IvS seminar 18/5/2018

# Master's thesis:

## FPGA-based Active Pointing Correction of Optical Instruments on Small Satellites

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External supervisor: Bram Vandoren

Master of Electronics and ICT Engineering Technology
Academic year: **2017-2018**

De gezamenlijke opleiding industrieel ingenieur is een initiatief van UHasselt en KU Leuven.

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# Introduction

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# Introduction: CubeSats

- Mini-satellite standard Introduced in 1999
- Collaboration between Cal Poly and SSFL
- Highly standardized: 1U: 10x10x10 cm
  ~1kg

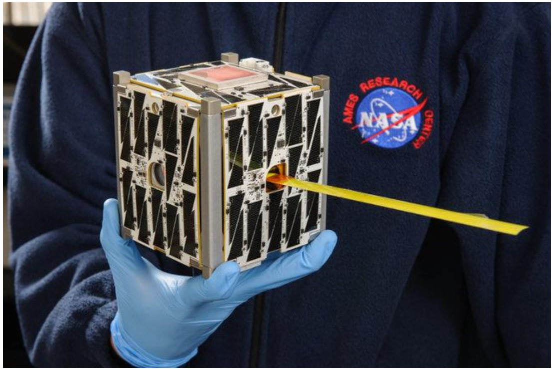


***Figure 1.*** *CubeSat size reference (image credit: NASA)*

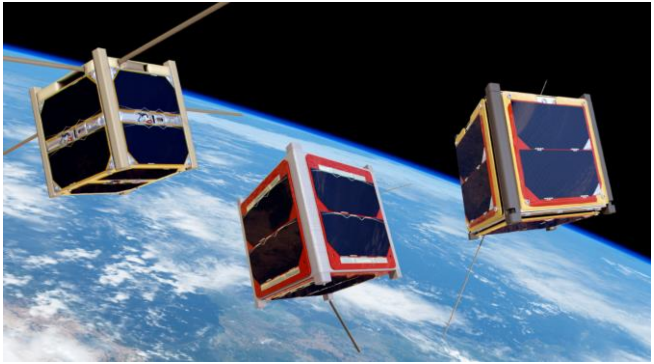

***Figure 2.*** *CubeSats in orbit (image credit: ESA)*

- On-orbit testing of various scientific payloads
- Wide spectrum of applications across the scientific community
- Made space more accessible

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# Introduction: CubeSats

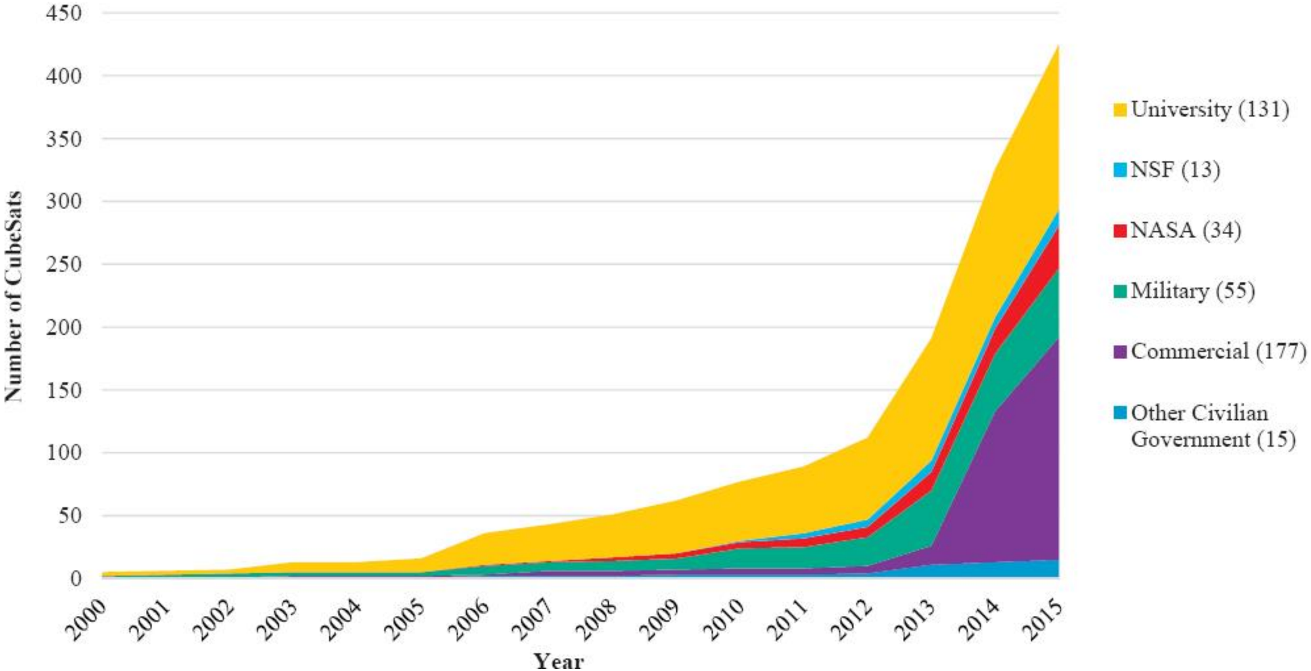


***Figure 3.*** *Number of cubesats launched between 2000 and 2015, categorized by user [2]*

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# Introduction: CubeSats

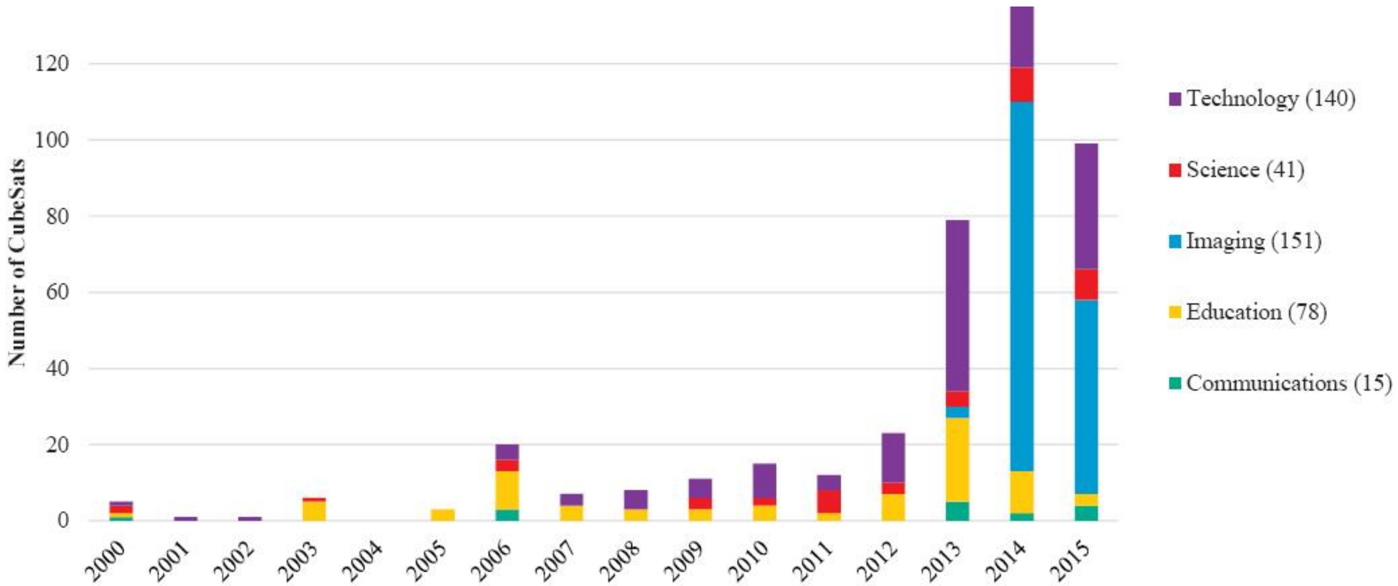


***Figure 4.*** *Number of cubesats launched between 2000 and 2015, categorized by research domain [2]*

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# Introduction: CUBESPEC

- Mission concept by KU Leuven Institute of Astronomy
- 6U cubesat dedicated to astronomy
- Detect exoplanets with transit photometry

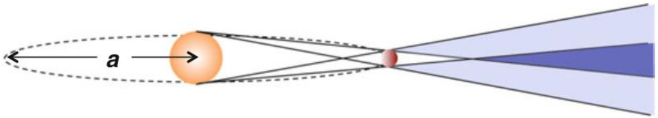


***Figure 5.*** *The transit method [9]*

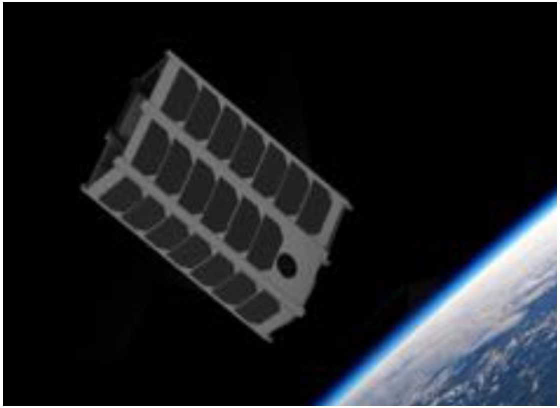

***Figure 6.*** *Artist's impression of CubeSpec [10]*

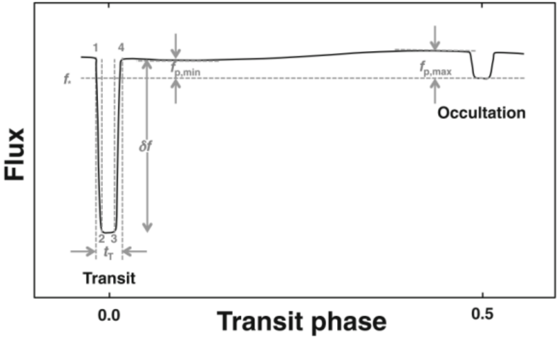


***Figure 7.*** *Graphical representation of a typical photometry measurement [9]*

Requirements:

- High photometric resolution
- **<u>Arcsecond</u>** level pointing accuracy and stability

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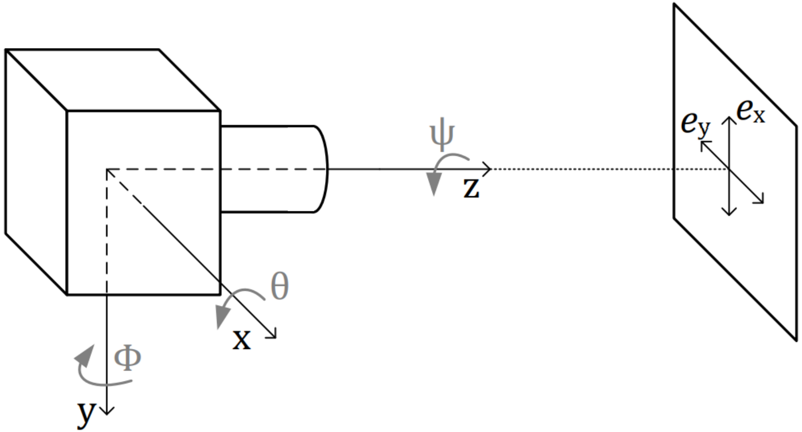
# Problem Statement

