MOONS
Multi Object Optical and
Near-infrared Spectrograph

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Control and Collision Avoidance with the MOONS Fibre Positioners

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Science and
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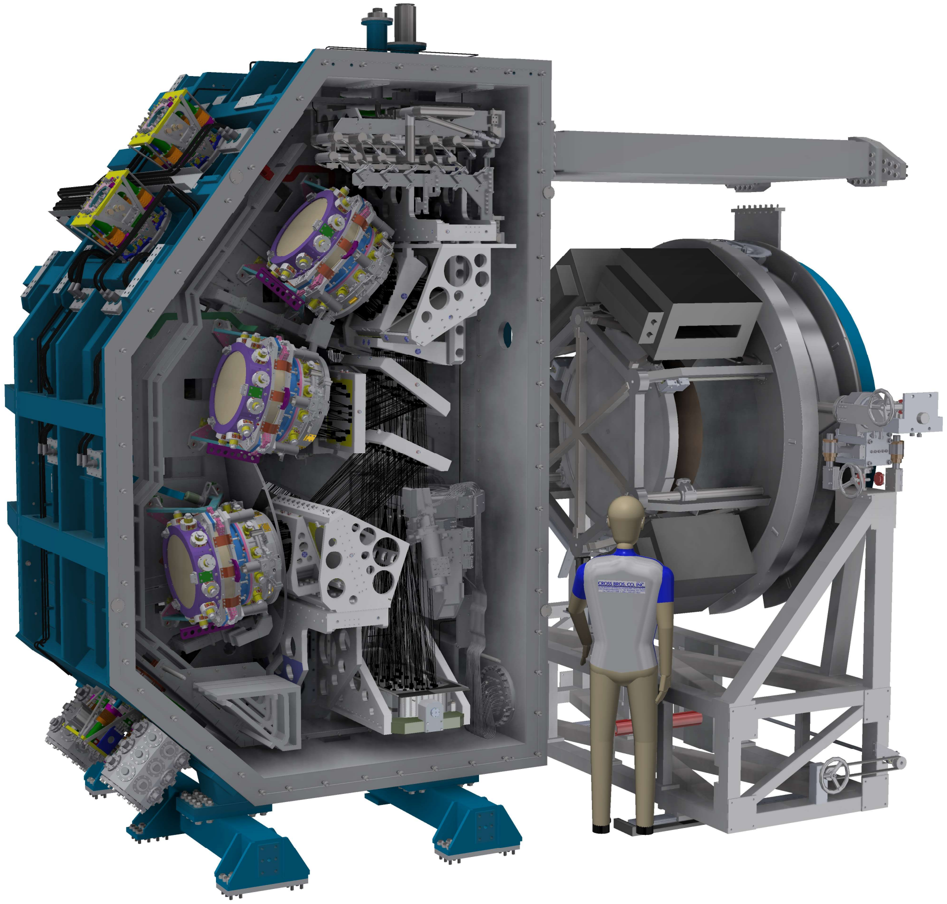
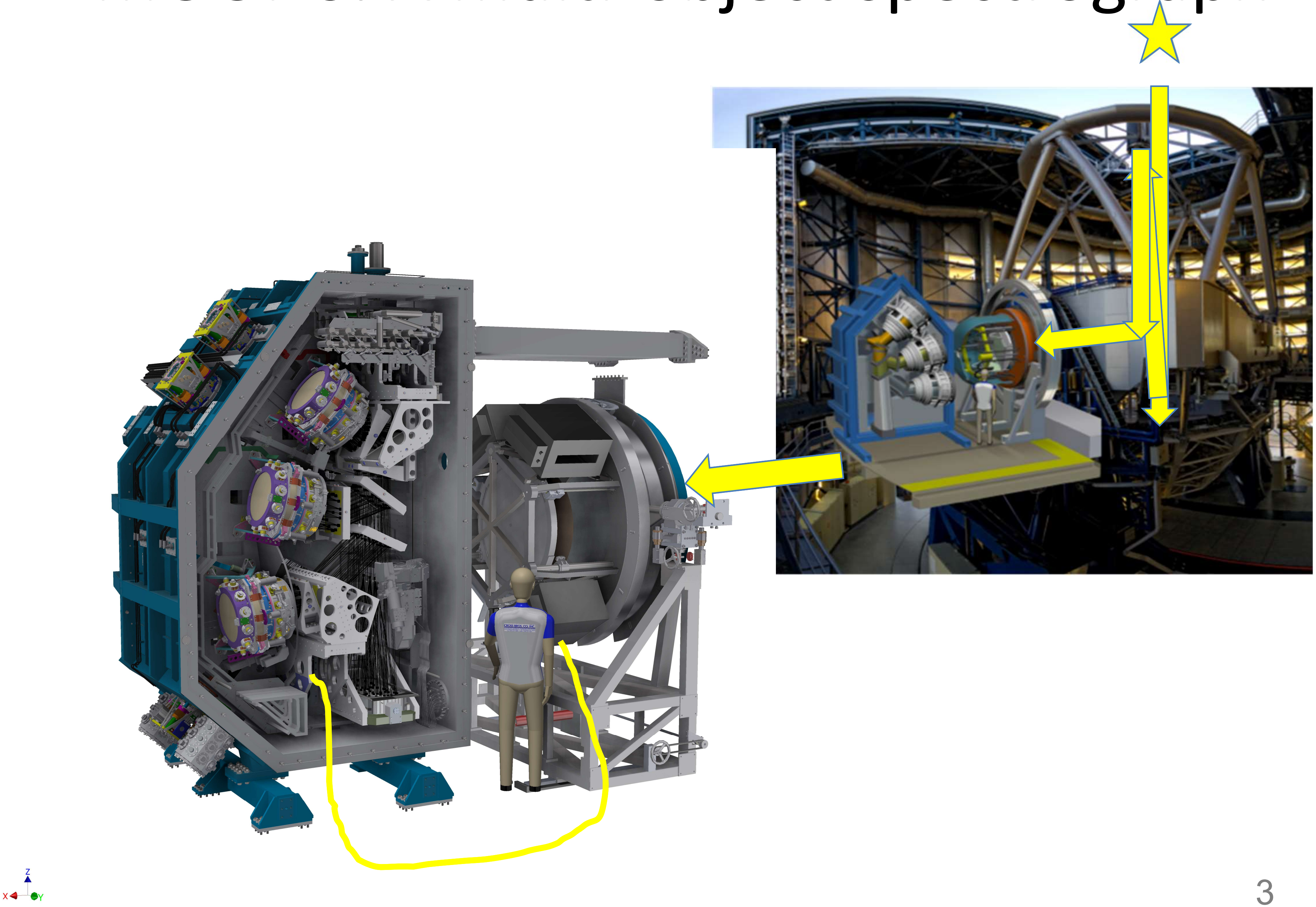
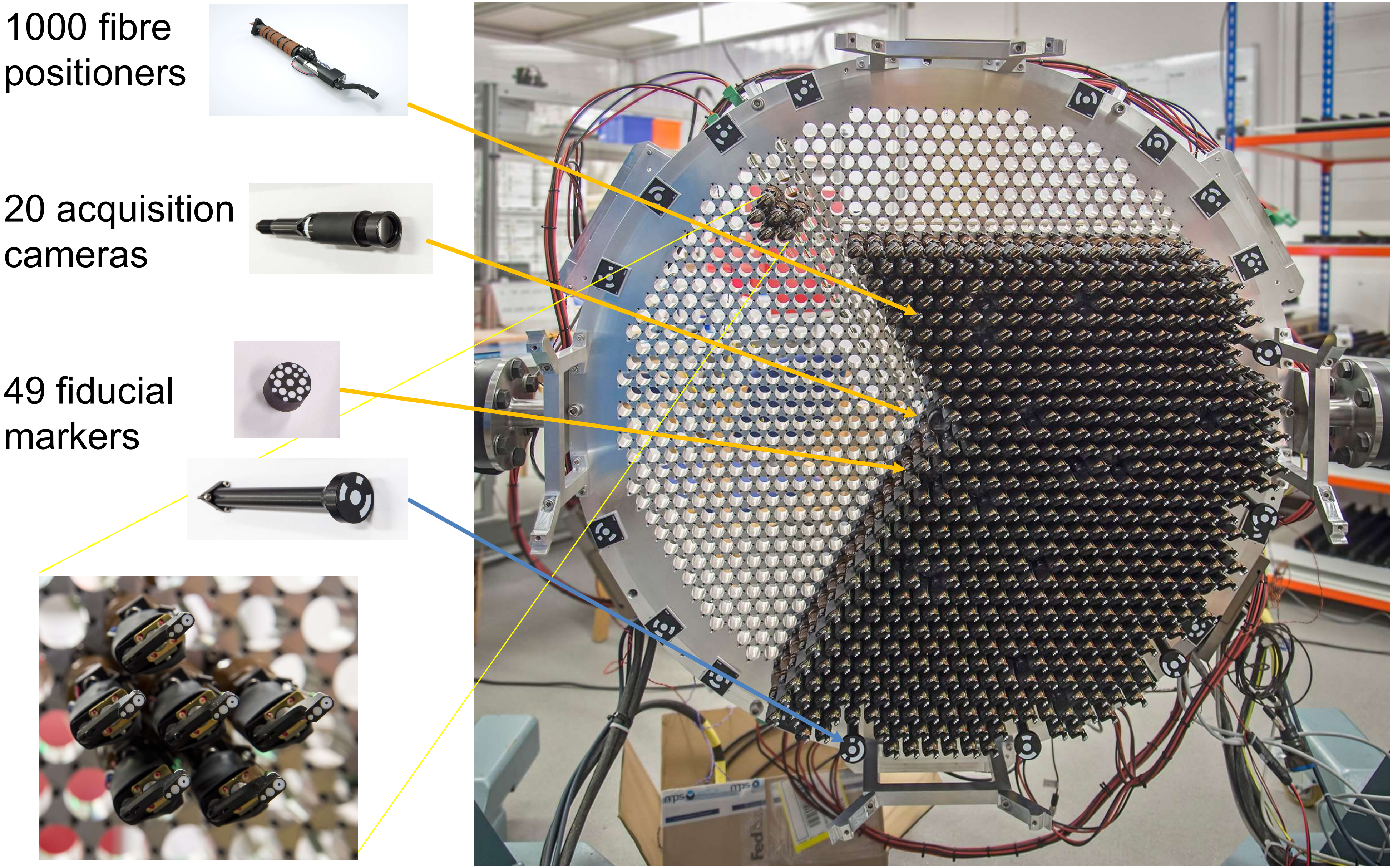
MOONS: A multi-object spectrograph



