H2020 OPTICON (730890)

THEME 2: Modern Production Methodologies (WP4 and WP5)

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UKRI – STFC – UK Astronomy Technology Centre

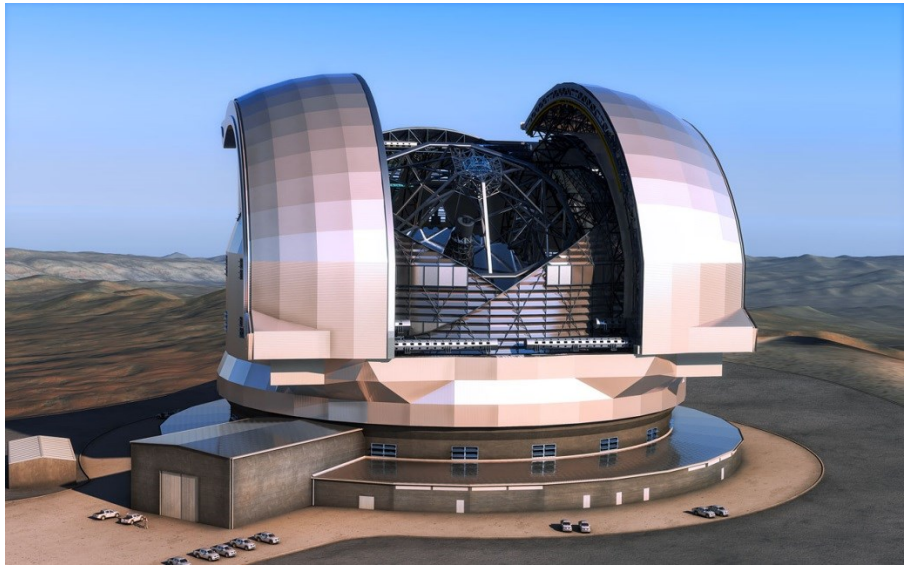
On behalf of WP4 and WP5 consortium

Talk Outline

- Why do we need to modernise our production methodologies
- WP4 – Unlocking the potential of freeform optics for astronomical instrumentation
  - Freeform optics
  - FAME to date
  - FAME+
  - Schedule
  - Summary
- WP5 – Additive Astronomical Integrated-component Manufacturing
  - Objectives
  - Progress to date (WP 5.1 & WP 5.2)
  - Schedule, Milestones and deliverables
  - Impact

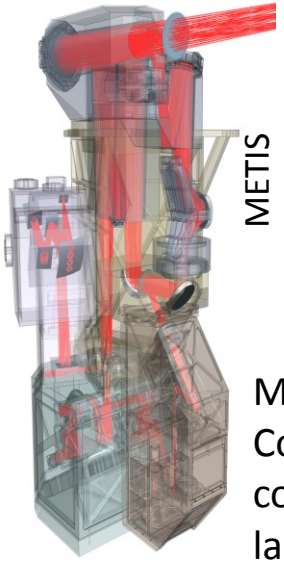
Extremely Large Telescope (ELT) Era

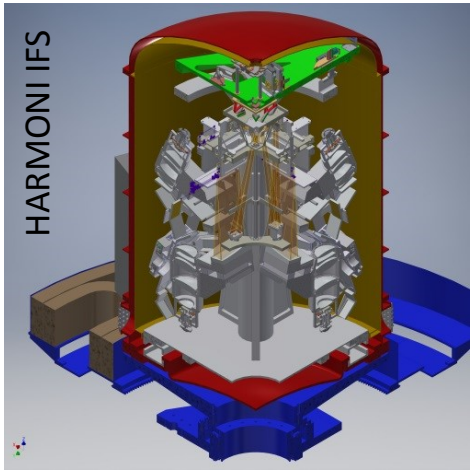
- Instruments scale with the aperture
- Instruments for ELT-class telescopes constitute a leap in
  - The number of optical surfaces
  - The size of their optics
  - The overall size and weight of the instrument
- While instruments grow larger and more complex, the tolerances on WFE become more demanding



HARMONI Integral field spectrograph dimensions:

- Height = 4.25 m
- Diameter = 3.5 m





Mid-IR imager and spectrograph: Cold optics height = 3 metre and consists of ~ 35 optical surfaces with largest mirror 30 cm diameter, 10 nm RMS surface shape requirement .

Modern production Methodologies

- JRA WP 4 and JRA WP5 are complementary research efforts focussed:
  - Complex optical surfaces,
  - Combining functionality within single components
- to reduce size, weight and cost of astronomical components by using
  - Using innovative manufacturing methods.
- Both are designed to raise the Technology Readiness Levels (TRL) of these techniques in readiness to be used in future instruments.
- The key teams and agencies and industries initially likely to benefit from these advances.
- Teams are also working closely with industry to leverage existing expertise and
- Assist in the transfer knowledge

FAME+

Unlocking the potential of freeform optics for astronomical instrumentation

Team

NOVA: Michiel Rodenhuis (lead),

ATC: Hermine Schnetler, Chris Miller, David Montgomery, Katherine Morris, Wayne Holland

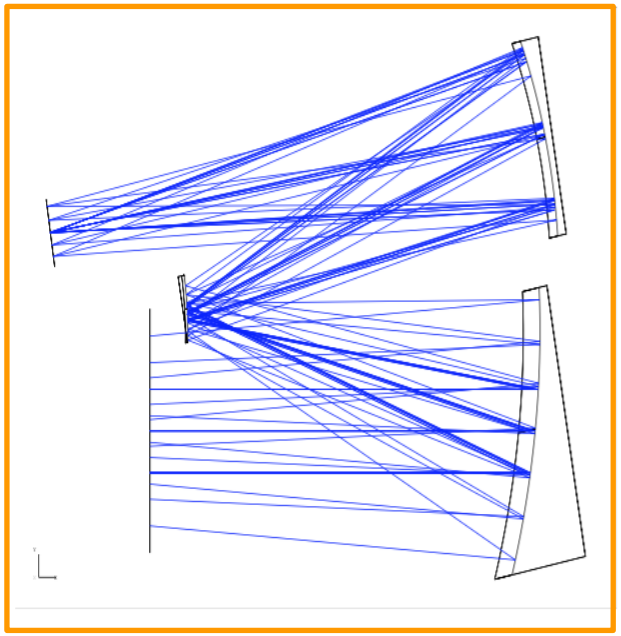
LAM: Emmanuel Hugo

Konkoly: Szigfrid FARKAS, Dávid JÁGER, György MEZŐ

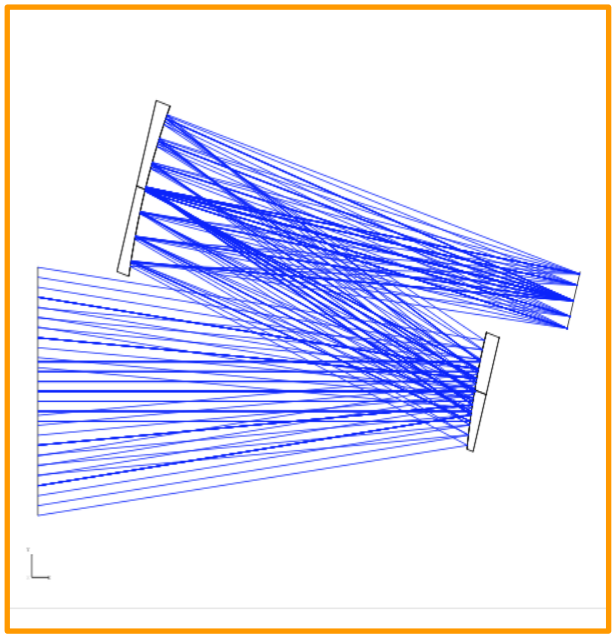
fame

Free-form optics (1)

- Allow optical designs that are compact, have fewer surfaces and offer better performance



Three-mirror anastigmat



Alternative with two mirrors, one freeform

Free-form optics (2)

- Allow optical designs that are compact, have fewer surfaces and offer better performance

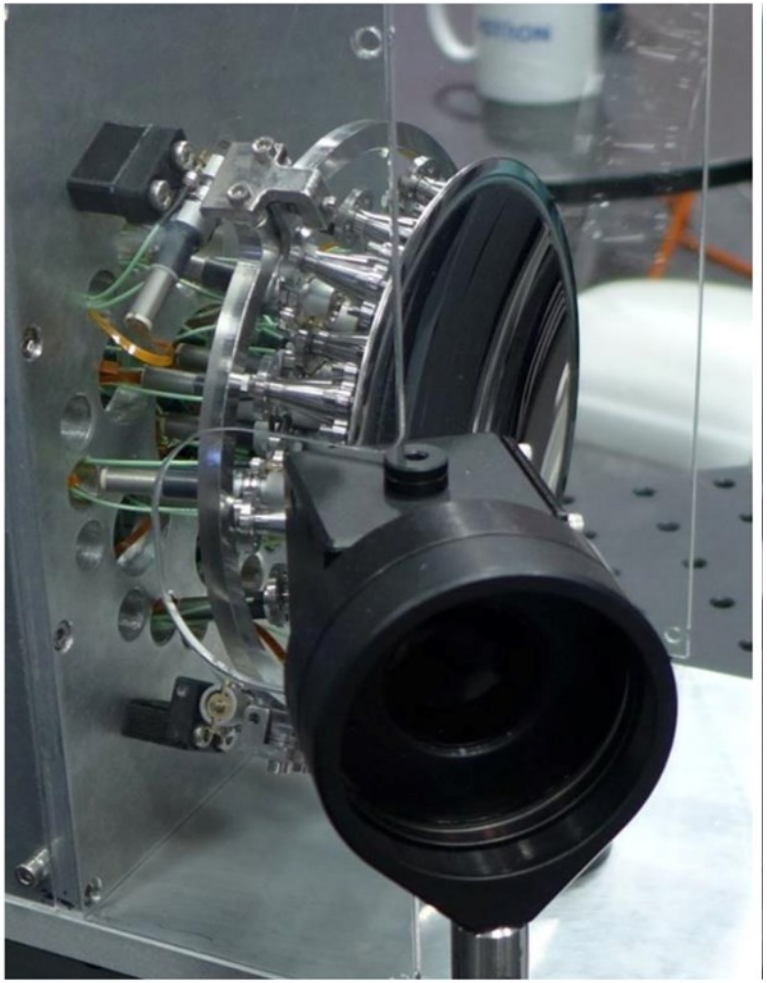
However:

- It is very difficult to manufacture Freeform Optics and
- It is also difficult to align components