# Problem Statement

Rotational errors around ***x*** and ***y*** result in pointing errors $\mathbf{e_x}$ and $\mathbf{e_y}$




$$e_1 = \begin{bmatrix} e_{x\theta} \\ e_{y\phi} \end{bmatrix} \quad \text{with} \quad |e_1| = \sqrt{e_{x\theta}^2 + e_{y\phi}^2}$$

***Figure 8.*** *General satellite pointing scheme [5]*

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# Problem Statement

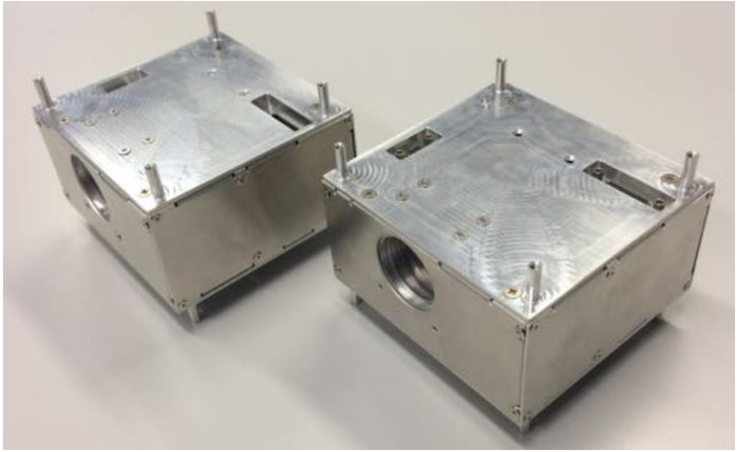

***Figure 9.*** *KU Leuven ADCS prototype (image credit: KU Leuven)*

- Attitude Determination and Control System (ADCS)
- Provides coarse attitude control (~100 arcsec)
- Arcsecond-level instrument pointing not possible with ADCS alone

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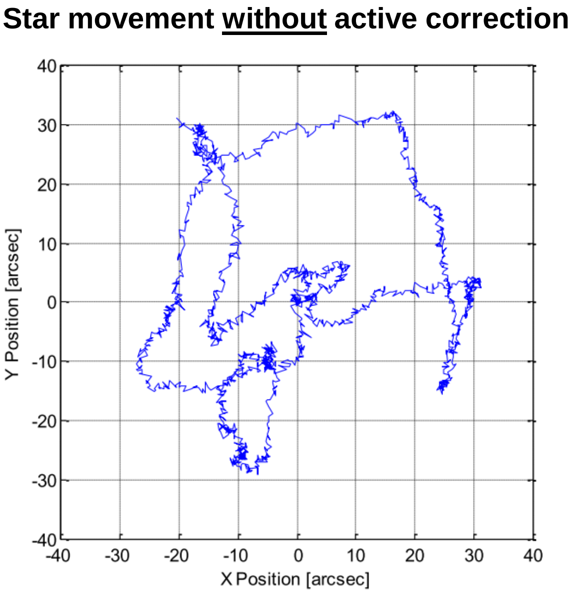
# Problem Statement



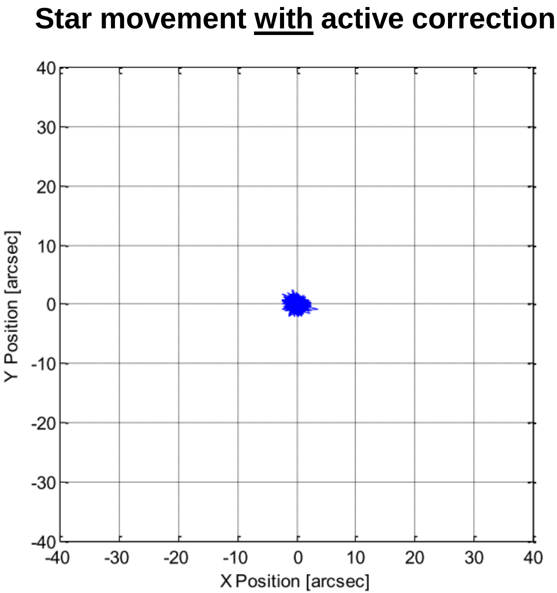




***Figure 10.*** *Star movement on image sensor without active correction (left) and with active correction (right) [6]*

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# Solution

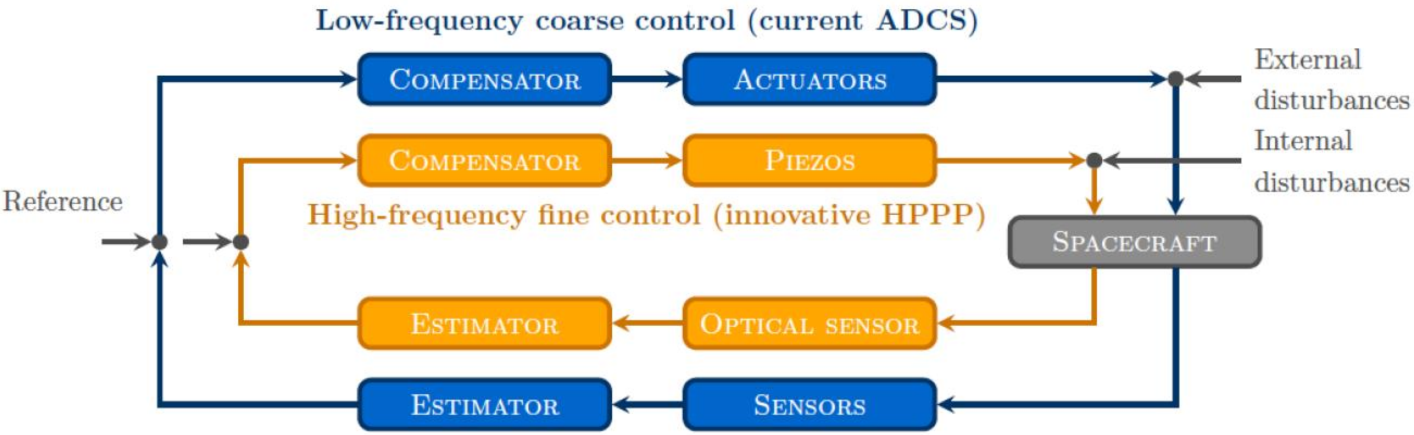


***Figure 11.*** *Control loop scheme with the active correction loop indicated in orange, ADCS loop in blue*

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# CUBESPEC: Solution

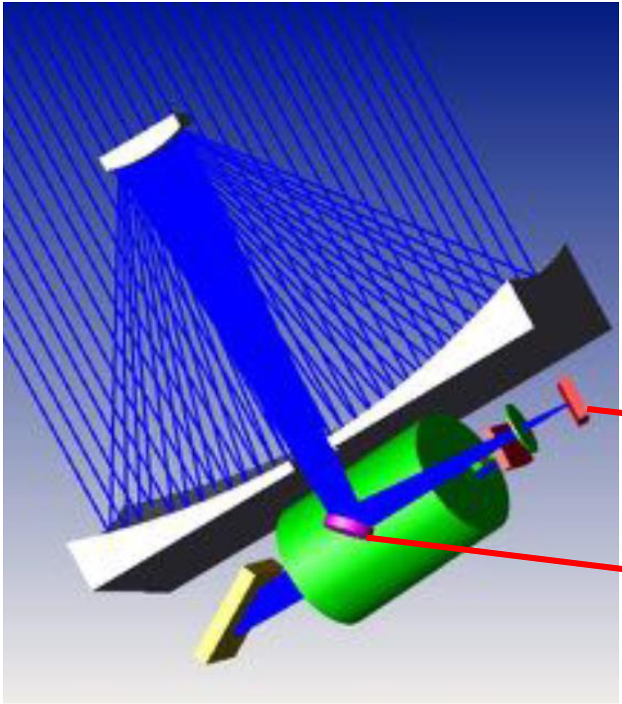

*Figure 12. Beam steering in CUBESPEC [3]*

- Off-axis Cassegrain telescope with f=1600mm
- Fine steering mirror (FSM) and fine guidance sensor (FGS) provide precise beam-steering

