGET\_DIA\_UPPER\_THRESH
  + METCAL\_LARGE\_TARGET\_DIA\_LOWER\_THRESH
  + METCAL\_LARGE\_TARGET\_DIA\_UPPER\_THRESH
  + METCAL\_TARGET\_CIRCULARITY\_THRESH
  + METCAL\_THRESHOLD\_VAL
  + METCAL\_PLATESCALE
* Potential errors
  + Positioning error in FPU or rotary stage leads to part of target being out of FoV
* Algorithm
  + Process target image (threshold)
  + Find contours
  + Filter contours on size and circularity to detect targets and reject contamination
  + Find centre of targeted contours using Centre of Mass

## Find backlit fibre from met-cal camera

* Function – to find coordinates for the metrology targets in real space using the met-cal camera. Used in the following tests:
  + Metrology calibration
* Inputs
  + 8bit bitmap image from met-cal camera
* Return
  + XY coordinates in real space of centres of backlit fibre
  + Quality metric of target detection
* Configurable constants
  + METCAL\_FIND\_GAUSSIAN\_BOX\_SIZE
  + METCAL\_PLATESCALE
* Potential errors
  + Overexposed fibre image leads to inability to run Gaussian fit
* Algorithm
  + Find fibre location (find maxima)
  + Find Gaussian fit around point

## Find metrology target heights from met-ht camera

* Function – to measure the height of the metrology targets above the beta arm surface to allow correction for elongation in the metrology system
* Inputs
  + 8bit bitmap image from met-ht camera
* Return
  + Height in microns of large target and small target above beta arm top surface
  + Quality metric of edge detection
* Configurable constants
  + METHT\_NOISE\_THRESH
  + METHT\_THRESHOLD\_VAL
  + METHT\_PLATESCALE
* Potential errors
  + Image out of focus so edges not clearly defined
  + Targets not clearly protruding
  + Noise in image from stray reflections
* Algorithm
  + Process image (convert, blur and threshold)
  + Check image noise
  + Find side of beta arm
  + At fixed offsets from arm side, find transition pixel representing top edge of arm and targets
  + Fit line through arm points
  + Find normal from line to target points
  + Average normals to give target height

## Find projected spot from pup-aln camera

* Function – to measure misalignment of the projected axis from a backlit fibre as the FPU rotates and thus determine the angular errors in each of the three mechanism axes
* Inputs
  + 8bit bitmap image from pup-aln camera
* Return
  + XY coordinates in real space of centre of projected spot
* Configurable constants
  + PUPIL\_CIRCULARITY\_THRESH
  + PUPIL\_THRESHOLD\_VAL
  + PUPIL\_DISTORTION\_MATRIX
  + PUPIL\_PLATESCALE
* Potential errors
  + Signal-to-noise too low due to upstream light loss or leakage through enclosure
  + Image contamination
  + Non-flat projection leading to bias in centre of mass
* Algorithm
  + Process image (distortion correct, convert, de-noise and threshold)
  + Find contours
  + Filter contours on size and circularity to detect targets and reject contamination
  + Find centre of targeted contour using Centre of Mass

# Performance parameter calculations

## Metrology target calibration

* Input – coordinates of small target, large target and fibre aperture
* Return
  + Distance between metrology targets and fibre aperture in mm

## Metrology height characterisation

* Input – heights of small target and large target above beta arm
* Return
  + In tolerance (pass/fail) – heights are within acceptable tolerances
  + Heights – in microns for input to metrology system correction algorithm

## Motor calibration

* Input – coordinates of both metrology targets for given alpha/beta angles in real space
* Return
  + Positional repeatability (pass/fail) – maximum error in microns for comparable points
  + Alpha gearbox lookup table – step correction values for given angles to flatten circumferential error as best as possible
  + Beta gearbox lookup table – step correction values for given angles to flatten circumferential error as best as possible

## Pupil alignment

* Input – coordinates of projected fibre aperture for given alpha/beta angles in real space
* Return
  + Pupil alignment (pass/fail) – maximum error in arcmin for total system
  + Pupil alignment breakdown – error magnitude/direction in arcmin for chassis, alpha and beta axes

## Positional accuracy

* Input - coordinates of both metrology targets for given alpha/beta angles in real space
* Return
  + Positional accuracy (pass/fail) – maximum error of real position against nominal position in microns

## Datum repeatability

* Input – coordinates of both metrology targets for given datum datasets in real space
* Return
  + Datum repeatability (pass/fail) – maximum error of datum error in microns
* Algorithm
  + Average all baseline coordinates
  + For each datum coordinate
    - Subtract baseline coordinate from datum coordinate to give ‘error – datum only’
  + For each move-then-datum coordinate
    - Subtract baseline coordinate from move-then-datum coordinate to give ‘error – move-then-datum’
  + Find average and maximum ‘error – datum only’ values
  + Find average and maximum ‘error – move-then-datum’ values