This is where the Freeform Active Mirror Experiment (FAME) comes in

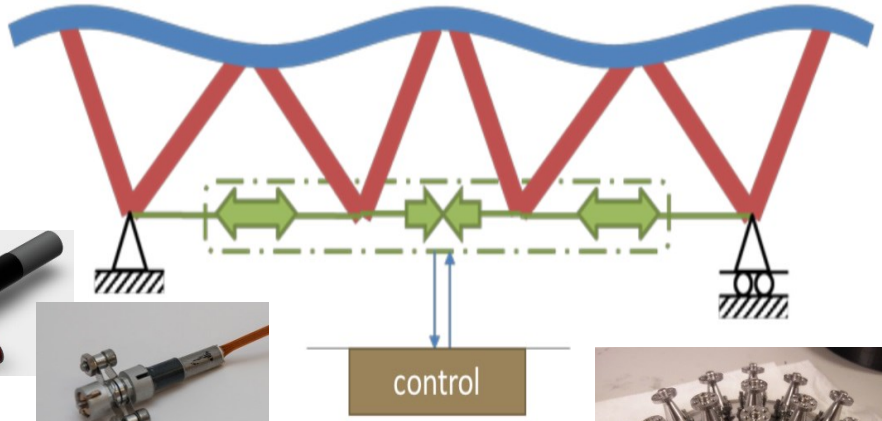
FAME+: Continuing the FP7 FAME project

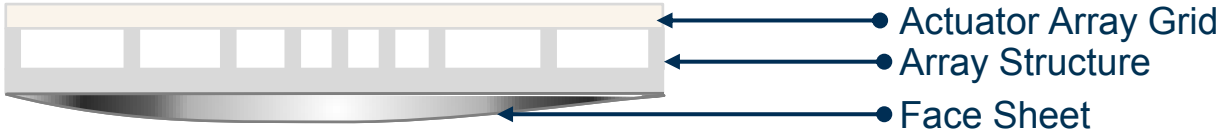
- Same consortium
- At the end of the original FAME project:
  - Mirror was assembled
  - Demonstrator setup was built
  - Mirror was not yet tested
- Scope of FAME+
  - Test & characterize the FAME mirror
  - Improve design tools
  - Develop 2nd generation design, cryogenic
  - Develop metrology & control system
  - Demonstrate existing mirror with metrology & control system



FAME: The freeform active mirrors experiment

- Concept: a freeform mirror that can be actively controlled to correct manufacturing & alignment errors
- Consisting of
  - Face sheet (blue)
  - Active array (red)
  - Actuators (green)
  - Control system
- Inherently stable: ”Set and forget”

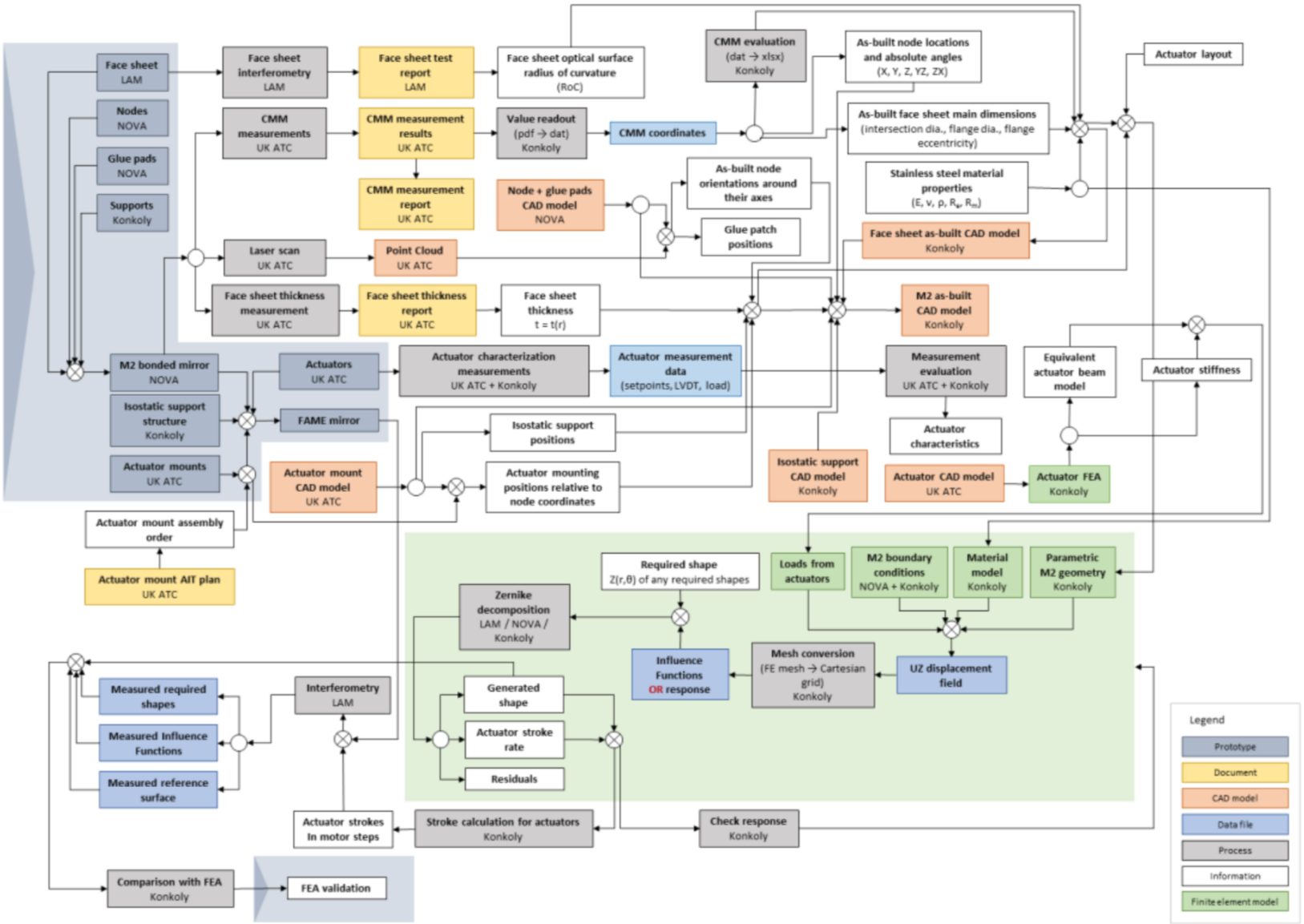




FAME mirror characterization

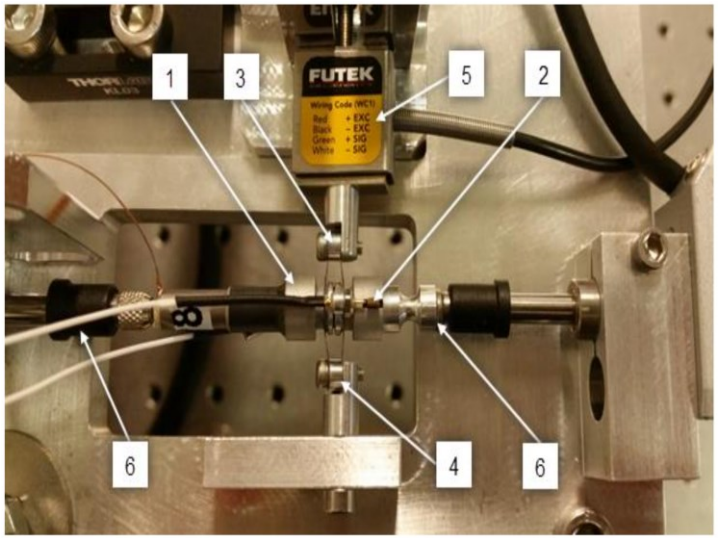
- Needed to predict performance from design, also for 2nd generation mirrors
- Improve finite element design models
- Issues
  - Large effect of deviations of as-built mirror from design
  - Variation between actuators significant due to manufacturing and assembly processes
- Extensive test and measurement campaign was undertaken
- More effort than anticipated

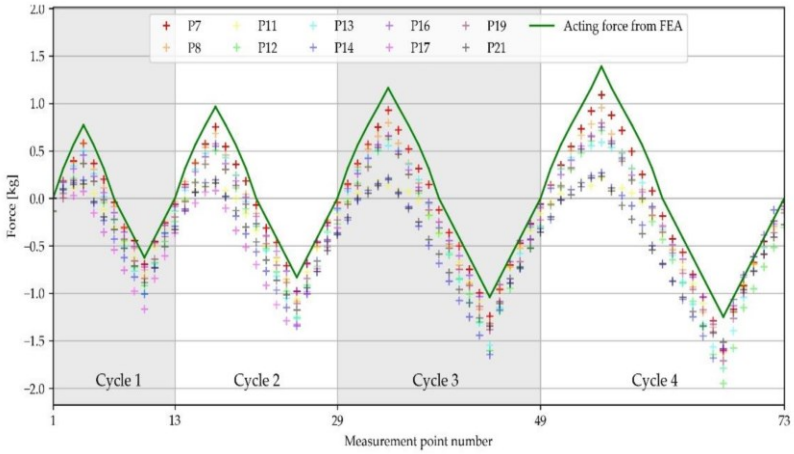
Process Flow Diagram



Actuator characterization

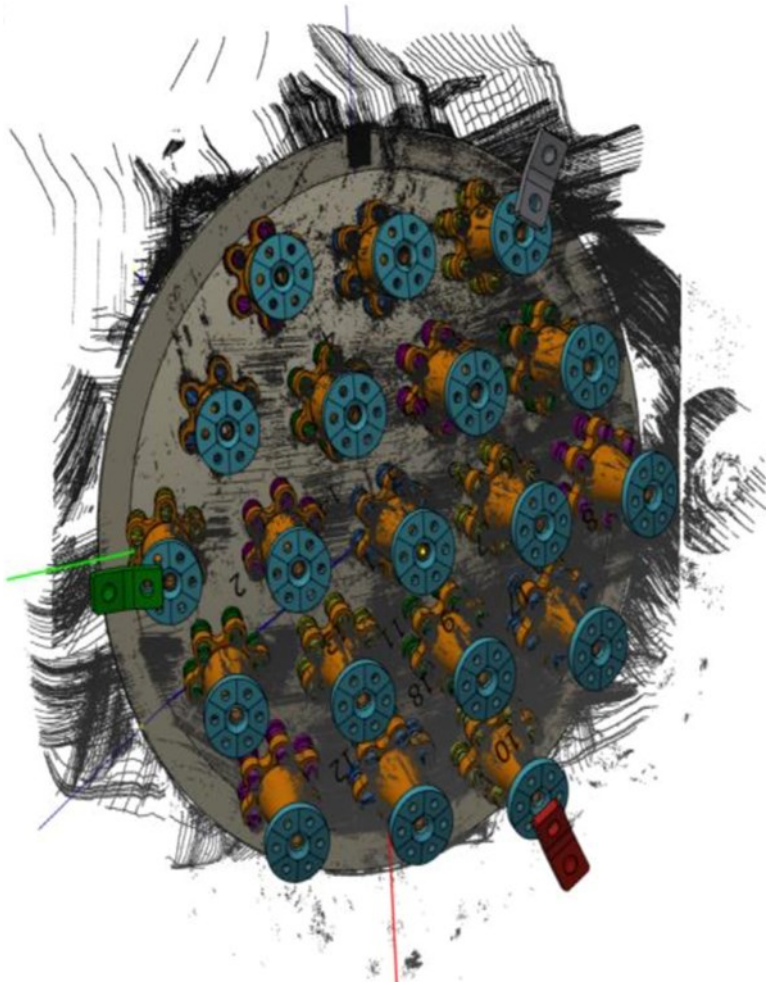
- Precise measurement of force vs. translation profile
- Dedicated test setup and automated test procedures developed
- 18 actuators tested
- Each individual actuator behave repeatable
- Variation between actuators significant