FGS

FSM

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# Hardware and Setup

# Hardware and Setup

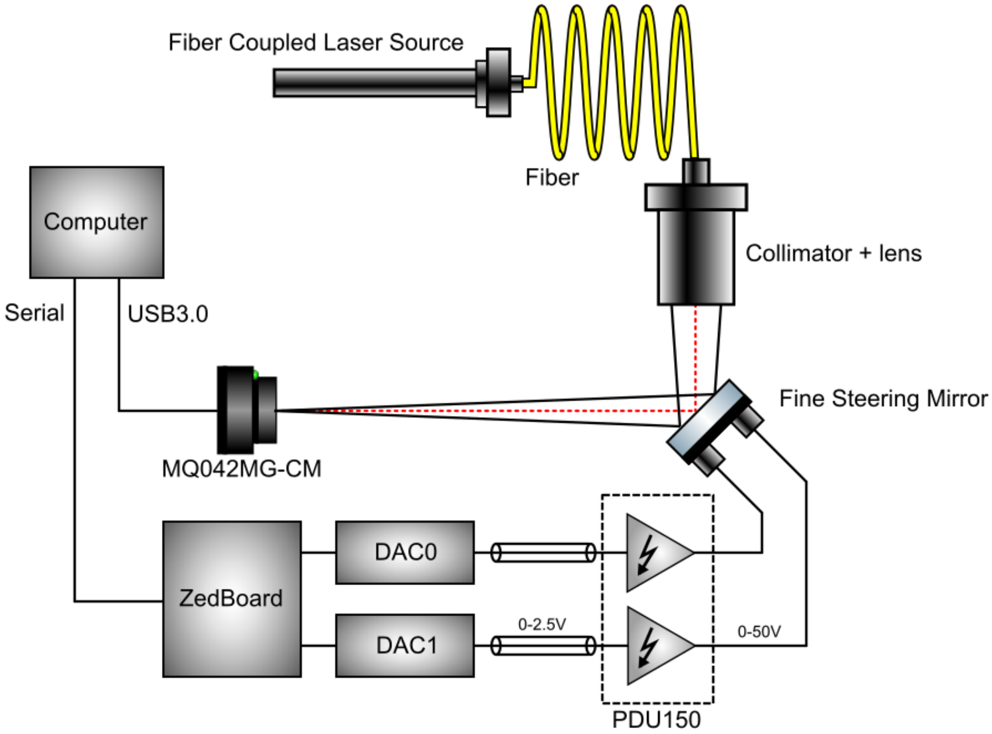


***Figure 13.*** *Graphical representation of the active correction setup*

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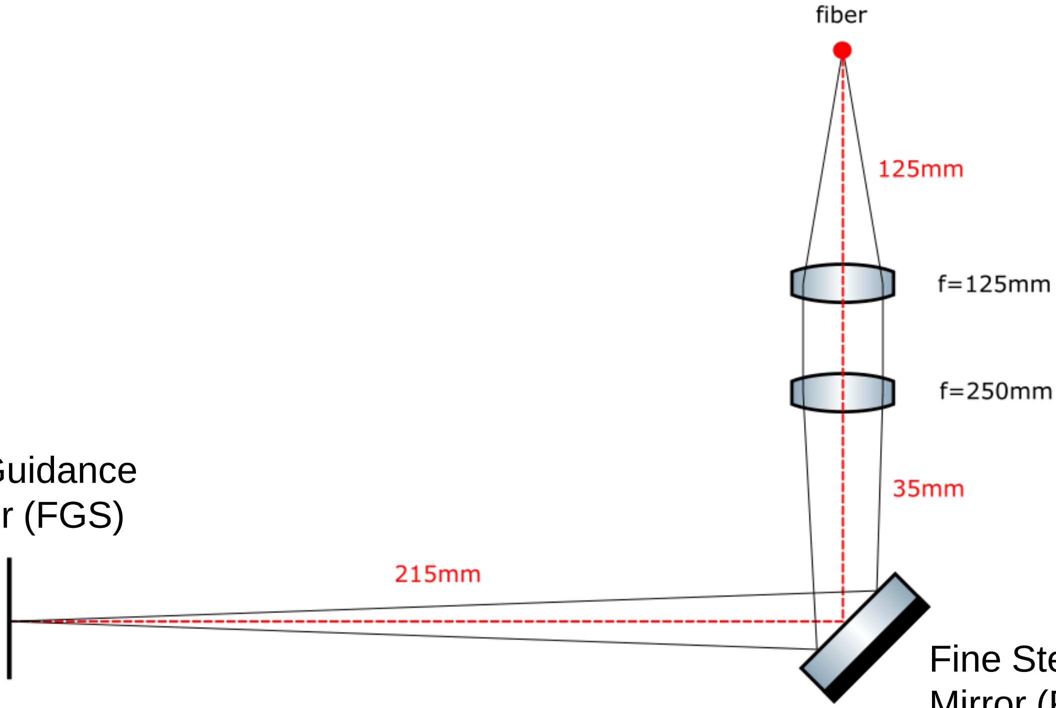
# Hardware and Setup: Optics

Fine Guidance Sensor (FGS)




Fine Steering Mirror (FSM)

***Figure 14.*** *Optical configuration of the active correction setup*

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# Hardware and Setup

1. Laser
2. Collimator + lens
3. Steering mirror
4. Guidance Sensor
5. Piezo amplifier
6. DACs
7. FPGA

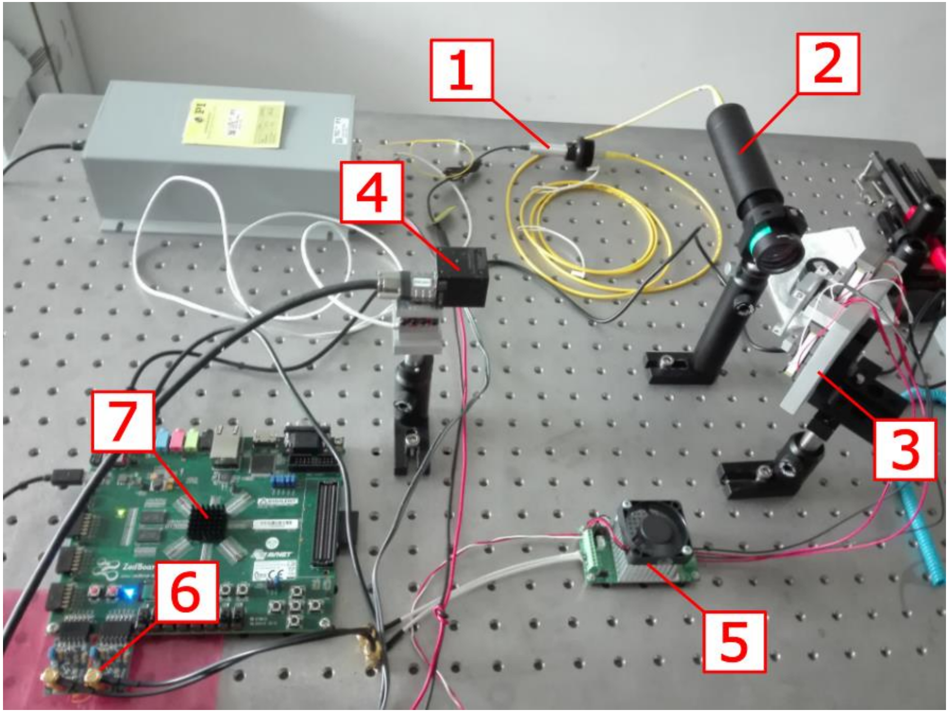


***Figure 15.*** *The test setup installed on the optical bench*

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# The Control Loop

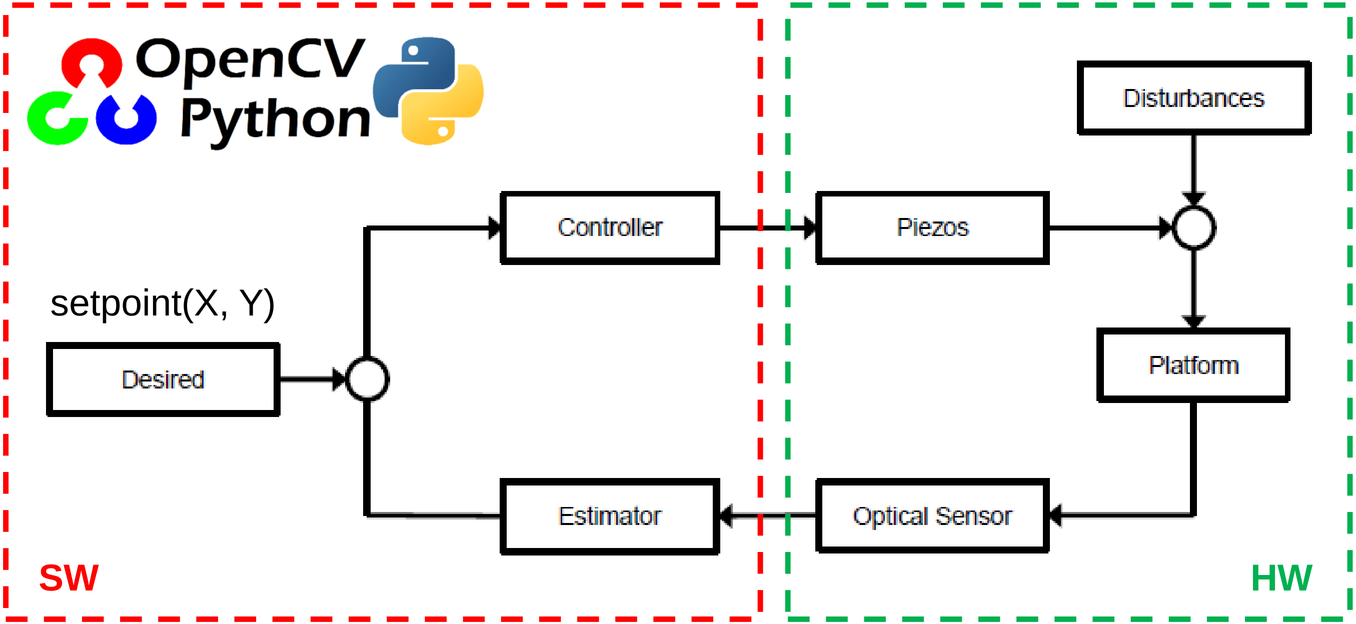


***Figure 16.*** *Diagram of the control loop*

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# Hardware and Setup: FSM

- Tip-tilt fine steering mirror (FSM)
- One fixed pivot point and two actuators
- Resultant mirror movement is a linear combination of the actuator movement
- Linear combination of piezo driving required to move star in cartesian grid

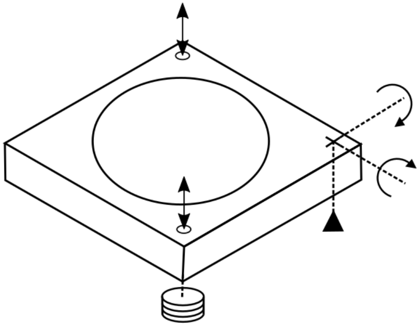

***Figure 17.*** *Steering mirror tip-tilt configuration*

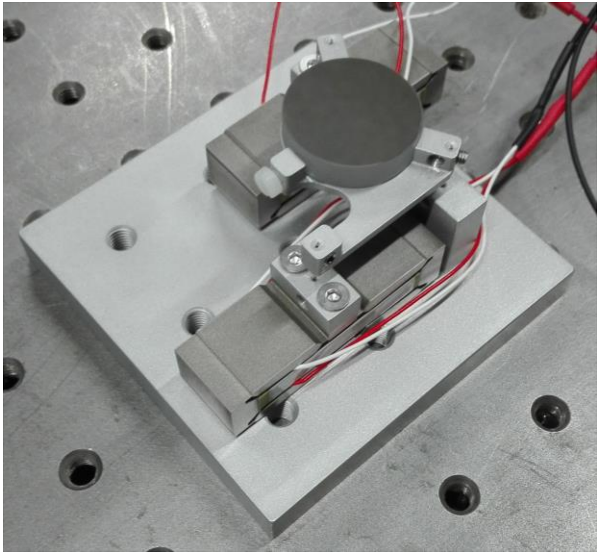

***Figure 18.*** *Fine steering mirror*

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# Hardware and Setup: FSM

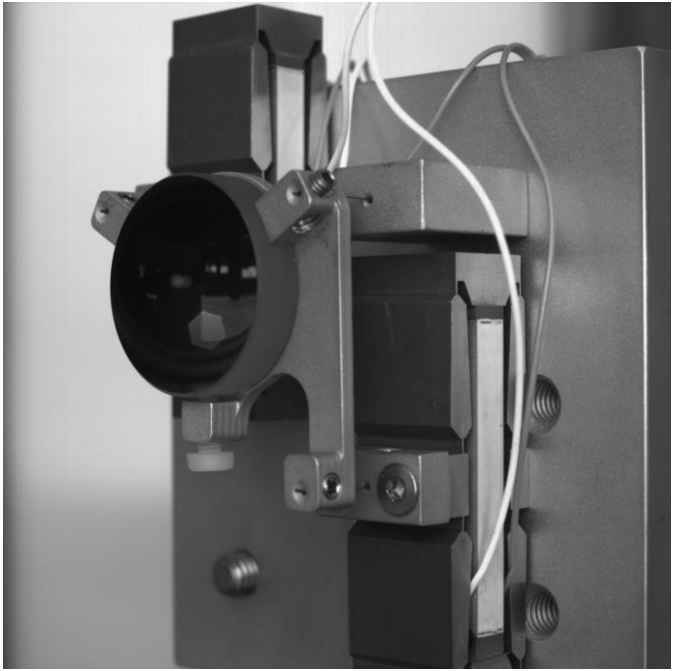

***Figure 19.*** *Front facing view of the steering mirror*

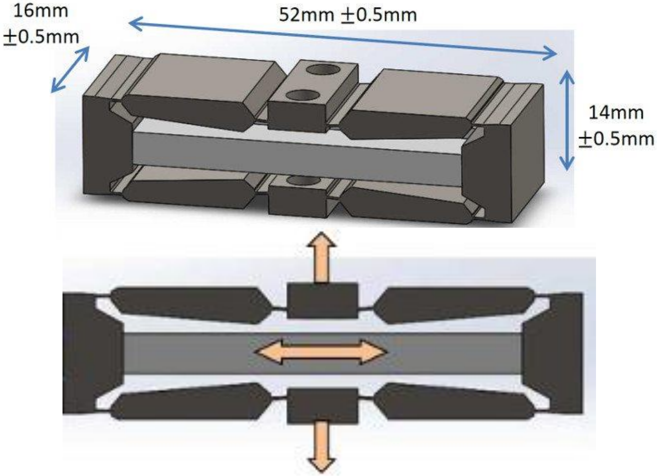


***Figure 20.*** *Amplified stack piezo actuator (image credit: Piezodrive)*

860 µm stroke

~150V

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# Alternative FSM

TNO innovation for life

- Mirror steering via magnetic fields
- Larger optical steering range
- ± 2° optical steering range (vs ± 0,75°)
- Highly linear
- Eddy current feedback sensors
- More complex interfacing