MOONS: A multi-object spectrograph



The MOONS Focal Plane: Status

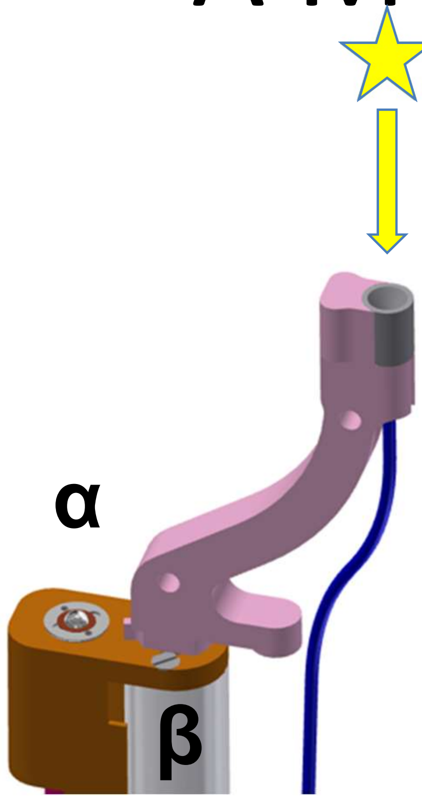


1000 fibre positioners

20 acquisition cameras

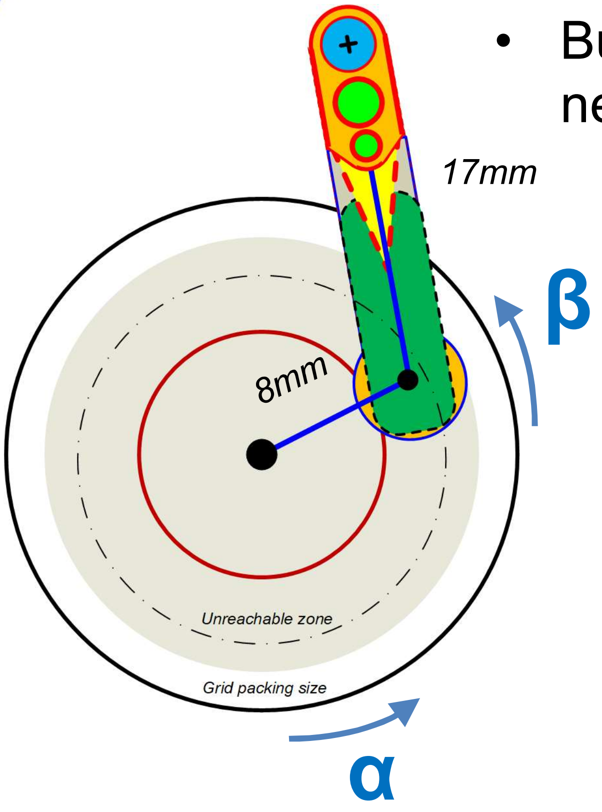
49 fiducial markers

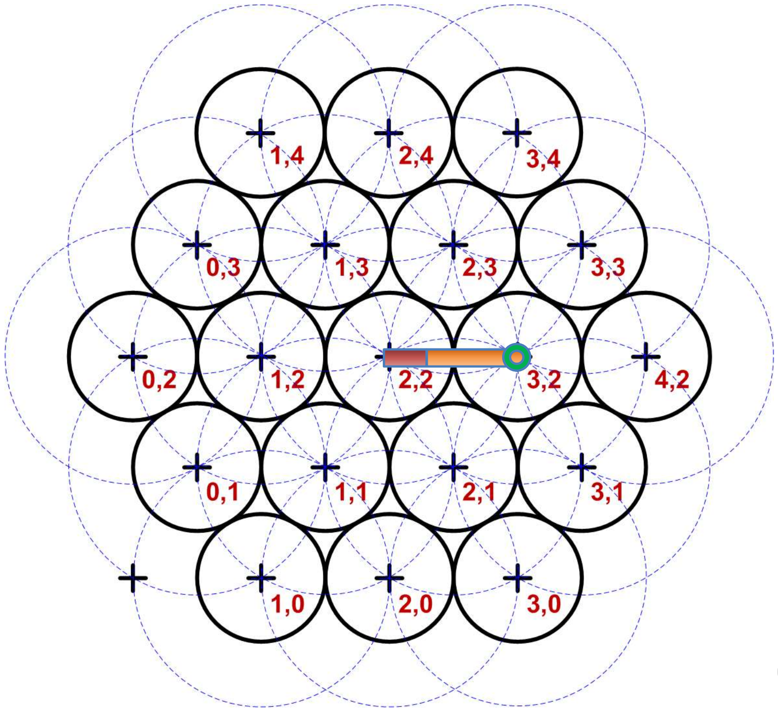
A MOONS Fibre Positioner



- Positioned using two motors:
    - Alpha motor swivels a short arm around central axis.
    - Beta motor rotates a second arm at the end of the alpha arm.