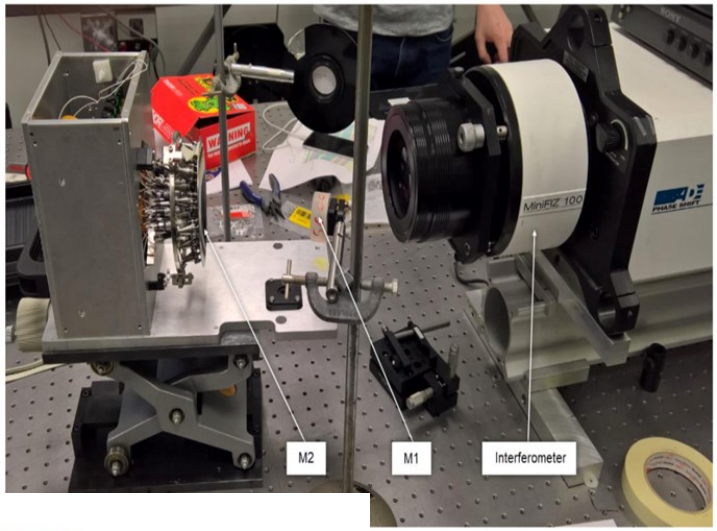
As-built FEM model

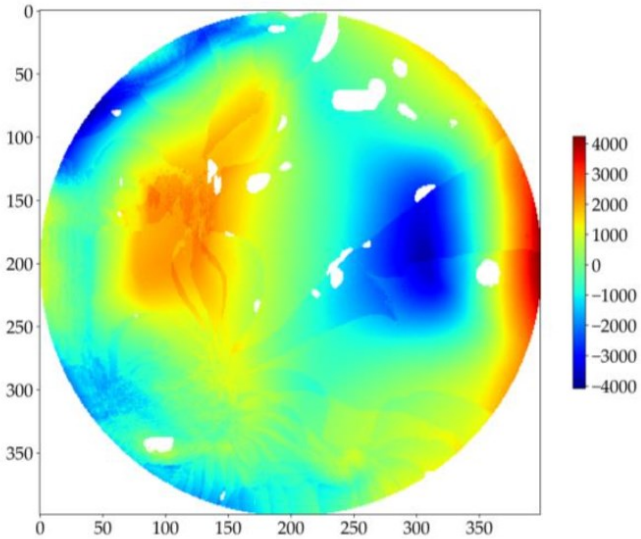
- Exact position of nodes critical for accurate modelling of mirror behavior
- Small deviations in position, despite custom alignment tool
- FEM model updated based on extensive CMM & laser scanner measurements



Interferometric characterization measurements

- Sequence:
  - Mirror shape measured without actuators
  - One actuator mounted, deviations measured
  - All actuators mounted, influence functions measured
  - measured
  - Mirror deformed to predefined shape





FAME 2nd generation design: actuators

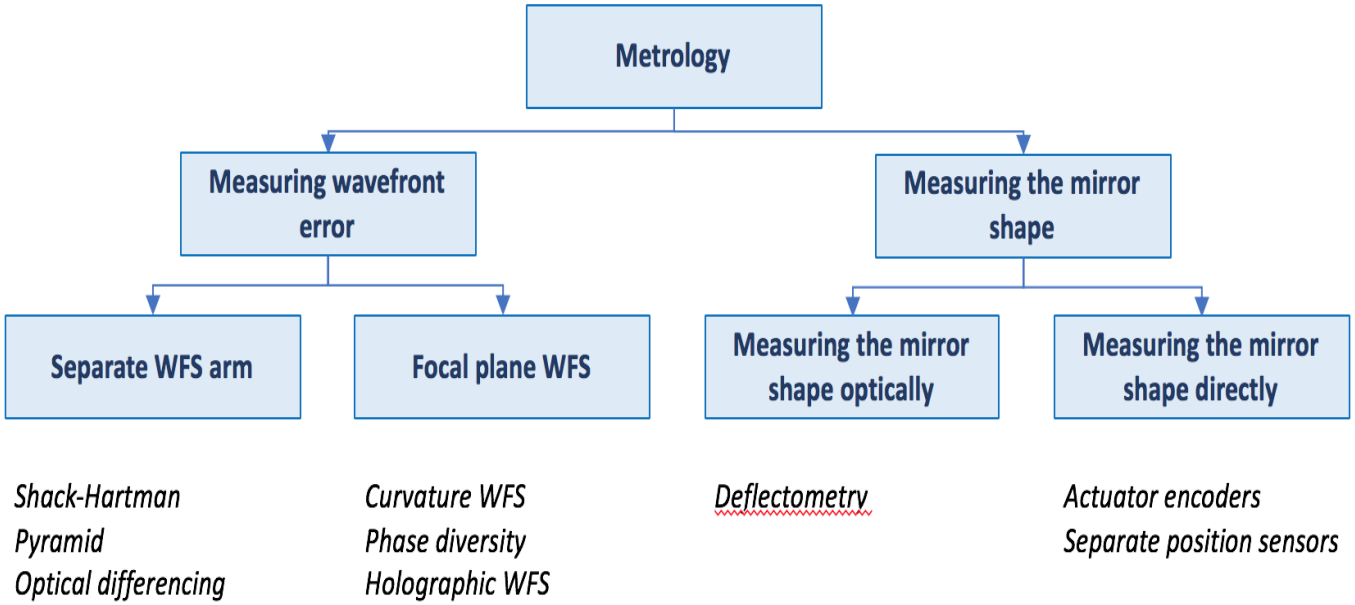
- Performance of single actuator repeatable
- Variation between actuators significant
- Actuator consists of many small parts
- Flexures manufactured using wire-EDM, thereafter each flexure need to be formed – it is very difficult even when using a special made jig - to get each flexure identical
- Developing improved actuator using flexure made as single structure
- Actuators should work in a cryogenic environment

FAME 2nd generation design: Face sheet and active layer

- First generation:
  - using hydroforming to manufacture the mirror face sheet introduced stresses and local in homogeneities
  - gluing nodes onto the back of the face sheet resulted in through print and resulted in an interface that is not well understood and introduced unwanted effects
- FAME+:
  - Developing a design where the face sheet and active layer can be manufactured as a single component
- Excellent case for OPTICON A^2IM WP
- Joint design workshop scheduled for November 2018

Metrology

- Not just a single solution but a methodology
- Aim to provide optimal solution based on use case
- Applicable to other active mirrors

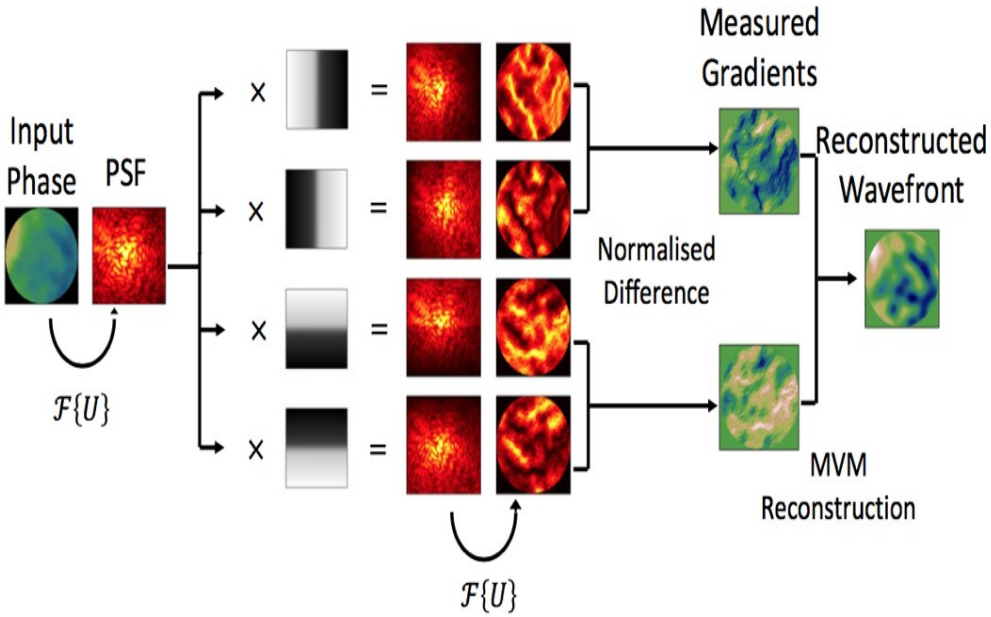


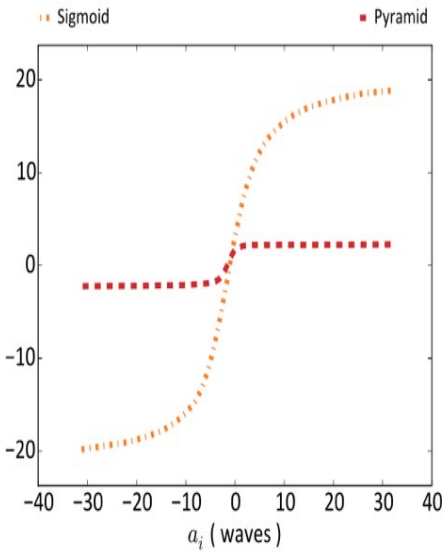
Metrology: Particularities of FAME-type active mirrors

- Initial shape deviations may be large
- Required precise shape control to match the as "as-designed" shape
- Requires high dynamic range and precise accuracy measurement metrology with a slow update rate (minutes – hours)
- Iterative approach allowed
- Emphasis on the mid-spatial frequencies