***Figure 21.*** *TNO fine steering mirror based on variable reluctance actuators (image credit: TNO)*

workshop on innovative technologies for space optics
12 - 16 February 2018 | European Space Agency ESA/ESTEC | The Netherlands
esa

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# FSM Calibration

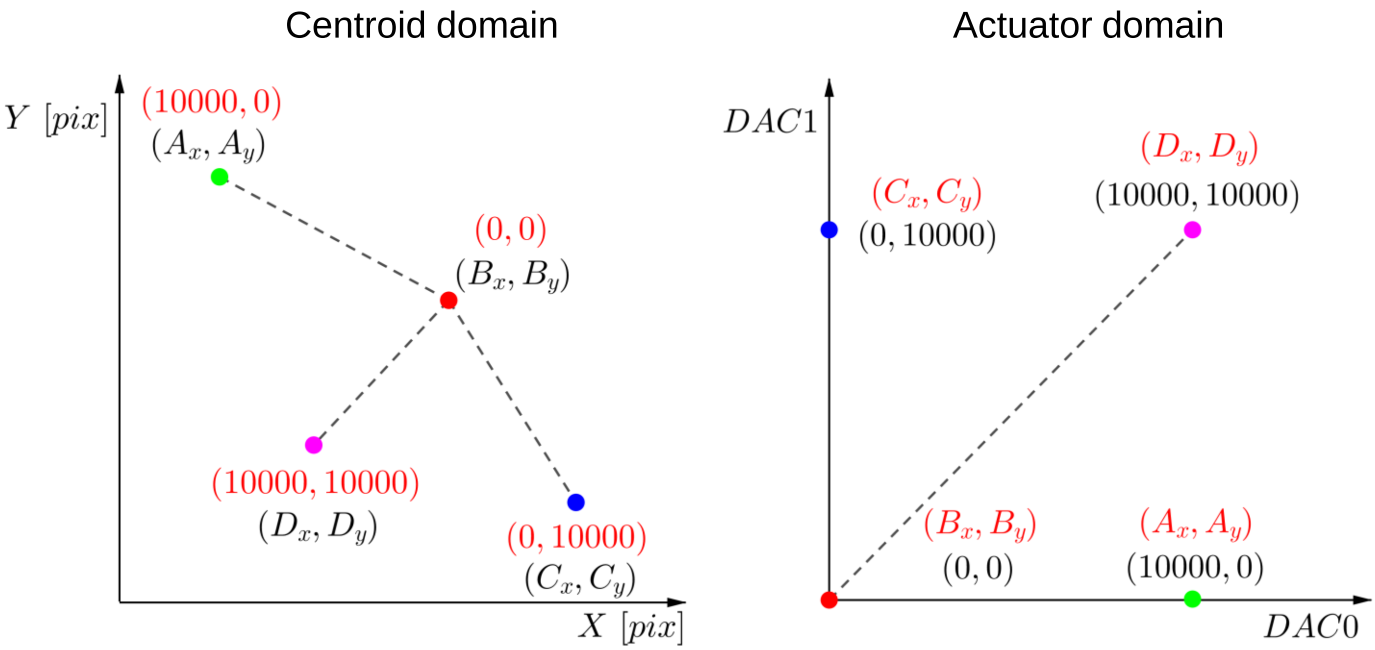


***Figure 22.*** *Affine transformation from warped centroid domain to actuator values*

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# FSM Calibration

M

$$\begin{bmatrix} x_b \\ y_b \\ 1 \end{bmatrix} = \begin{bmatrix} a_0 & a_1 & a_2 \\ b_0 & b_1 & b_2 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} DAC0 \\ DAC1 \\ 1 \end{bmatrix}.$$

Desired star position on imager

Steering mirror actuator values (16-bit)

M = cv2.estimateRigidTransform(P1, P2, True)
With:

P1 the calibration centroids
P2 the corresponding actuator values

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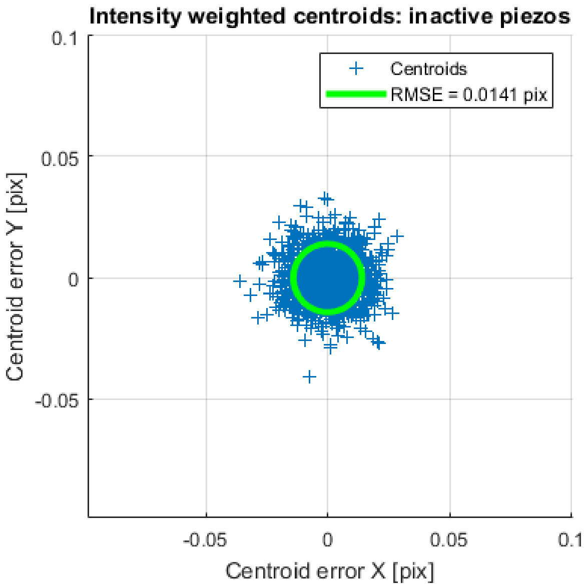
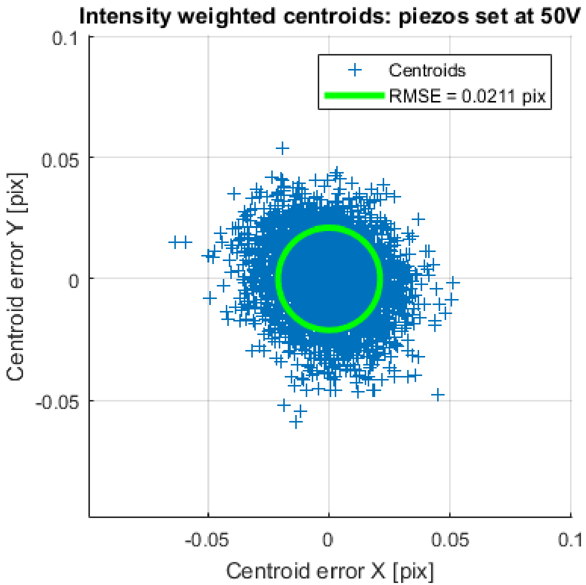
# Results

# Centroiding Error




**RMSE = 0,0141 pix**

**RMSE = 0,0211 pix**

***Figure 23.*** *Results from static testing –*
*disabled piezo stage (left), piezos fixed at 50V (right)*

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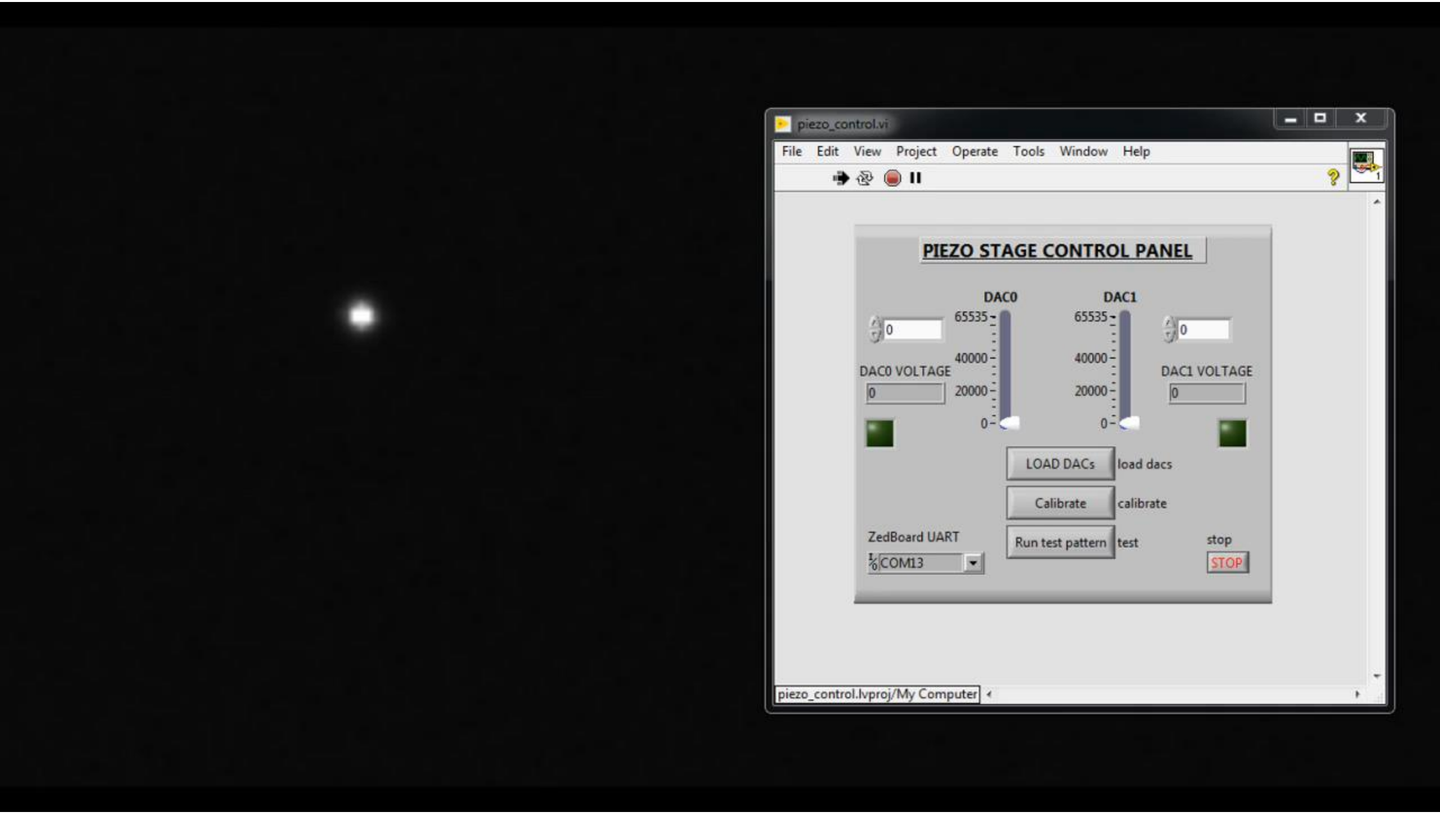
# FSM Calibration