- A positioner cannot reach its own centre.
- But it can reach the centre of a neighbouring positioner.



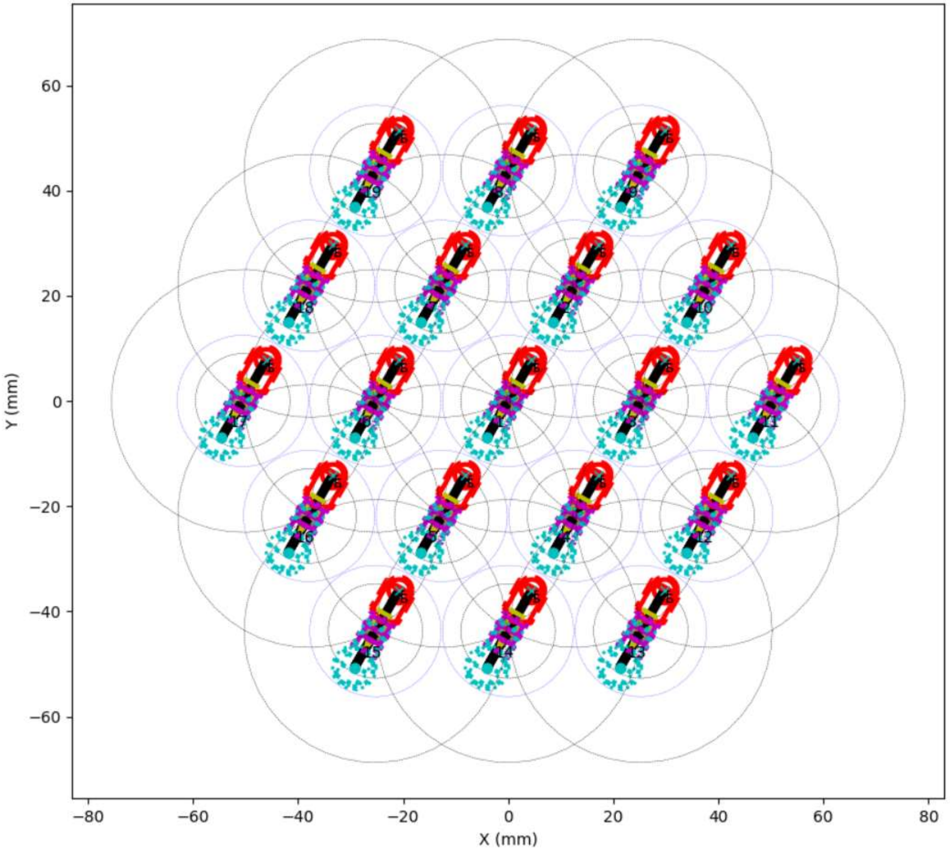


- 6 near neighbours

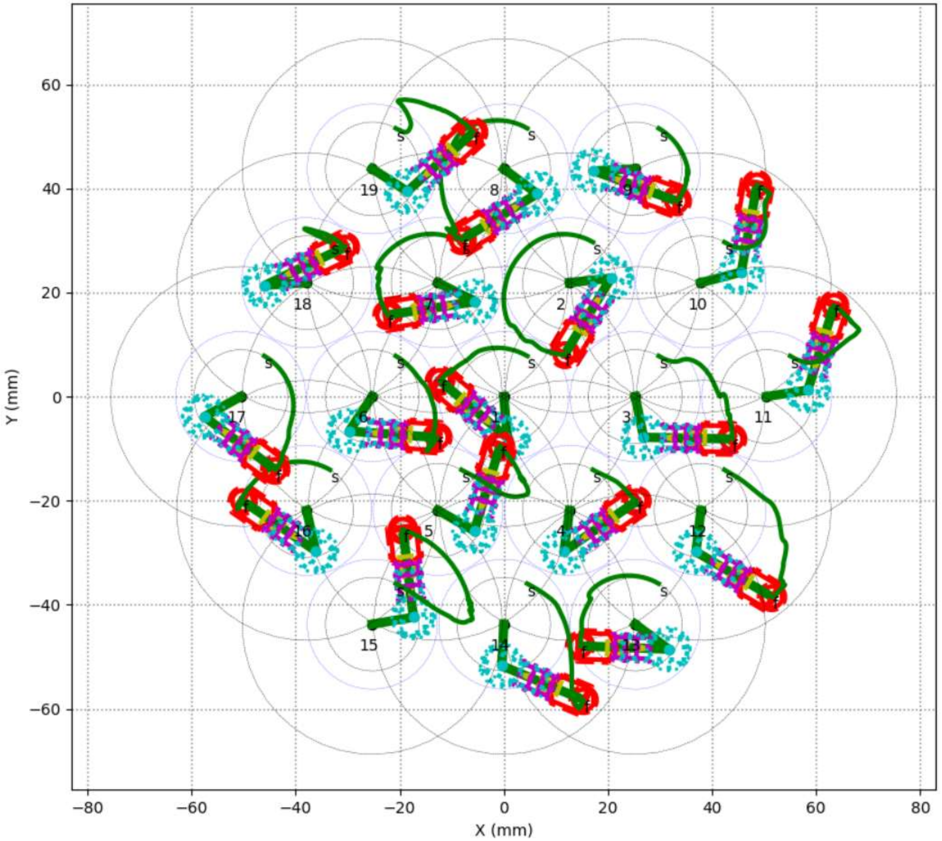
- 12 far neighbours

MOONS: The problem to solve

Move fibre positioners from starting location…



…to targets.