Example metrology option: Generalised optical differencing

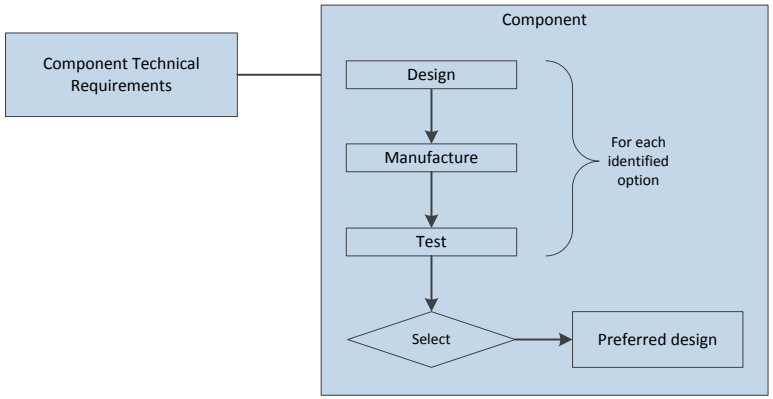
- Principle similar to pyramid WFS, but with tunable, non-linear response

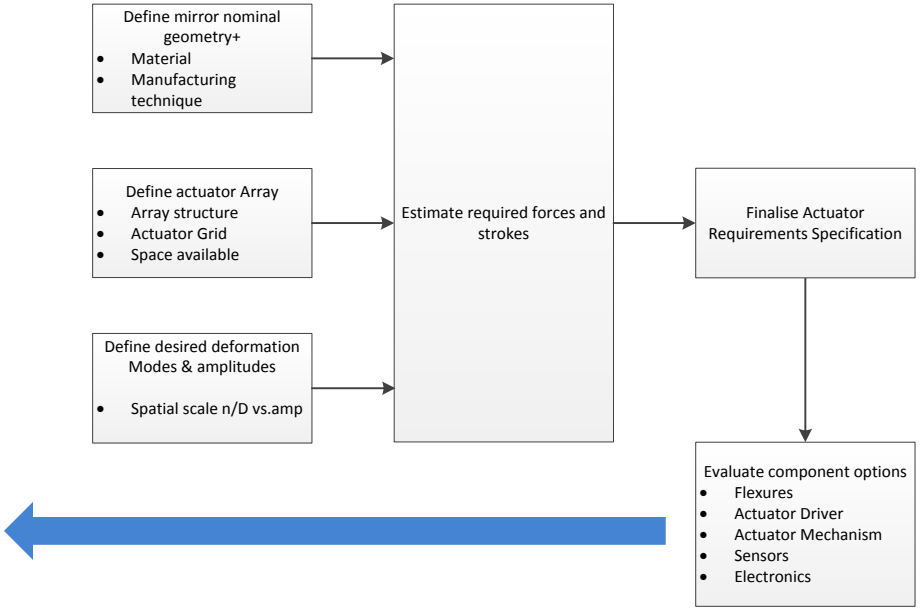


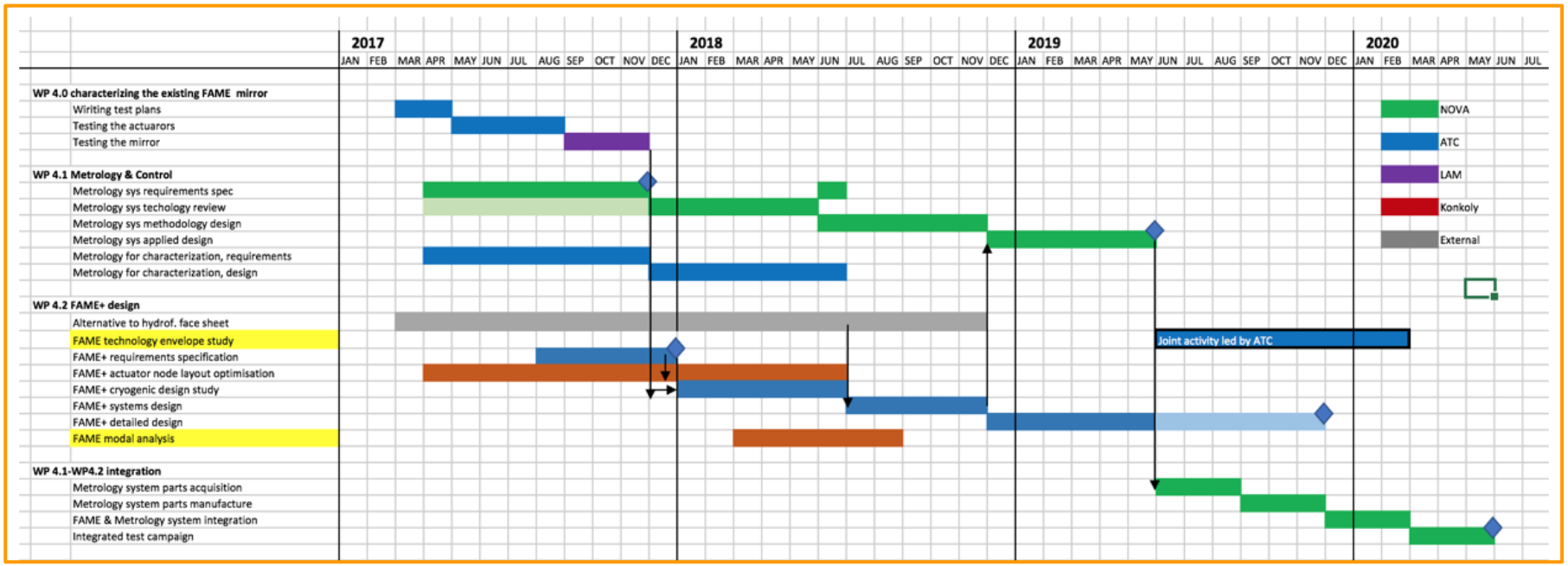


Courtesy: S. Y. Haffert, Leiden Observatory

FAME+ planning







Summary

- FAME+ developing active free-form mirror technology for next generation of astronomical instruments.
- Has potential to reduce complexity and thus size and weight at similar or better performance.
- Less components could also have a cost advantage.
- Aim to realize a simple and robust system.
- Active but stable mirror could allow the correcting of the wavefront error (WFE) of other instrument components.
- Could possibly correct drift in performance (due to environment affects) by active control.
- Qualified design concept ready by mid-2020.

Additive Astronomy Integrated-component Manufacturing (A^2IM)

<u>Team</u>

ATC: Hermine Schnetler (lead), Chris Miller, David Montgomery, Katherine Morris, Wayne Holland

AIP: Roger Haynes

LAM: Emmanuel Hugo, Melanie Roulet

Konkoly: Szigfrid FARKAS, Dávid JÁGER, György MEZŐ

NOVA:

A²IM

Exploiting additive manufacturing

Reduction / redistribution

Mass

Structural

Stiffer, stronger, lighter, more shapes

Thermal Control

Higher resistance to thermal shock / variation

Cost

Lower life-cycle costs – from design to end of life

Complexity

Reduction of seams, welds and joins

A solution ready for a problem!

AM in astronomy – the motivation

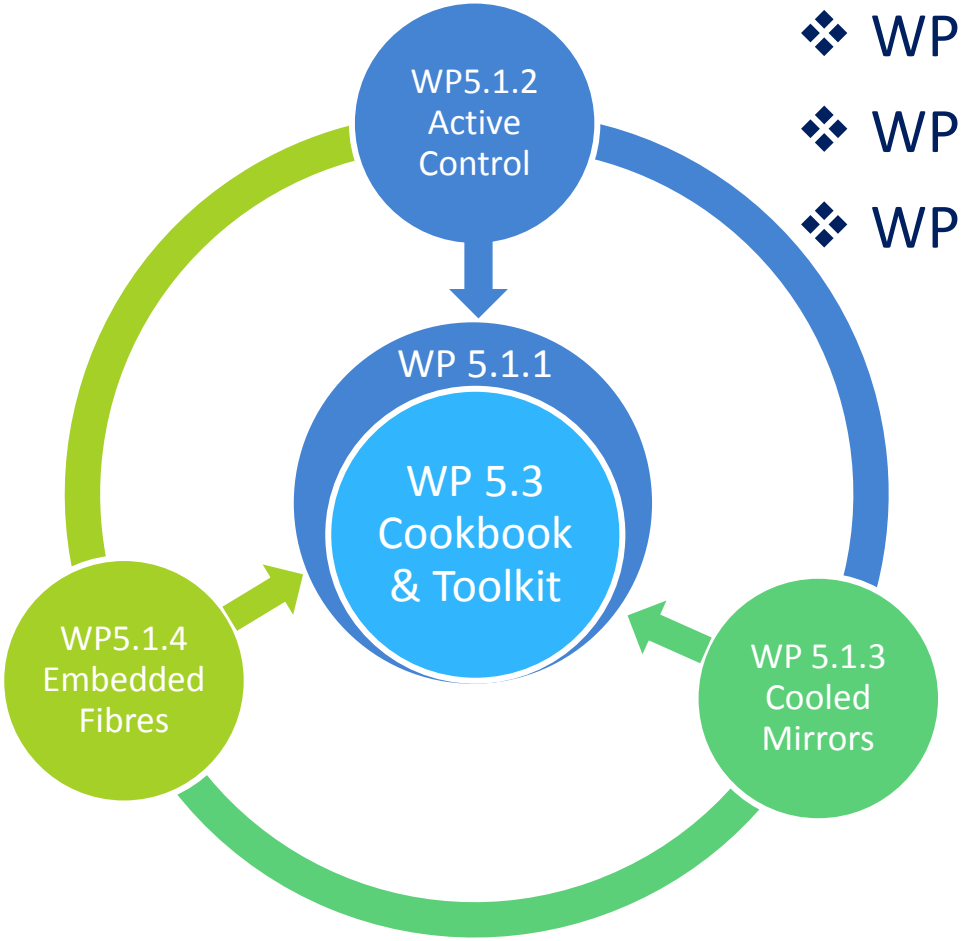
- Not used much so far (instruments tend to be “one-offs”, little time for prototyping, etc…)
- Operation in extreme environments (high vacuum, cryogenic temperatures, space, etc…)
- Component parts need to be reliable and made to last a long time (deep space missions)
- Pressure to have cost savings (design, production and running costs – often no time for R&D – pressure to deliver)

Objectives for A^2IM

- Investigate the use of AM components for astronomy instruments (materials, manufacture techniques and post processing)
- Develop 3-D printable test samples and evaluate (surface quality, stiffness, porosity, outgassing, CTE, etc…)
- Down select and prototype an integrated components that can be used in an actual instrument
- Develop a cookbook and toolkit (best practices)