# FSM Calibration

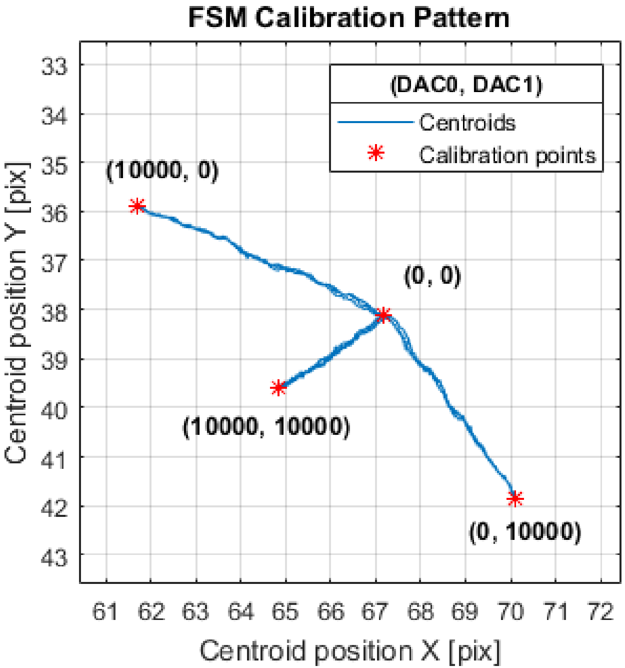



***Figure 24.*** *Steering mirror calibration pattern*

- FSM Calibration pattern
- Four mirror positions and corresponding DAC settings
- Calculation of the rigid transformation
- Steering resolution well below centroiding error

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# FSM Calibration

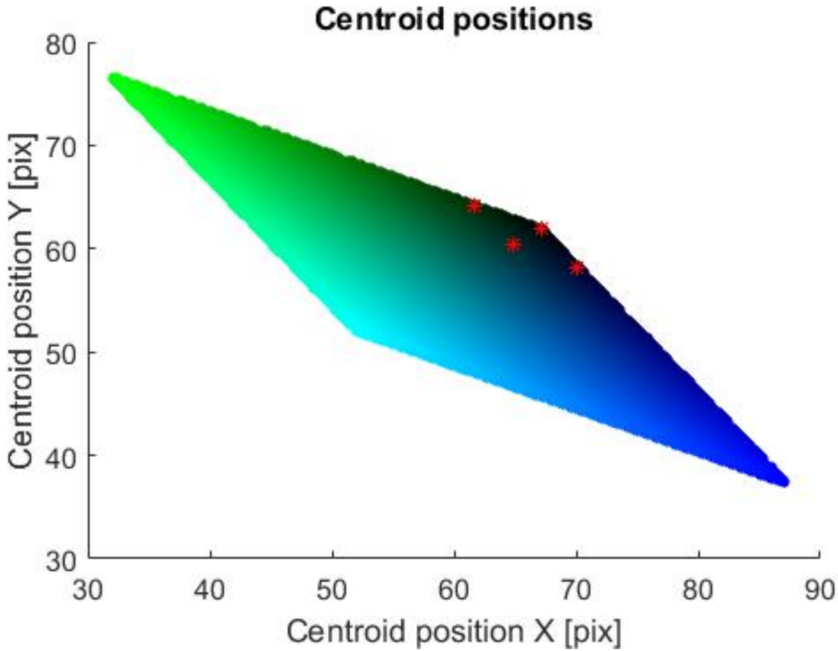


***Figure 25.*** *Calibration centroids*

# FSM Calibration

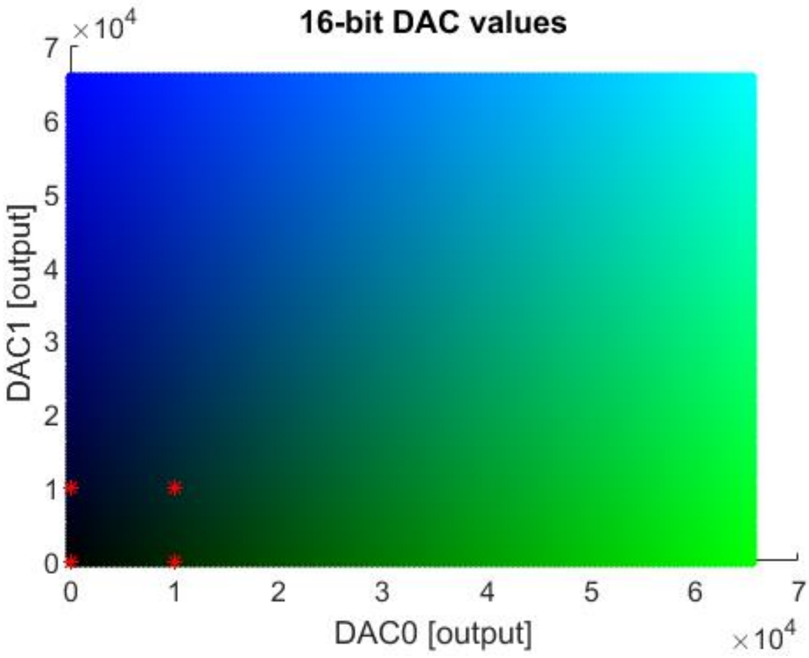


***Figure 26.*** *Cartesian actuator domain*

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# FSM Calibration

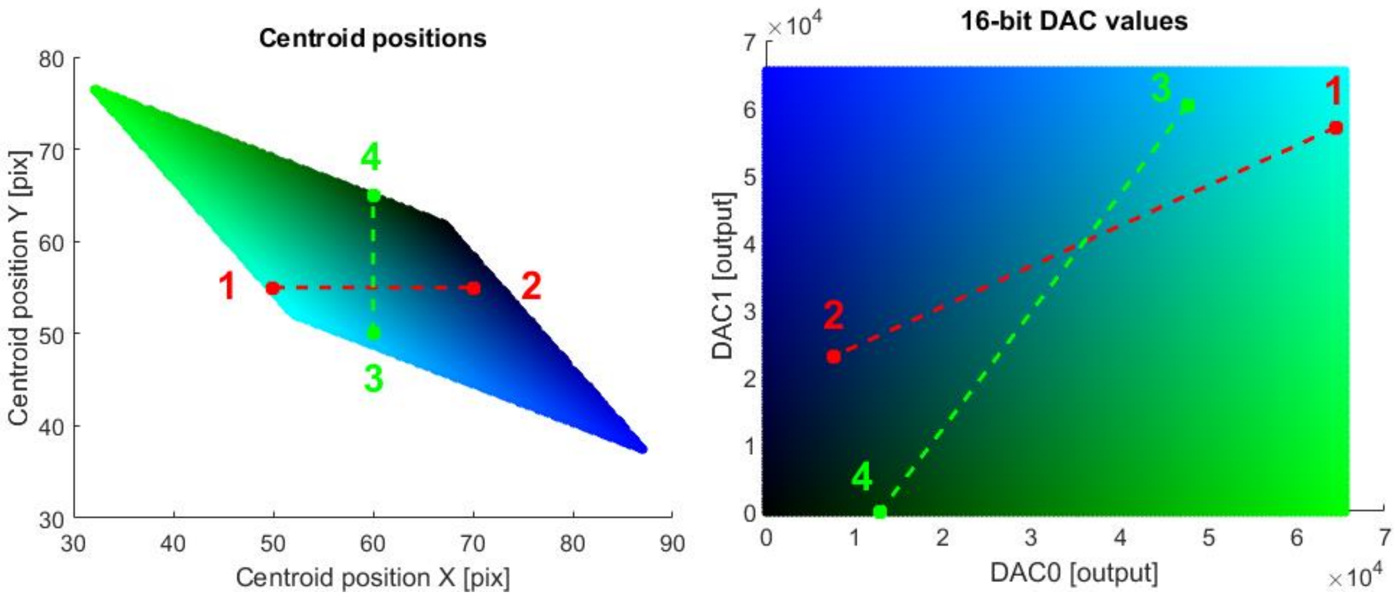


*Figure 27. Horizontal and vertical centroid movement (left) linearly transformed to the cartesian actuator grid (right)*

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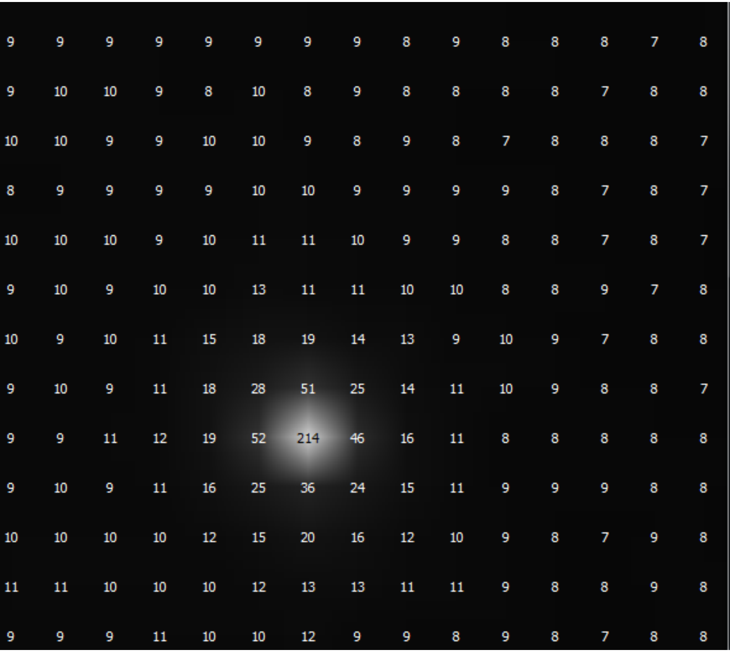
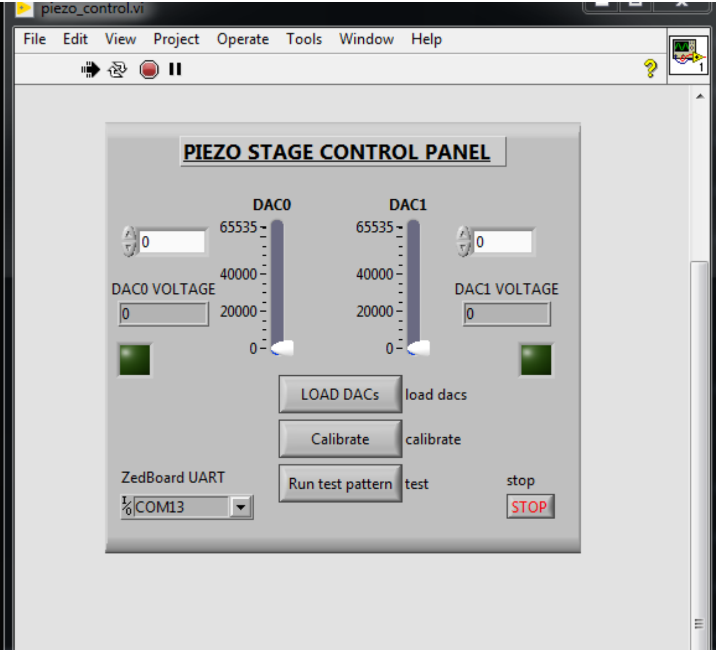
# FSM Calibration