MOONS Fibre Positioner Requirements

- Fibre positioners must move from their starting point to targets without colliding, despite the high overlap.
- Fibre positioners must synchronise their movements to within a few milliseconds.
- The outcome must be predictable (to allow observation planning)
- Fibre positioners must be resilient to unexpected faults
  - Collisions
  - Software bugs
  - Power failures
- Positioning accuracy must be <20 microns.
  - Stepper motor speed and acceleration limits must be maintained.
- Configuration time must be ~30 seconds.

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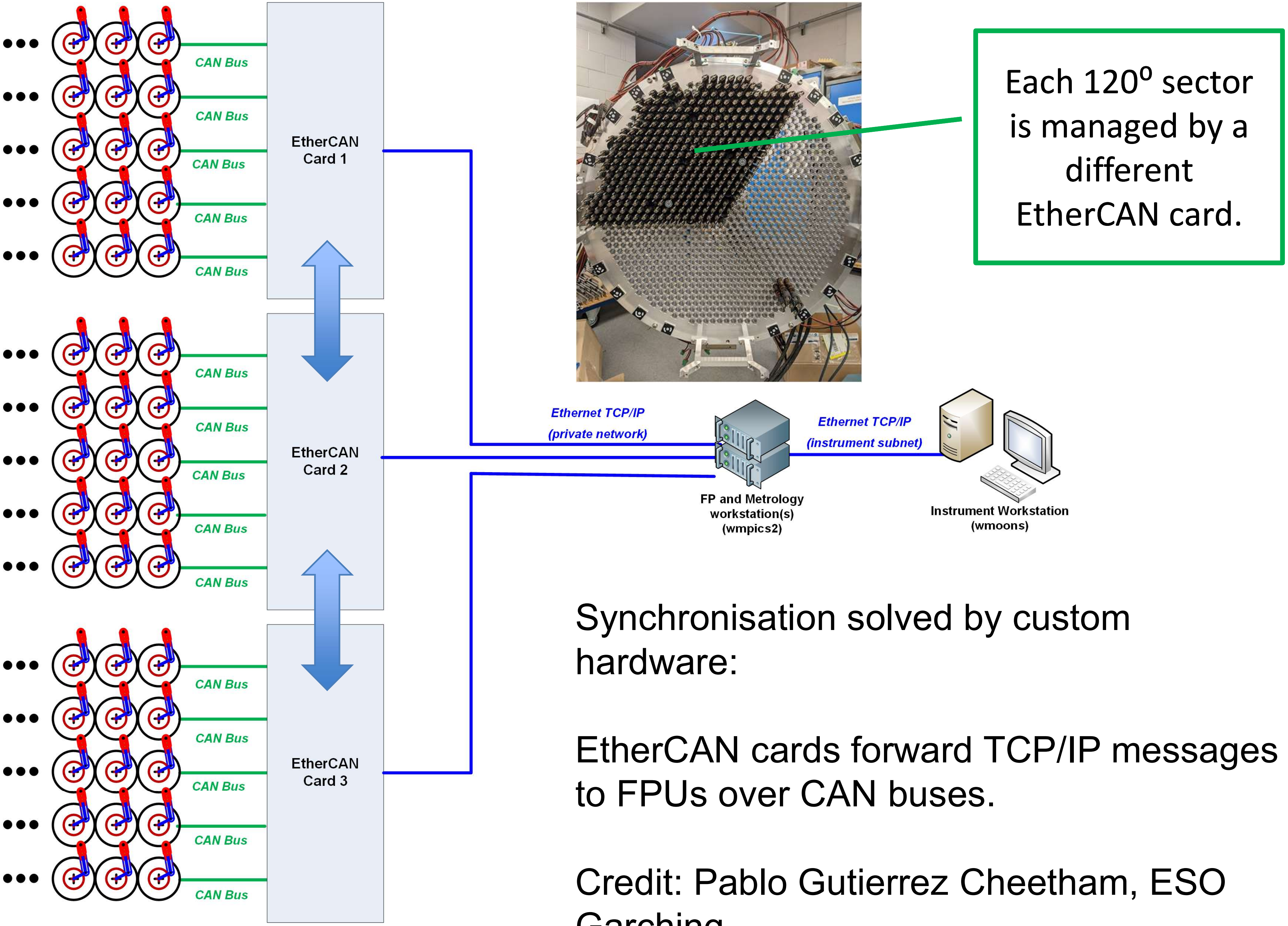
Fibre positioner communication architecture