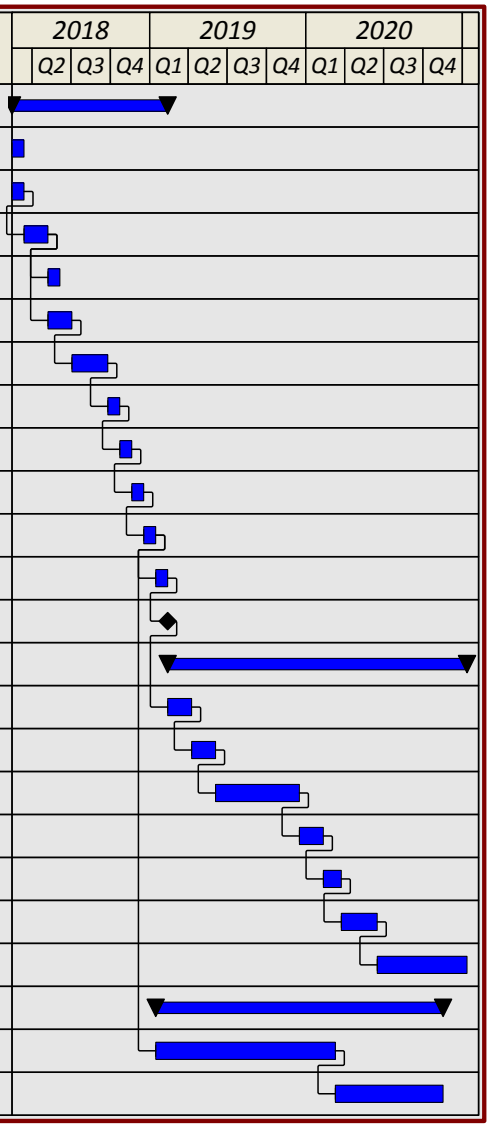
WP 5.1 - Material investigation

- WP5.1.1 Material characterisation (Sheffield University)
- WP5.1.2 Active Control (STFC)
- WP5.1.3 Cooled mirrors (IAC)
- WP5.1.4 Embedded fibres (AIP)

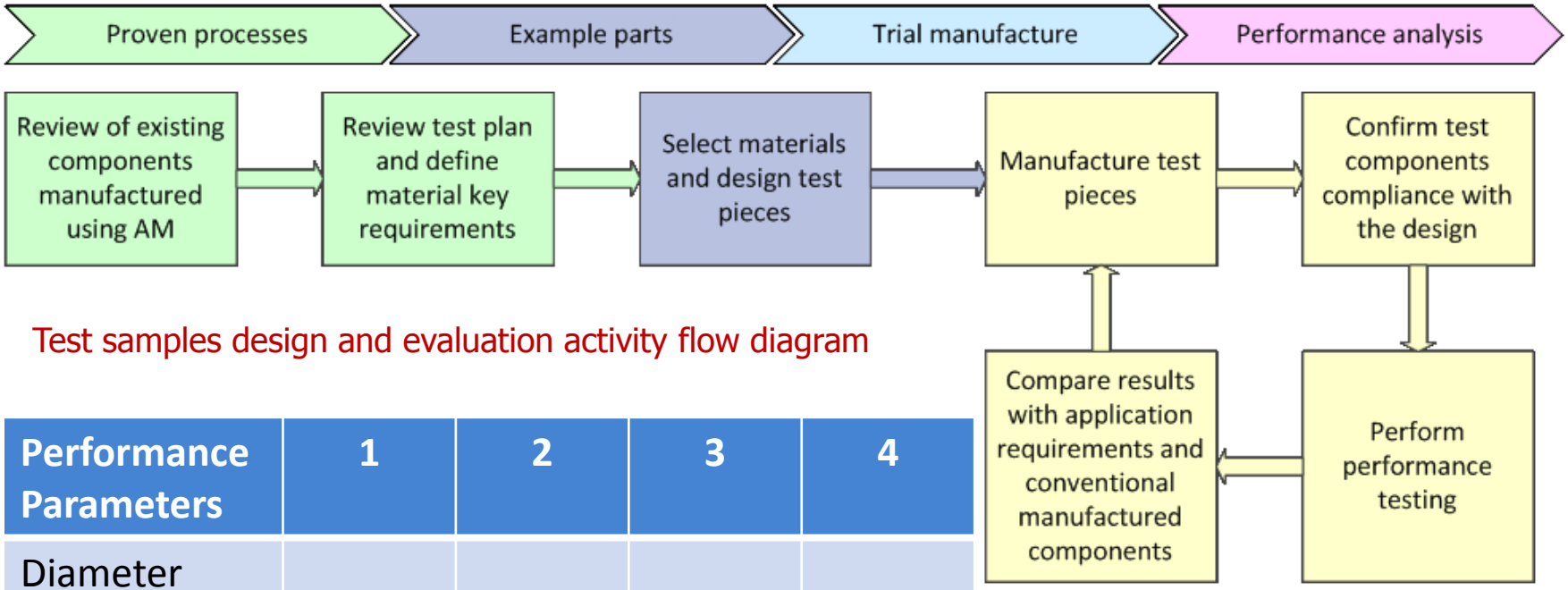


Programme of work and milestones

ID	Task Name	Start	Finish	Duration
1	**WP 5.1 Investigating additive materials for cryogenic use**	**13/02/2018**	**12/02/2019**	**52w**
2	Select and procure material samples	13/02/2018	12/03/2018	4w
3	Investigate integrated component manufacturing techniques	13/02/2018	12/03/2018	4w
4	Design test samples	13/03/2018	07/05/2018	8w
5	Prepare test plan	08/05/2018	04/06/2018	4w
6	Manufacture test samples	08/05/2018	02/07/2018	8w
7	Characterise material samples	03/07/2018	24/09/2018	12w
8	Prepare Additive Manufacturing Report (D5.1)	25/09/2018	22/10/2018	4w
9	Prepare Test Sample Characterisation Report (D5.2)	23/10/2018	19/11/2018	4w
10	Internal Review	20/11/2018	17/12/2018	4w
11	Update reports (D5.1 and D5.2)	18/12/2018	14/01/2019	4w
12	External review	15/01/2019	11/02/2019	4w
13	Milestone 13: Additive Materials Review	12/02/2019	12/02/2019	0w
14	**WP 5.2 Prototyping Astronomy Integrated Components**	**12/02/2019**	**11/01/2021**	**100w**
15	Identify two prototypes and develop concept designs	12/02/2019	08/04/2019	8w
16	Develop the integrated component requirements	09/04/2019	03/06/2019	8w
17	Perform detailed integrated component design	04/06/2019	16/12/2019	28w
18	Prepare integrated component design report (D5.3)	17/12/2019	10/02/2020	8w
19	Milestone 14: Review Design(s)	11/02/2020	23/03/2020	6w
20	Manufacture component(s)	24/03/2020	15/06/2020	12w
21	Characterise components in accordance with the test plan	16/06/2020	11/01/2021	30w
22	**WP 5.3 Additive manufacturing cookbook and toolkit**	**15/01/2019**	**16/11/2020**	**96w**
23	Define material selection guidelines and design rules	15/01/2019	09/03/2020	60w
24	Develop Additive Manufacturing Best Practice Guideline (D5.4)	10/03/2020	16/11/2020	36w



Work Package Life-cycle

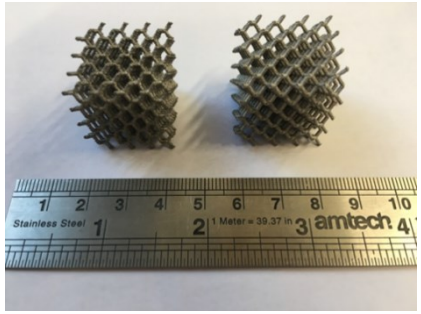


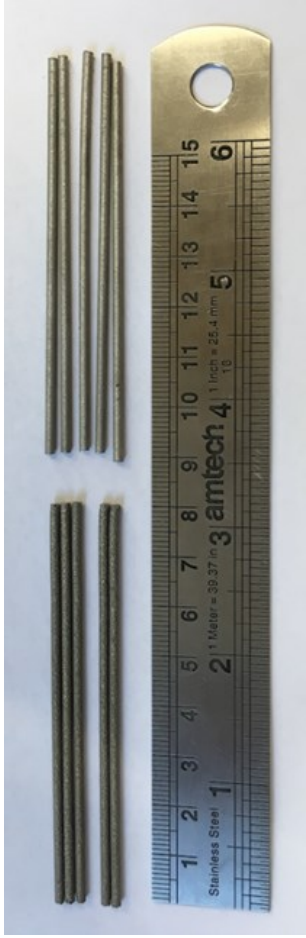
Test samples design and evaluation activity flow diagram

Performance Parameters	1	2	3	4
Diameter				
Thickness				
Post processing				

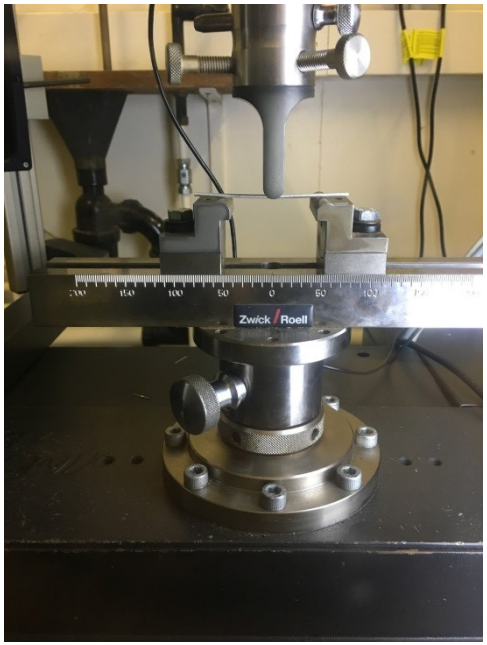
WP 5.1.1 Material characterisation

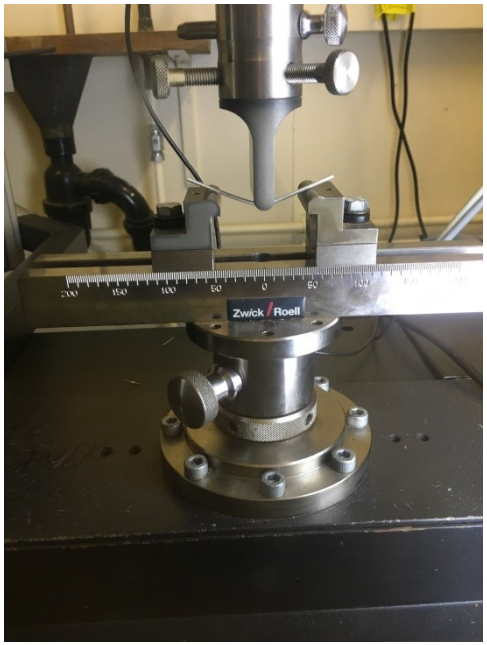
- Objectives: To formulate a database of materials and manufacturing methods and use AM to produce test structures relevant to our designs
- Status:
  - Metals tested - SS316, Ti64 and Al
  - Metals still to be tested - Inconel IN718
  - Under test - Al_2O_3, SiC, SiSiC, ZrO_2 and B_4C
  - Polymers to be identified and tested
    - Tusk XC, Proto G,
    - Taurus (ABS like)
    - Extreme (High Impact)
  - SLS polymer technology:
    - Alumide (Blend aluminum powder and Polyamid powder)
    - PA 12
    - PA-GF Glass filled PA
    - TPU 92A – 1 (rubbery like material)
    - PA 2241 FR