# FSM Calibration – Test Pattern

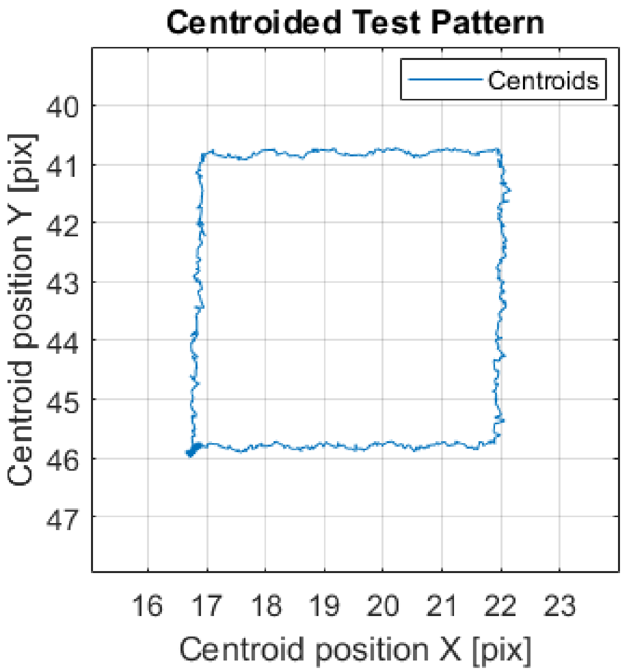



***Figure 28.*** *Centroided steering mirror testpattern*

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# Steering Mirror Frequency Response

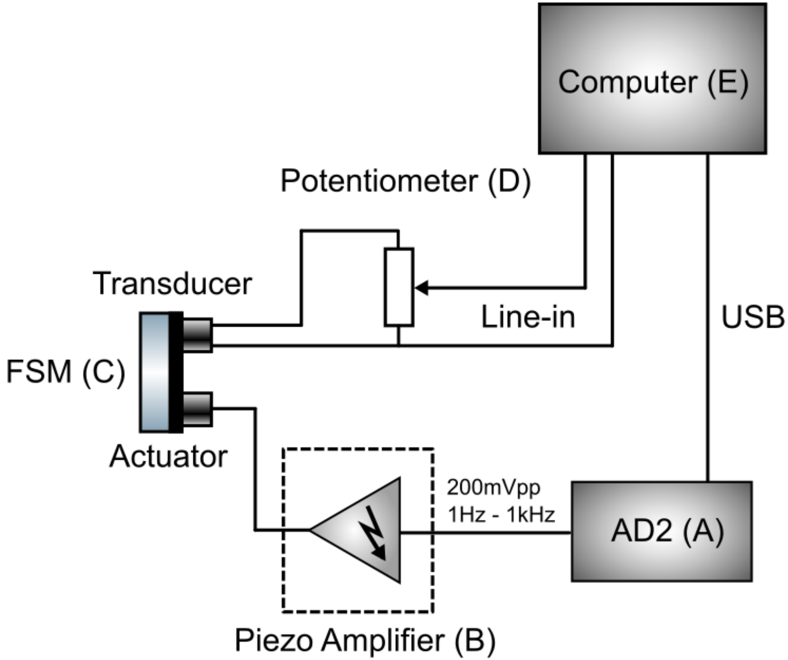


***Figure 29.*** *Setup for the determination of the steering mirror frequency response*

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# Steering Mirror Frequency Response

A. Frequency sweep
B. Piezo amplifiers
C. Steering mirror
D. Potentiometer
E. Computer

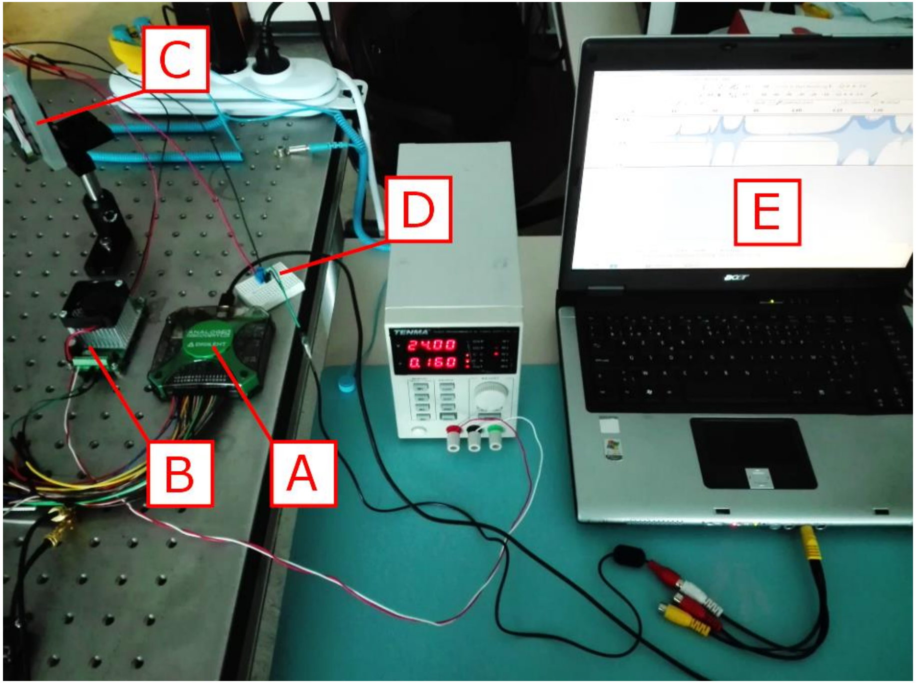


***Figure 30.*** *Photograph of the frequency response measurement setup*

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# Steering Mirror Frequency Response

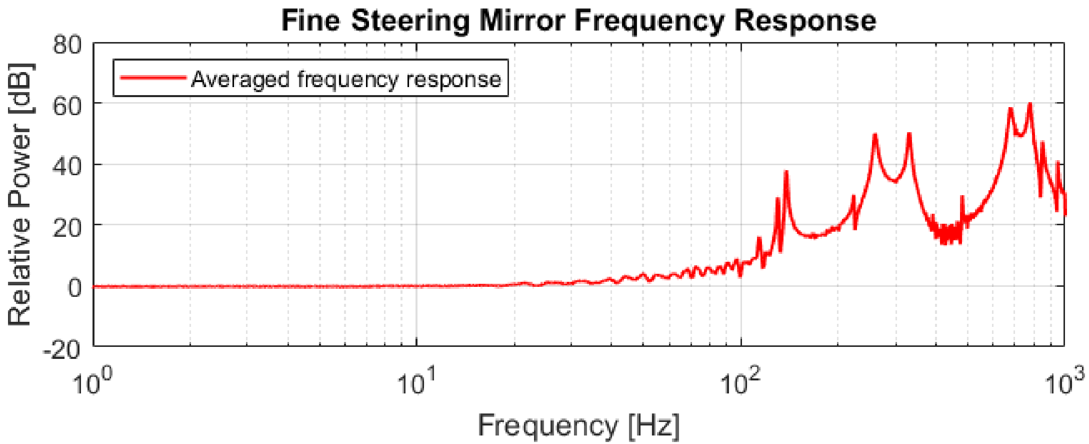


***Figure 31.*** *Steering mirror frequency response*

# Steering Mirror Frequency Response

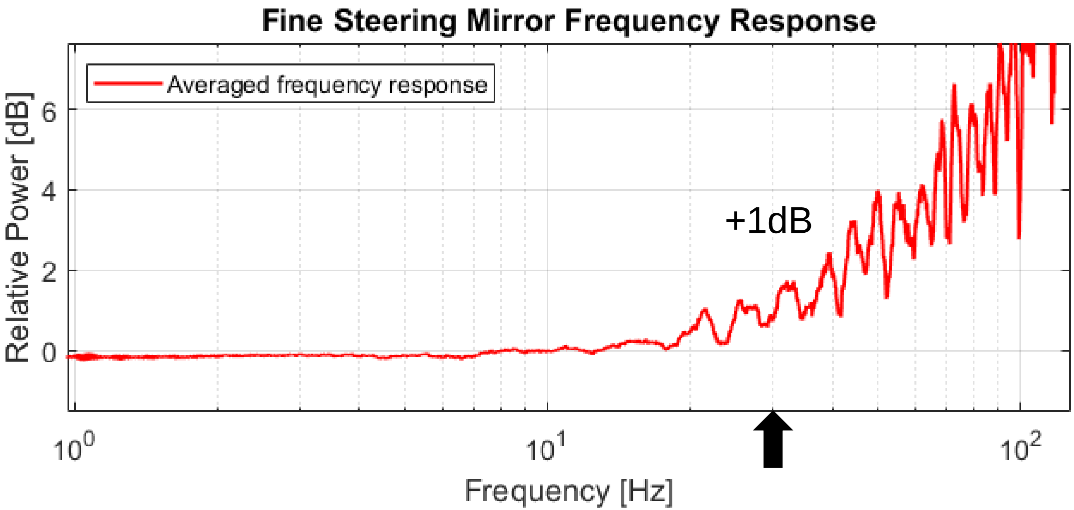


***Figure 32.*** *Close-up of the Steering mirror frequency response*

# Control Loop Results: Step Response

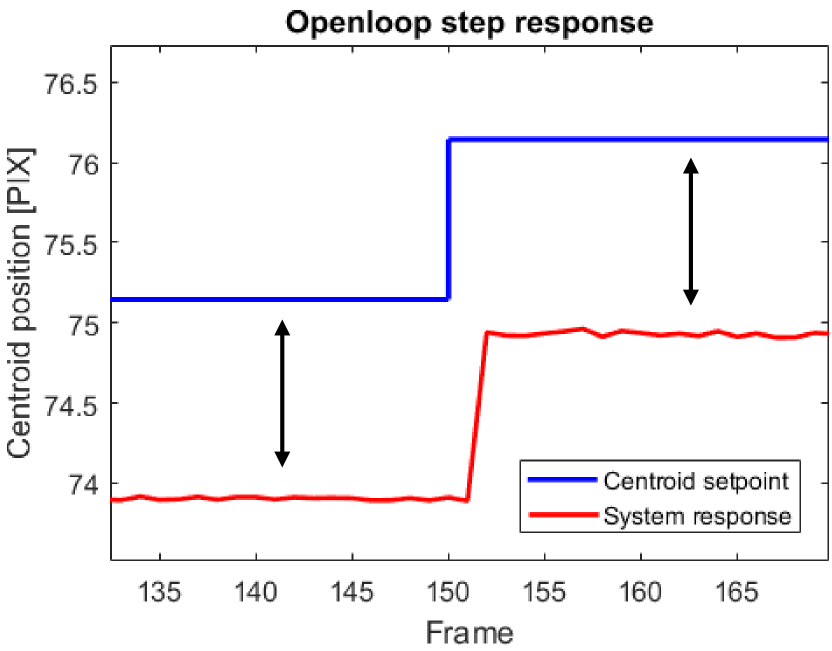


***Figure 33.*** *Step response in open loop (framerate = 30 fps)*

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# Control Loop Results: Step Response