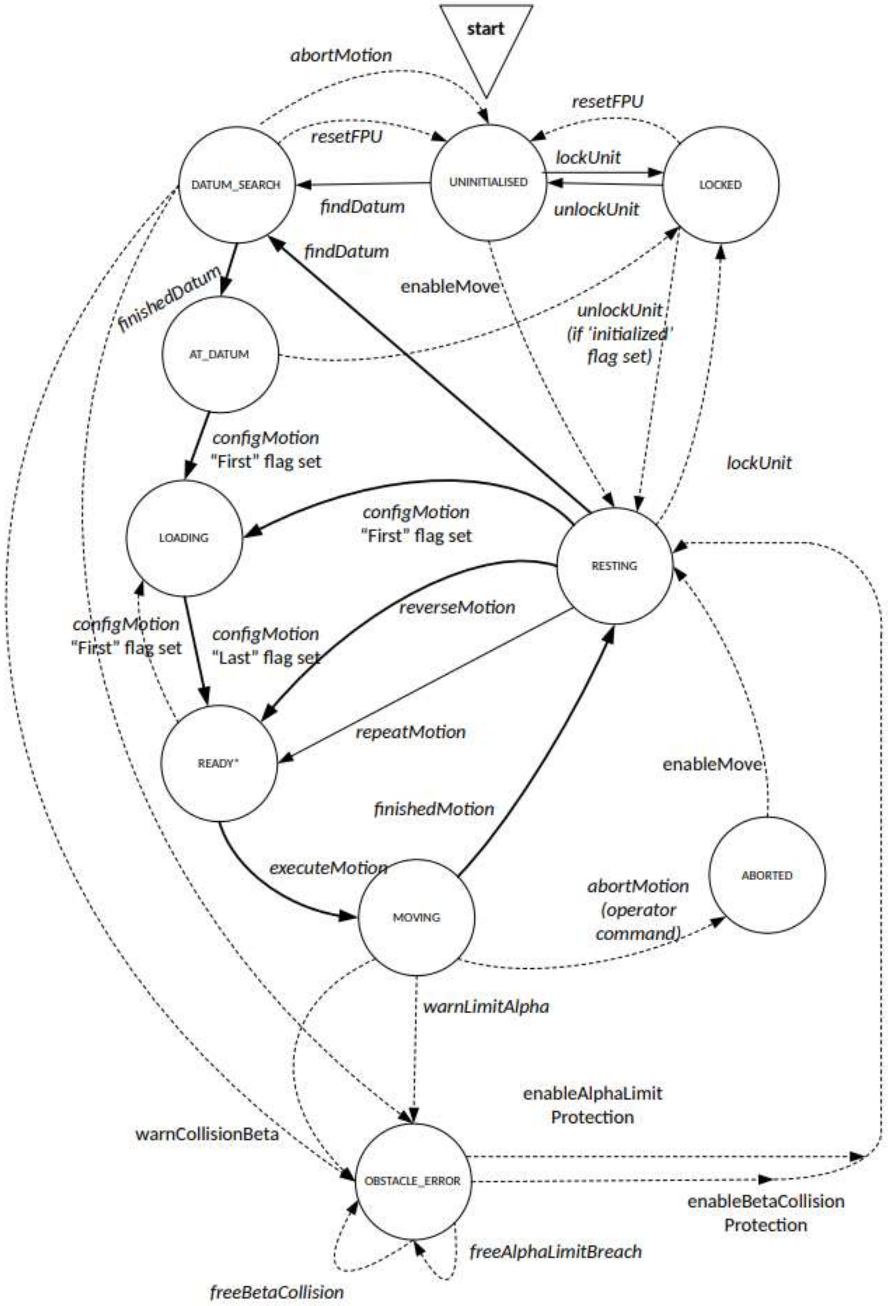
Each 120^{0} sector is managed by a different EtherCAN card.

Synchronisation solved by custom hardware:

EtherCAN cards forward TCP/IP messages to FPUs over CAN buses.