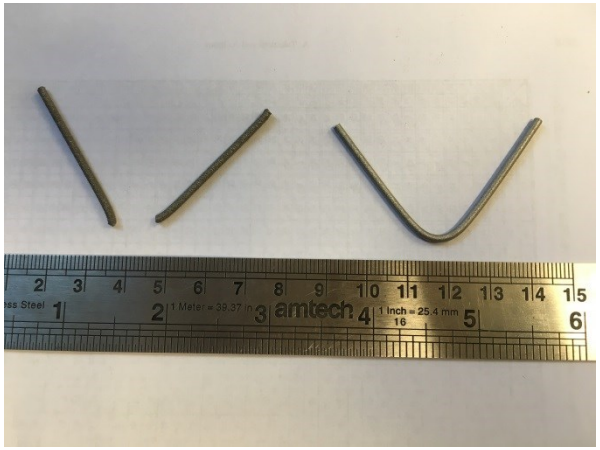




Bending tests (Ti and Stainless Steel)

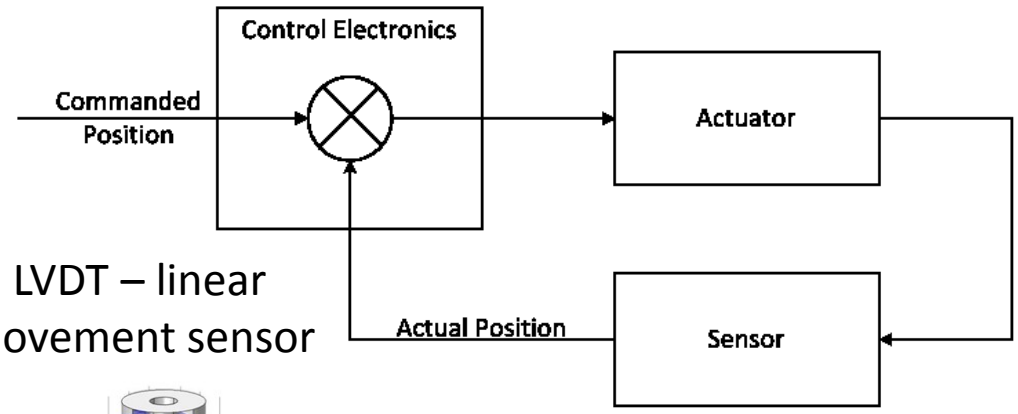




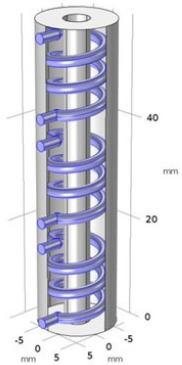


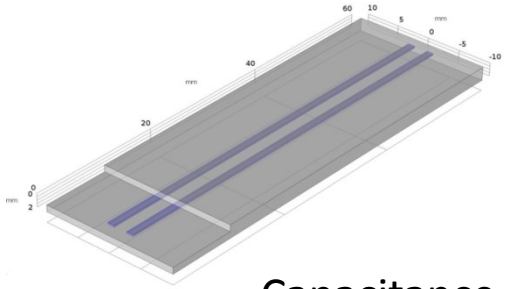
WP 5.1.2 Active control

- Objectives: To identify actuation components that would benefit from AM and test samples
- Status:

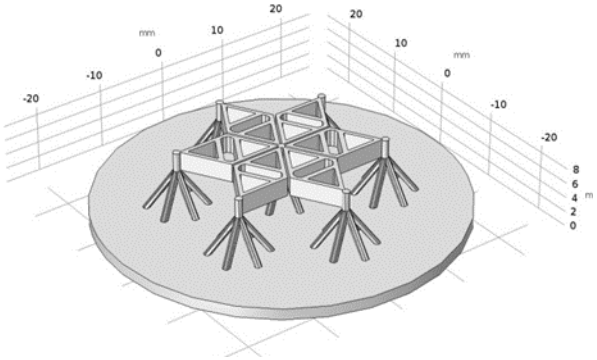


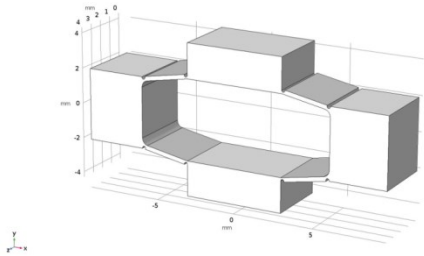
LVDT – linear movement sensor

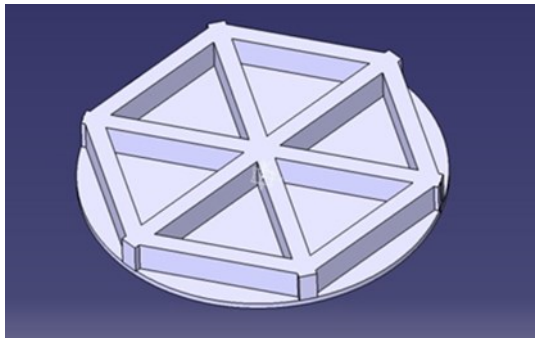




Capacitance concept

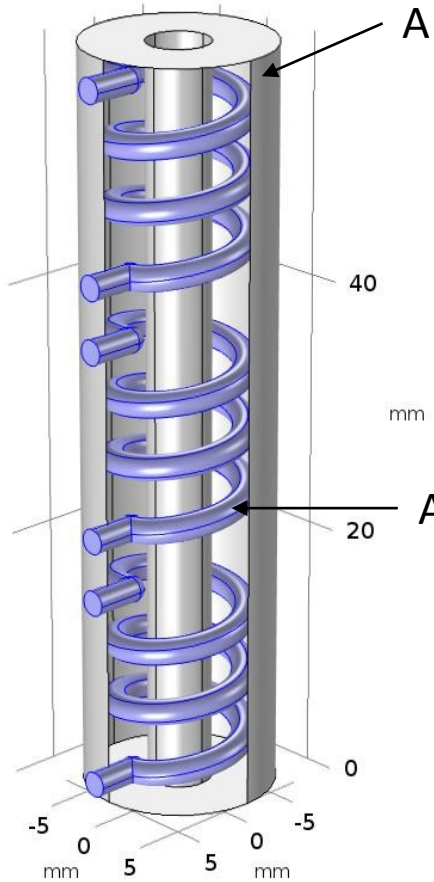






LVDT concept

Sample ID	LVDT001
Why?	The ability to print a better, customisable and job specific LVDTs.
Key feature?	Printing the two materials in one piece
Material?	Plastics and conductive