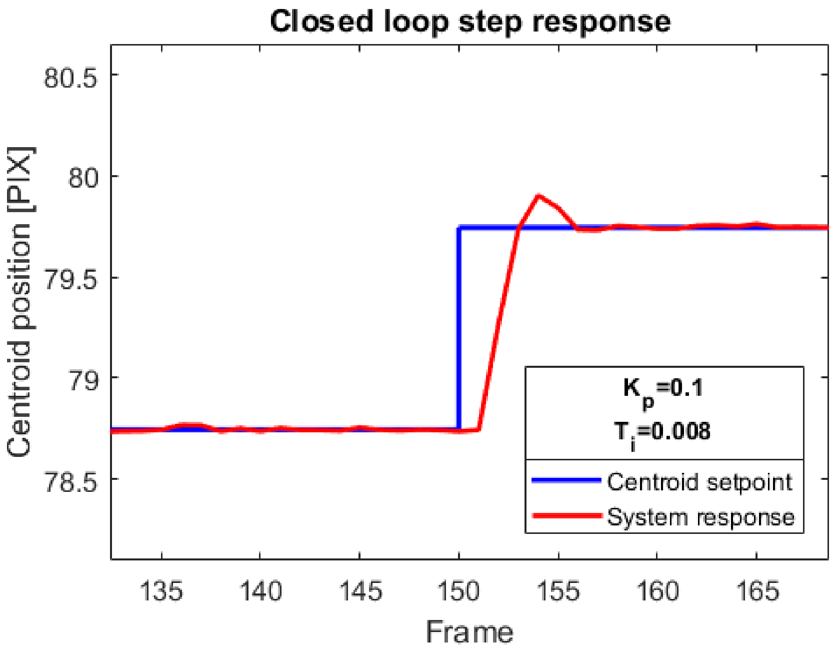


***Figure 34.*** *Closed loop step response with PI controller (framerate = 30 fps)*

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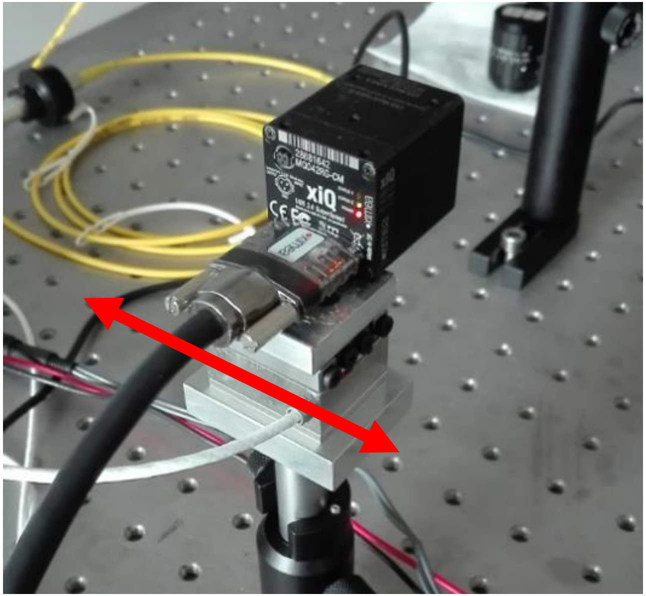
# Control Loop Results: Disturbance Attenuation



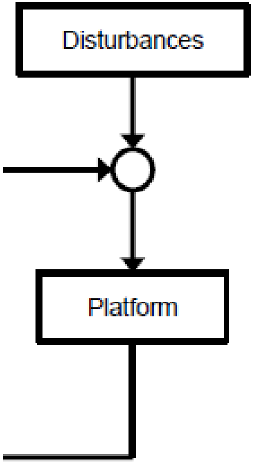



***Figure 35.*** *Fine guidance sensor mounted on linear piezo stage*

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# Control Loop Results: Disturbance Attenuation

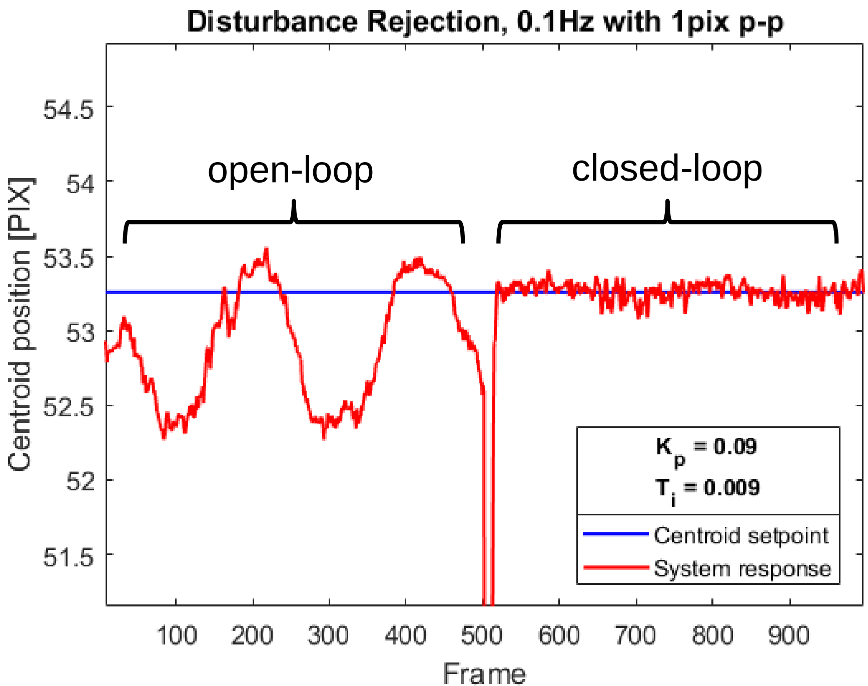


***Figure 36.*** *0,1 Hz disturbance, ~1 pixel p-p magnitude, without and with closed loop enabled (framerate = 30 fps)*

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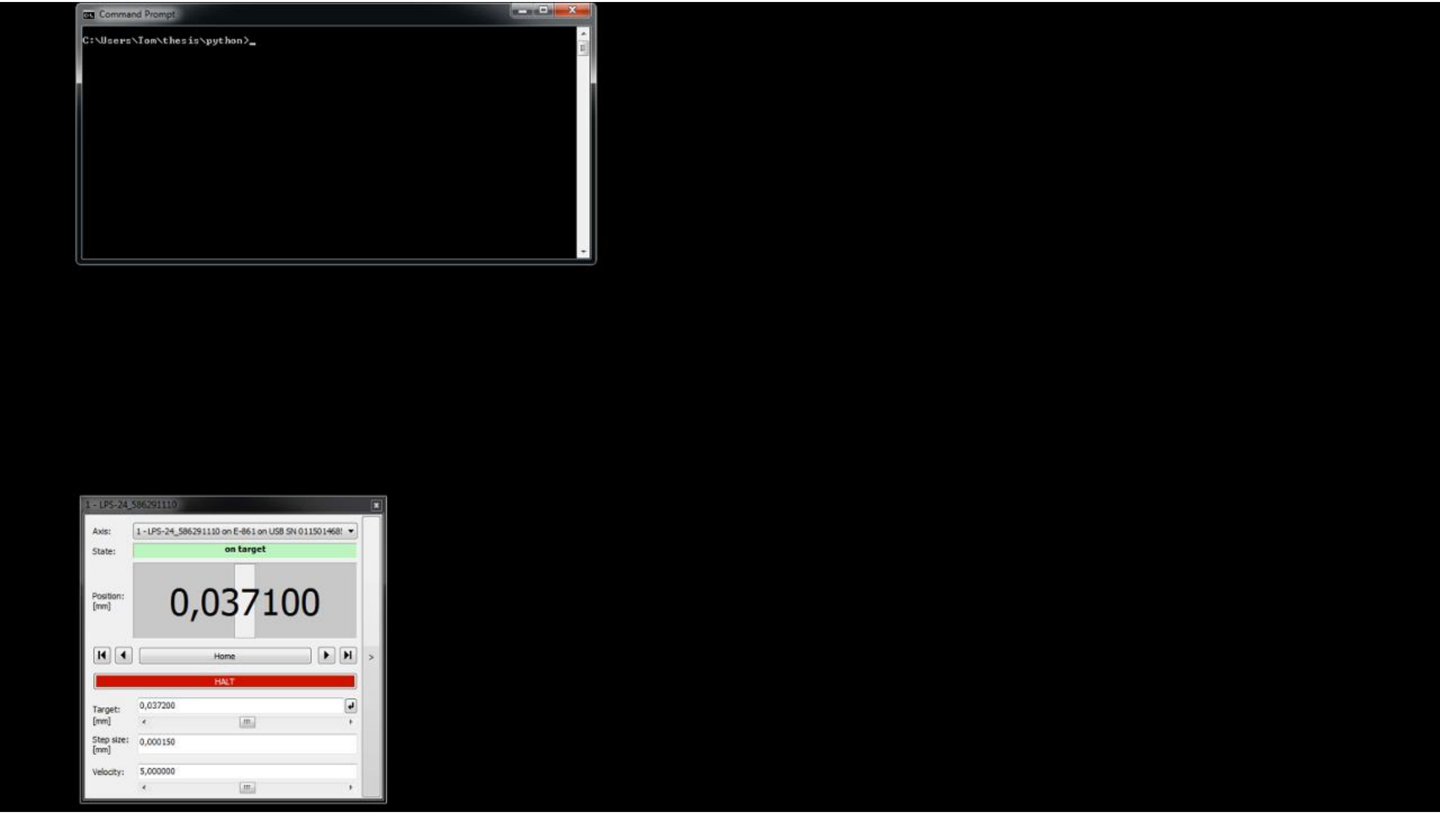
# Control Loop Results: Disturbance Attenuation



# Control Loop Results: Disturbance Attenuation

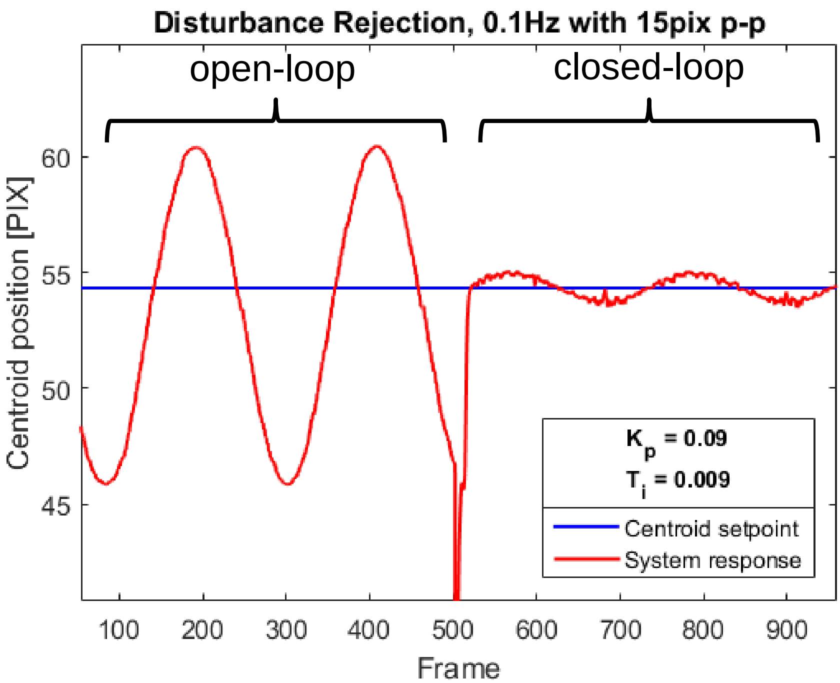



***Figure 37.*** *0,1Hz disturbance with, 15 pixel p-p magnitude, without and with closed loop enabled (20dB attenuation)*