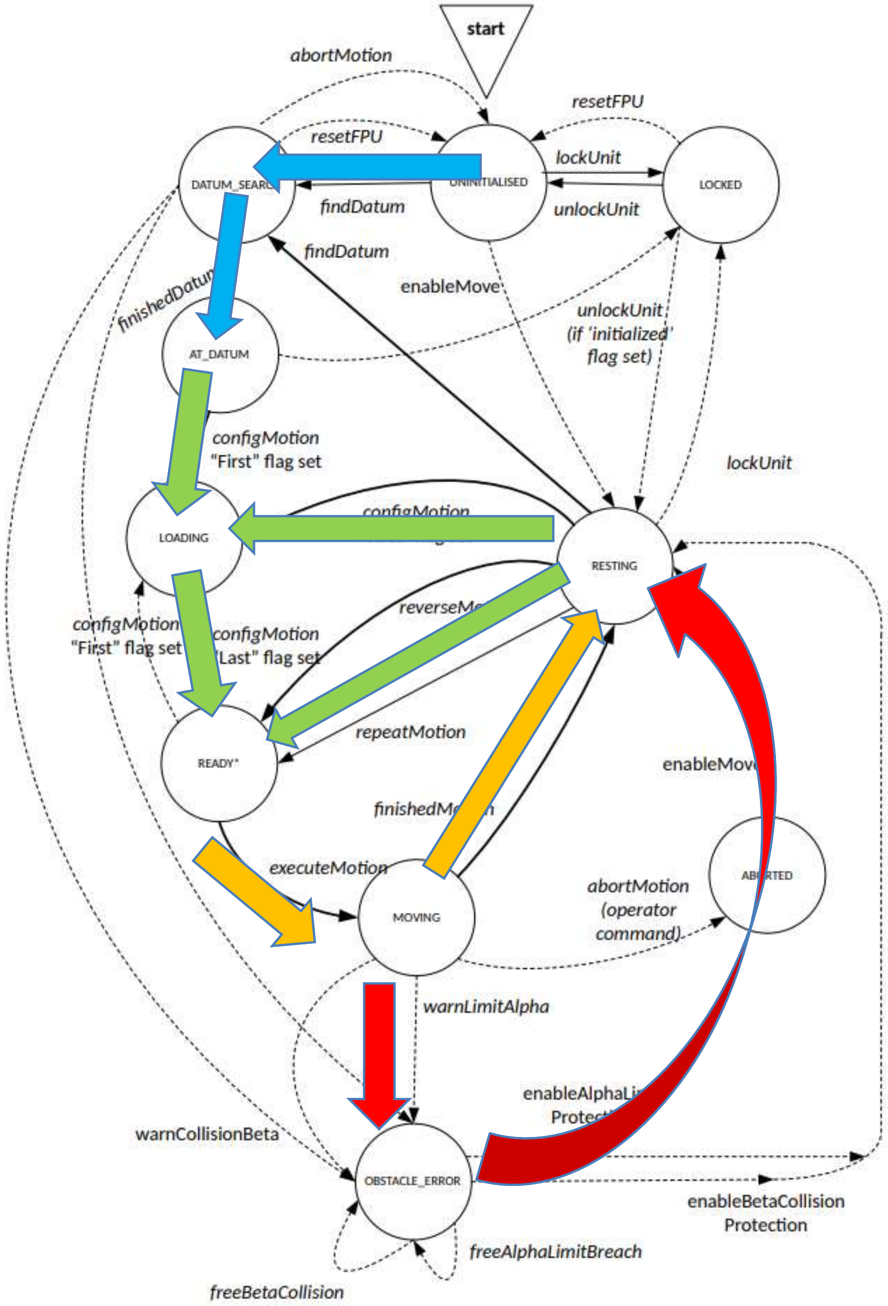
Credit: Pablo Gutierrez Cheetham, ESO Garching.

MOONS Fibre Positioner State Diagram



- FPU firmware accepts a selection of commands.
- Each command can cause a change of state (see left).
- findDatum must first be used to establish reference point.
- Movements are programmed by configMotion (which loads a <=256 element waveform).
- Synchronised motion started with executeMotion.
- A motion can be exactly reversed with the reverseMotion command.
- There are low-level commands to recover from faults.

MOONS Fibre Positioner State Diagram



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🟥 There are low-level commands to recover from faults.

Path planning algorithms

Discretized Navigation Function (DNF)

- Based on *Laleh Makarem et al*. (2014). "Collision Avoidance in Next-Generation Fiber Positioner Robotic System for Large Survey Spectrograph", Astronomy & Astrophysics, 566, p.A84.

Greedy Choice (GC)/Markov Chain (MC)

- SLOAN Kaiju: Based on *Conor Sayers et al*. (2020). “Fast, Collision-Free Trajectory Planning for Heavily Overlapping Robotic Fiber Positioners”, Astronomical Journal.
- Scrooge: A Greedy Choice algorithm developed by the MOONS OPS team (Paolo Franzetti)

Path planning algorithms

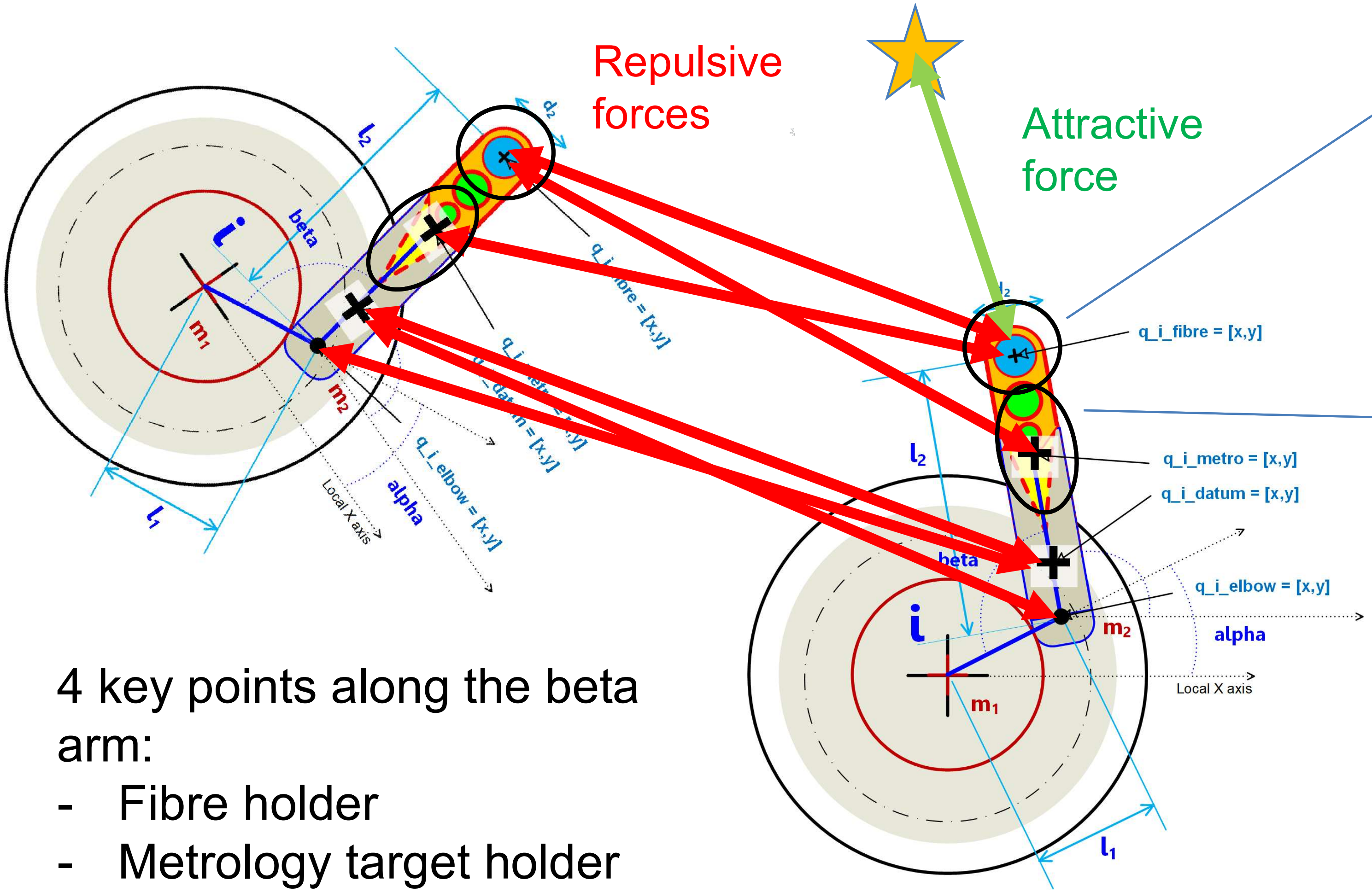
Discretized Navigation Function (DNF)