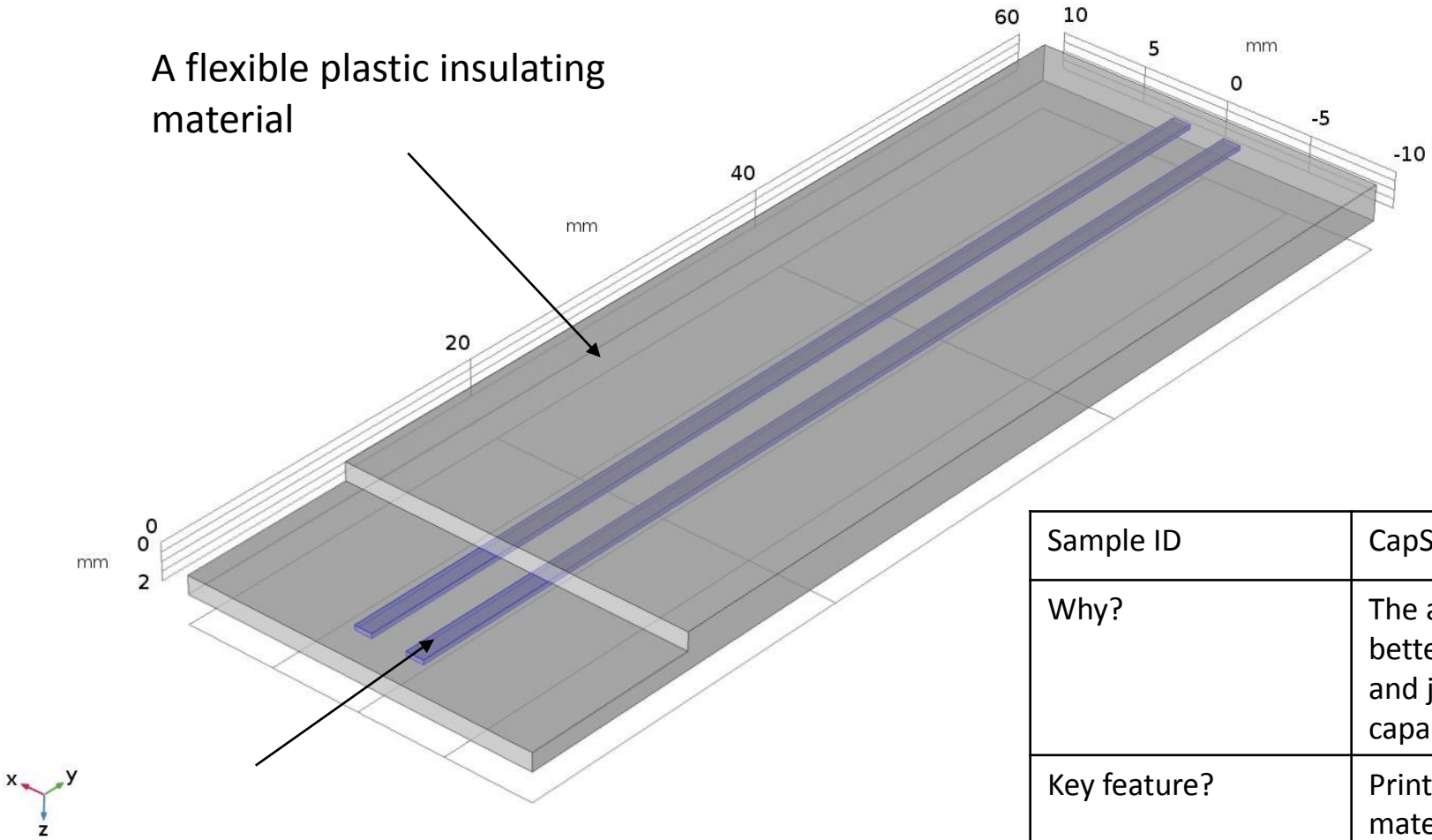


A plastic insulating material

Any conductive material

Capacitance sensor concept

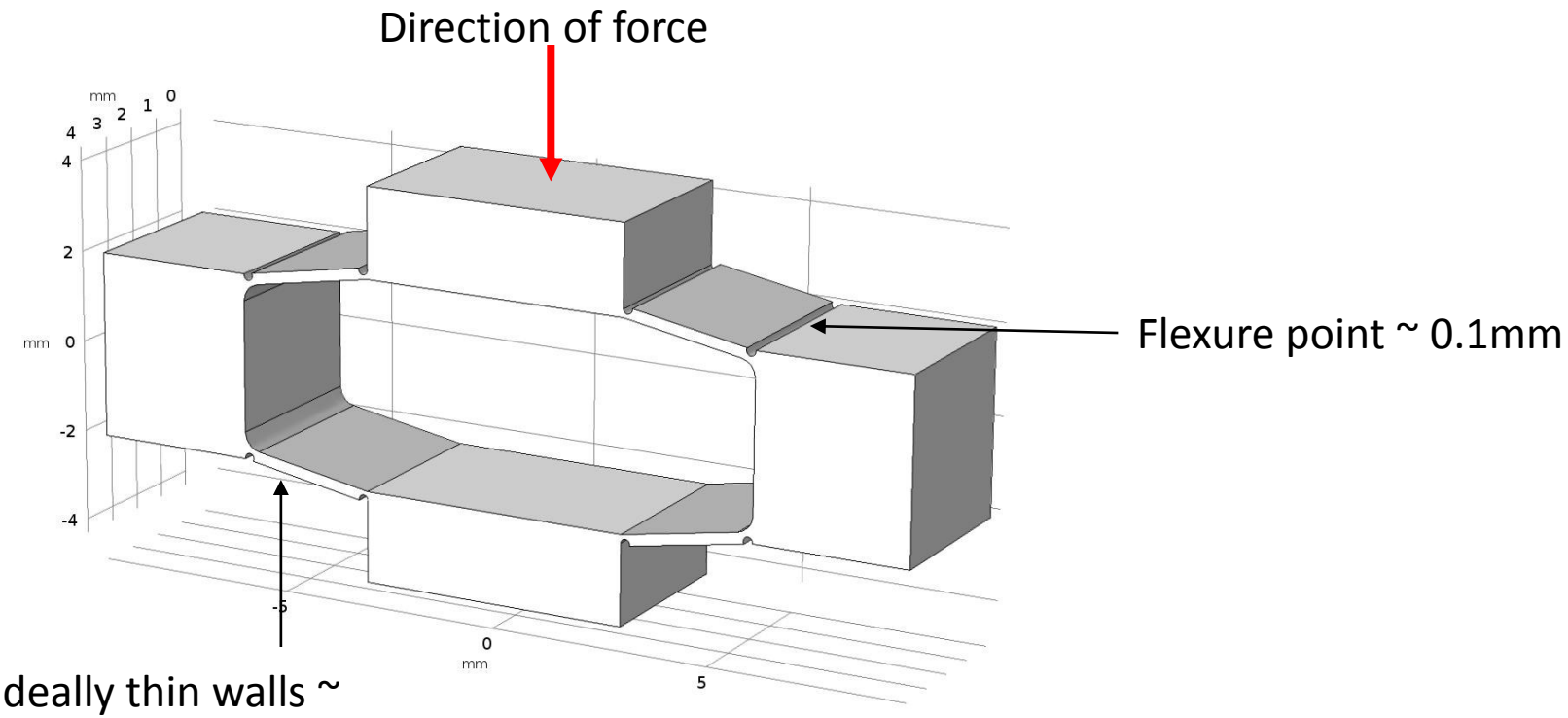
A flexible plastic insulating material



Any conductive material

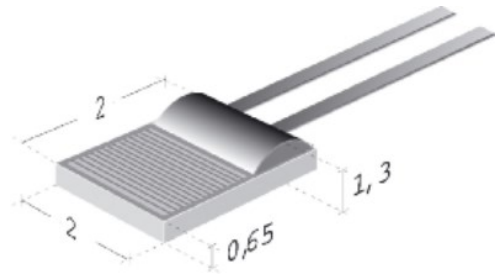
Sample ID	CapSen001
Why?	The ability to print a better, customisable and job specific capacitance sensors
Key feature?	Printing the two materials in one piece
Material?	Plastics: insulator (flexible) + conductive

Flexure



Sample ID	Flexure001
Why?	The ability to print a functional flexure in one piece without substantial machining.
Key feature?	Narrow walls, high aspect ratios
Material?	Metal: stainless steel, titanium

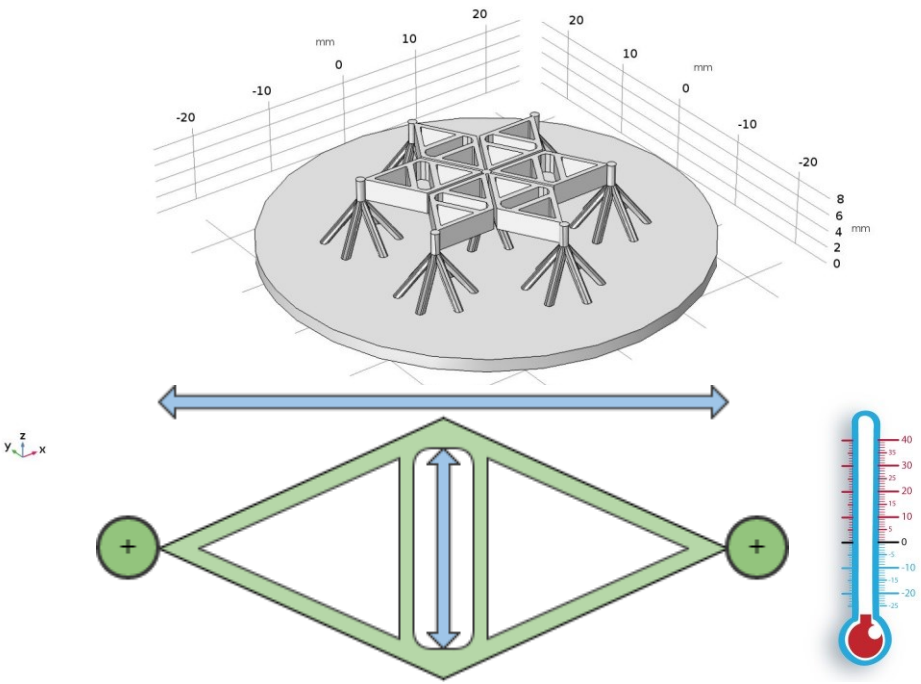
Integrated Active array



Sample ID	ActMir001
Why?	The ability to print the existing mirror structure in one material
Key feature?	Narrow walls in the actuator design
Material?	Metal: stainless steel, titanium, aluminium

A Restive Temperature Device (RTD) can be used to control the temperature in closed loop. The RTD is a resistor who's resistance changes with temperature and can therefore be used as the both the "heater" and the "sensor" for the actuator. ***Platinum, Nickel, and Copper*** metals are typically used measure positive temperature coefficients (PTC).

$$R_T = R_0\left[1+\alpha_1 T+\alpha_2 T^2+\cdots\alpha_n T^n+\right] \cong R_0\left[1+\alpha_1 T\right]$$



A high thermal expansion material is placed in the centre of a diamond structure.
As the material expands and contracts due to temperature it puts a perpendicular force on the attached nodes.
Using this technique it is possible to generate high forces from a miniature actuator.

Own manufactured Resistance Temperature Devices (RTDs)

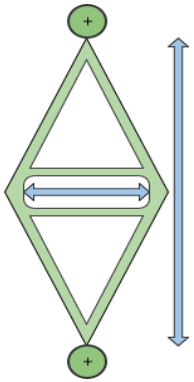
Metal	Resistivity [ohm/cmf]
Gold	13
Silver	8.8
Copper	9.26
Platinum	59
Tungsten	30
Nickel	36

The most common RTDs are made of either platinum, nickel, or nickel alloys. The economical nickel derivative wires are used over a limited temperature range. They are quite non-linear and tend to drift with time. For measurement integrity, platinum is the obvious and most common choice.

- A positive temperature coefficient (PTC) refers to materials that experience an increase in electrical resistance when their temperature is raised. Materials which have useful engineering applications usually show a relatively rapid increase with temperature, i.e. a higher coefficient. The higher the coefficient, the greater an increase in electrical resistance for a given temperature increase.
- Metals - All metals produce a positive change in resistance for a positive change in temperature. This, of course, is the main function of an RTD. As we shall soon see, system error is minimized when the nominal value of the RTD resistance is large. This implies a metal wire with a high resistivity. The lower the resistivity of the metal, the more material we will have to use

ABS mirror using a own developed and AM manufactured piezo actuator

A piezo actuator can be printed in the centre of a diamond structure using soft piezoelectric materials which is ideal for ***Piezo Actuators and Sensors.***

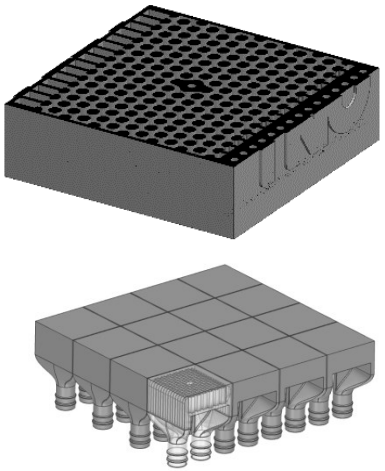


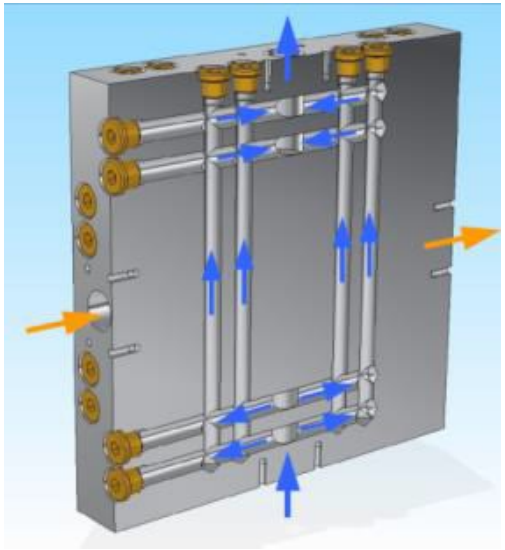
Ferro-electrically soft piezo ceramic materials can be polarized fairly easily even at relatively low field strengths. This is due to the comparably high domain mobility typical for them. The advantages of soft PZT materials are their large piezoelectric charge coefficient, moderate permittivities and high coupling factors.