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# Conclusion

# Conclusion

**Well-working piezo-FSM interface on FPGA:**

- Translation from desired cartesian pixel coordinates to mirror actuator values
- Mirror steering resolution well below centroiding error
- Minimal extra centroiding noise

**Universal testbed for active pointing correction:**

- Disturbance injection (X-only) with translating piezo
- Live monitoring and control parameter adjustment
- Analysis of step/frequency response and disturbance rejection of the control loop

# Meanwhile...

PicSAT

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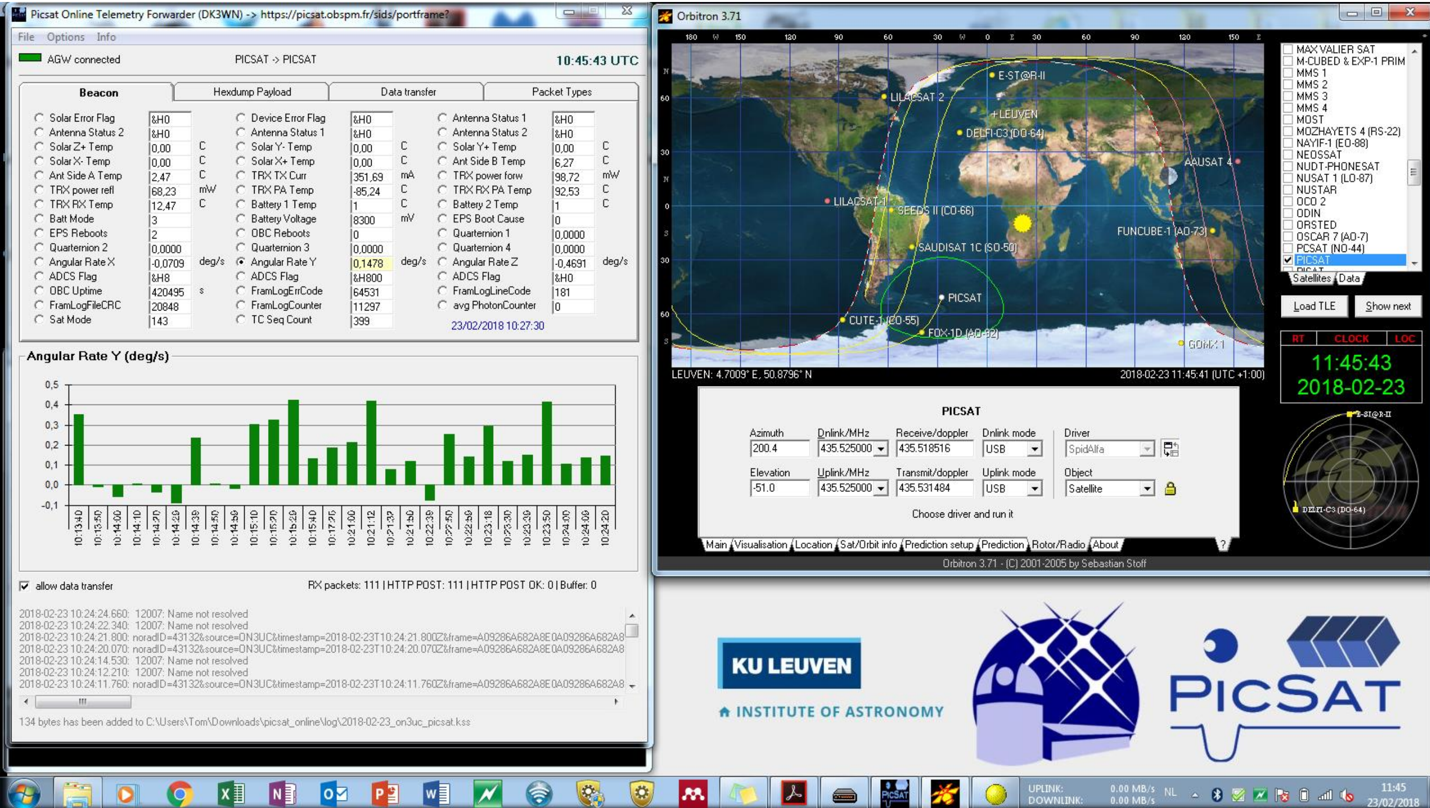
# Meanwhile...



Picsat Online Telemetry Forwarder (DK3WN) -> https://picsat.obspm.fr/sids/portframe?
File Options Info
AGW connected
PICSAT -> PICSAT
10:45:43 UTC
Beacon
Hexdump Payload
Data transfer
Packet Types
Solar Error Flag &H0
Antenna Status 2 &H0
Solar Z+ Temp 0,00 C
Solar X- Temp 0,00 C
Ant Side A Temp 2,47 C
TRX power refl 68,23 mW
TRX RX Temp 12,47 C
Batt Mode 3
EPS Reboots 2
Quarternion 2 0,0000
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FramLogFileCRC 20848
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Solar X+ Temp 0,00 C
TRX TX Curr 351,69 mA
TRX PA Temp -85,24 C
Battery 1 Temp 1 C
Battery Voltage 8300 mV
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Ant Side B Temp 6,27 C
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Angular Rate Y (deg/s)
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2018-02-23 10:24:22.340: 12007: Name not resolved
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LEUVEN: 4.7009° E, 50.8796° N
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PICSAT
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Elevation -51.0
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Uplink/MHz 435.525000
Receive/doppler 435.518516
Transmit/doppler 435.531484
Dnlink mode USB
Uplink mode USB
Driver SpidAlfa
Object Satellite
Choose driver and run it
Main Visualisation Location Sat/Orbit info Prediction setup Prediction Rotor/Radio About
Orbitron 3.71 - (C) 2001-2005 by Sebastian Stoff
Load TLE
Show next
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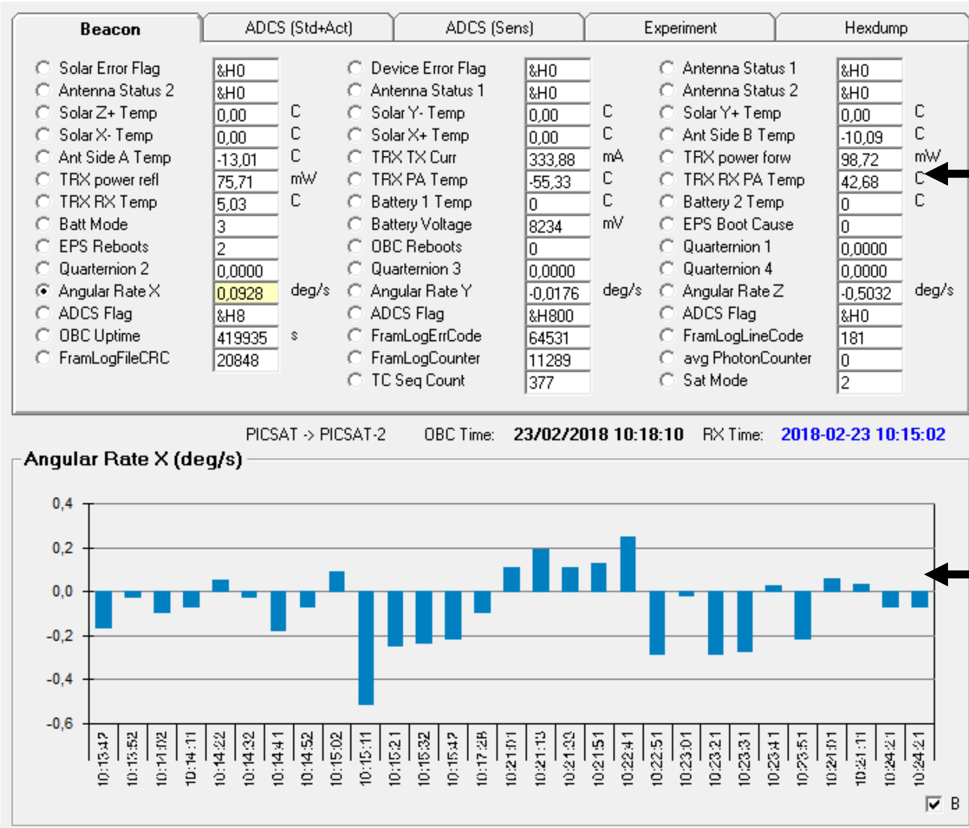
2018-02-23
KU LEUVEN
INSTITUTE OF ASTRONOMY
PICSAT

# Meanwhile...




Telemetry

Angular Rate X

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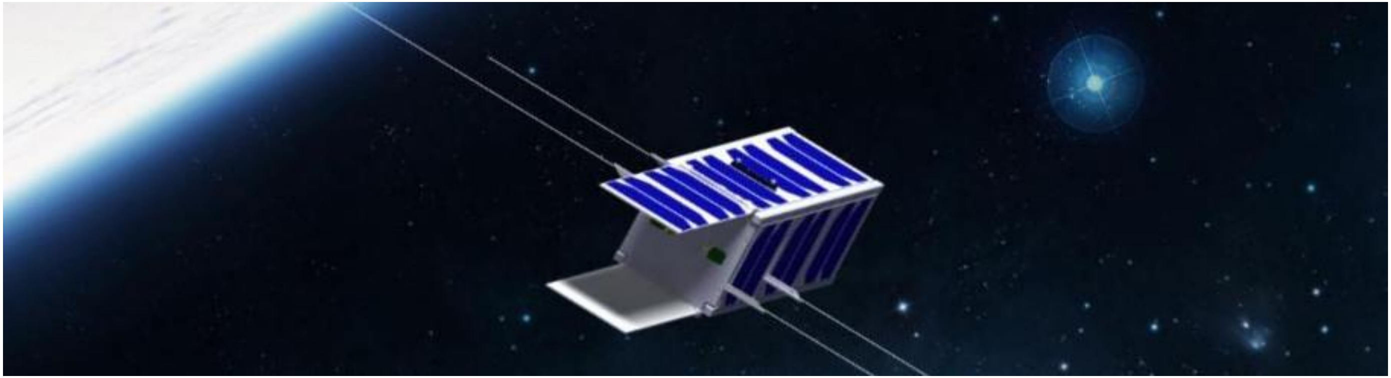
# Meanwhile...



**RIS** April 5th, 2018

*Image credit: LESIA*

# Thank you for your attention!

# References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