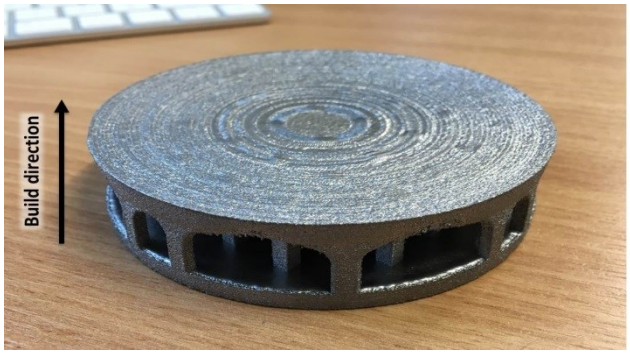
PIC151	Standard material for actuators of the PICA Stack/Thru and Piezo Tubes series
Material	Modified lead zirconate titanate
Characteristics	High permittivity, large coupling factor, high piezoelectric charge coefficient, relatively high Curie temperature
Suitable for	***Actuators***, low-power ultrasonic transducers, low-frequency sound transducers
Classification in accordance with EN 50324-1	600
MIL-Standard DOD-STD-1376A	II

WP5.1.3 Cooled mirrors

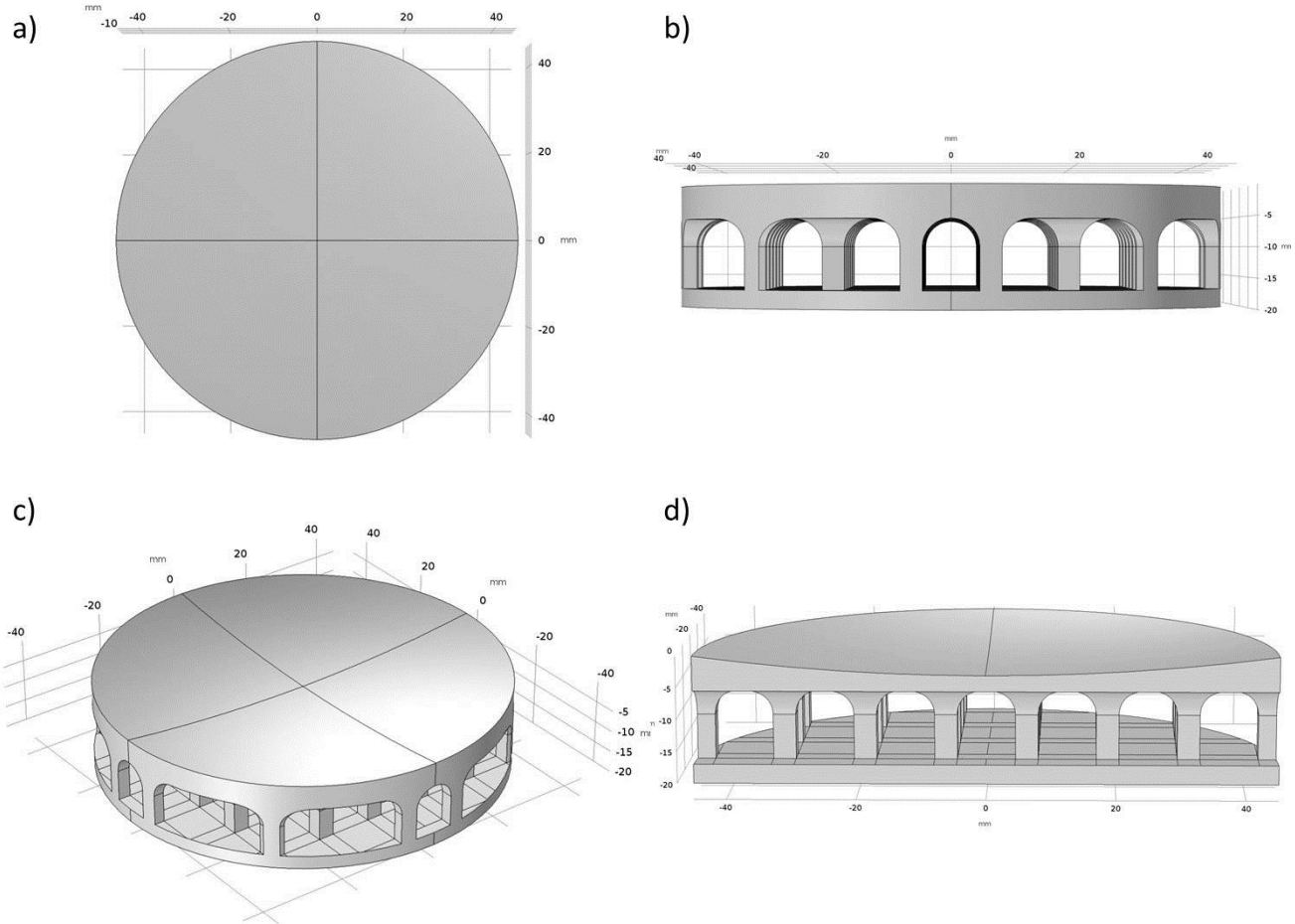
- Objectives: To investigate and manufacture structurally-optimised AM mirror samples and cooling topologies
- Status:
  - Extensive literature study has been conducted
  - Ti64 mirror sample have been printed and evaluated
  - Sample pieces to be printed to evaluate the diameter vs thickness relationship
  - It is also necessary to evaluate the various post processing methodologies







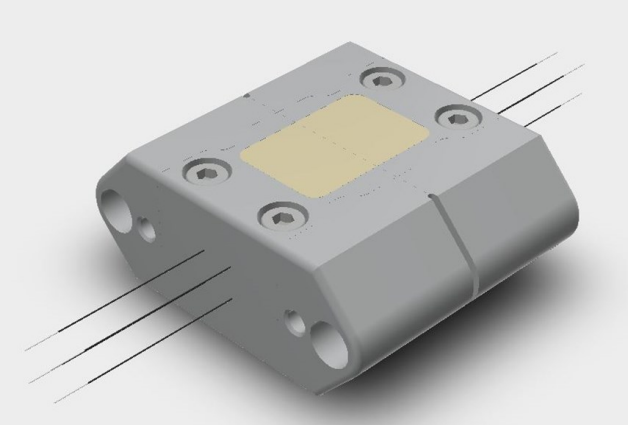
Computer aided design of Ti mirror



a) external xy orientation, b) external yz orientation, c) external xyz orientation and d) internal yz cross-sectional view

WP 5.1.4 Embedded fibres

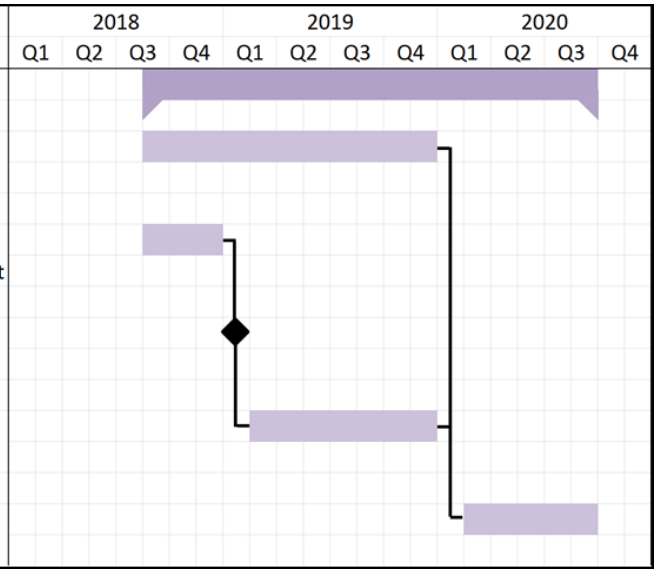
- Objectives: To evaluate whether optical fibres can be embedded in a AM mechanical structure
- Status:
  - Currently busy with a preliminary experiment
  - Evaluating cutting methodologies
  - Locating features will be added prior to cutting the device



WP5.3 Cookbook

- Objectives:
  - To establish “best practice” design rules for the design of astronomical components that can be additively manufactured
  - Develop training methods that could lead to established training courses (e.g. presented at conferences etc.)

Task#	Task description
1	WP 5.3 Additive manufacturing cookbook and toolkit
2	Define/collate material selection guidelines and design rules
3	Development of sample outputs for cookbook and toolkit
4	Milestone: evaluation of output samples and definition of final output style/structure.
5	Implement output style and structure with collated information
6	Develop *'Additive Manufacturing Best Practice Guideline'* (D5.4)



Deliverables

Del. No.	Deliverable title	Lead Beneficiary	Due Date	Status
D5.1	Additive manufacturing material and design report	STFC	Mar 2018 (15 m)	KOM re-planning exercise – new proposed delivery date is Dec 2018
D5.2	Component prototype design and test report	STFC	Dec 2019 (36 m)	Due to start in Apr 2019
D5.3	Astronomical component prototypes	STFC	Jun 2019 (30 m)	Will start once the prototype designs have been reviewed
D5.4	AM “Best practices guidelines”	NOVA	Dec 2019 (36 m)	Request new delivery date of Jun 2020

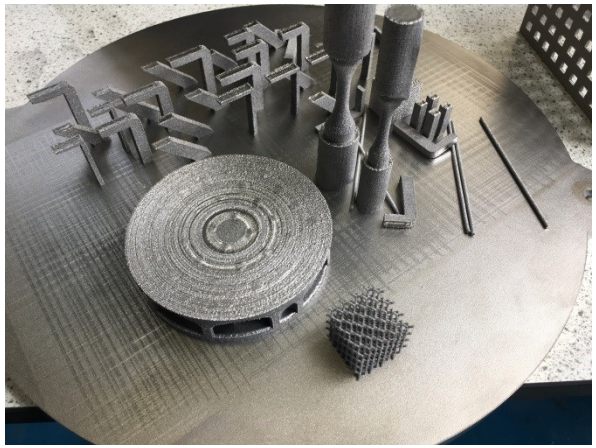
Milestones

Milestone No.	Milestone Name	Related work package	Due Date (months)	Means of verification
M13	Additive Manufacturing Materials Review	WP1	18*	External Review Panel
M14	Prototype Design Review(s)	WP2	30	Critical Design Review
M15	Prototype Test Report Review	WP2	47	Final review

* This milestone is coupled to deliverable D5.1 and is now planned to take place during the 1st quarter of 2019.

Impact

- AM has the potential to build instruments (and components) that are:
  - Lighter;
  - Smaller;
  - Multi-functional;
  - Self-contained;
  - Easier to assemble;



- Resulting in improved performance and
- Potentially more compact, reliable and cheaper
- Promote and provide the “know how” and test data required for designers to feel comfortable in using AM.