- Each positioner is guided by a “navigation function” where targets generate an attractive force and collision zones generate repulsive forces.
- Similar to an N-body simulation.
- Theoretically “collision free”, until you take real motors into account.

Greedy Choice (GC)/Markov Chain (MC)

- At each step, each motor decides whether to nudge its arm clockwise or anticlockwise, or stay still.
  - i.e. each positioner can choose to do one of 9 things.
- Motors must be able to stop any time.
- Can achieve higher efficiency than DNF but expensive on processor time.

How does the DNF algorithm work?



Repulsive forces

Attractive force

Fibre holder has circular weighting

Beta arm components have elliptical weighting

4 key points along the beta arm:

- Fibre holder
- Metrology target holder
- Middle of datum actuator
- Elbow joint

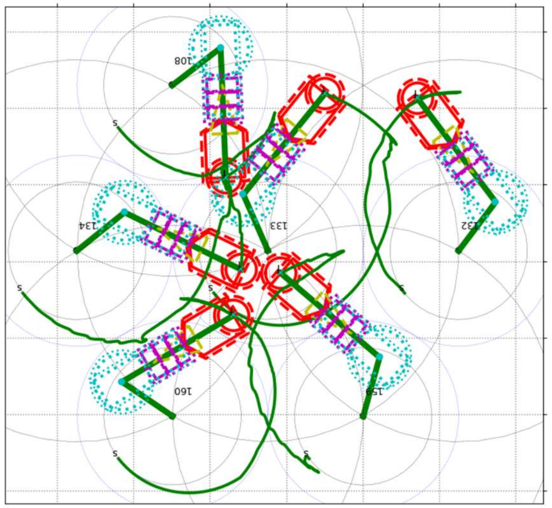
DNF Algorithm (highly simplified)

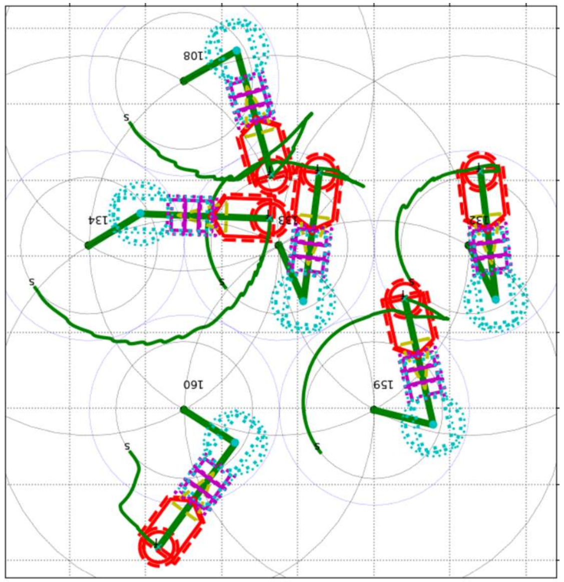
```
For each path element
    For each fibre positioner
        Determine locations of 4 key points
        Determine chain derivatives from arm angles
        For each neighbouring positioner
            Determine locations of 4 key points
            Use distances between points to derive
            repulsive part of navigation function
        Determine distance to target
        Use target distance to derive attractive
        part of navigation function
        Convert navigation function to motor demands
        Adjust motor demands to meet constraints
    Next fibre positioner
Next path element
```

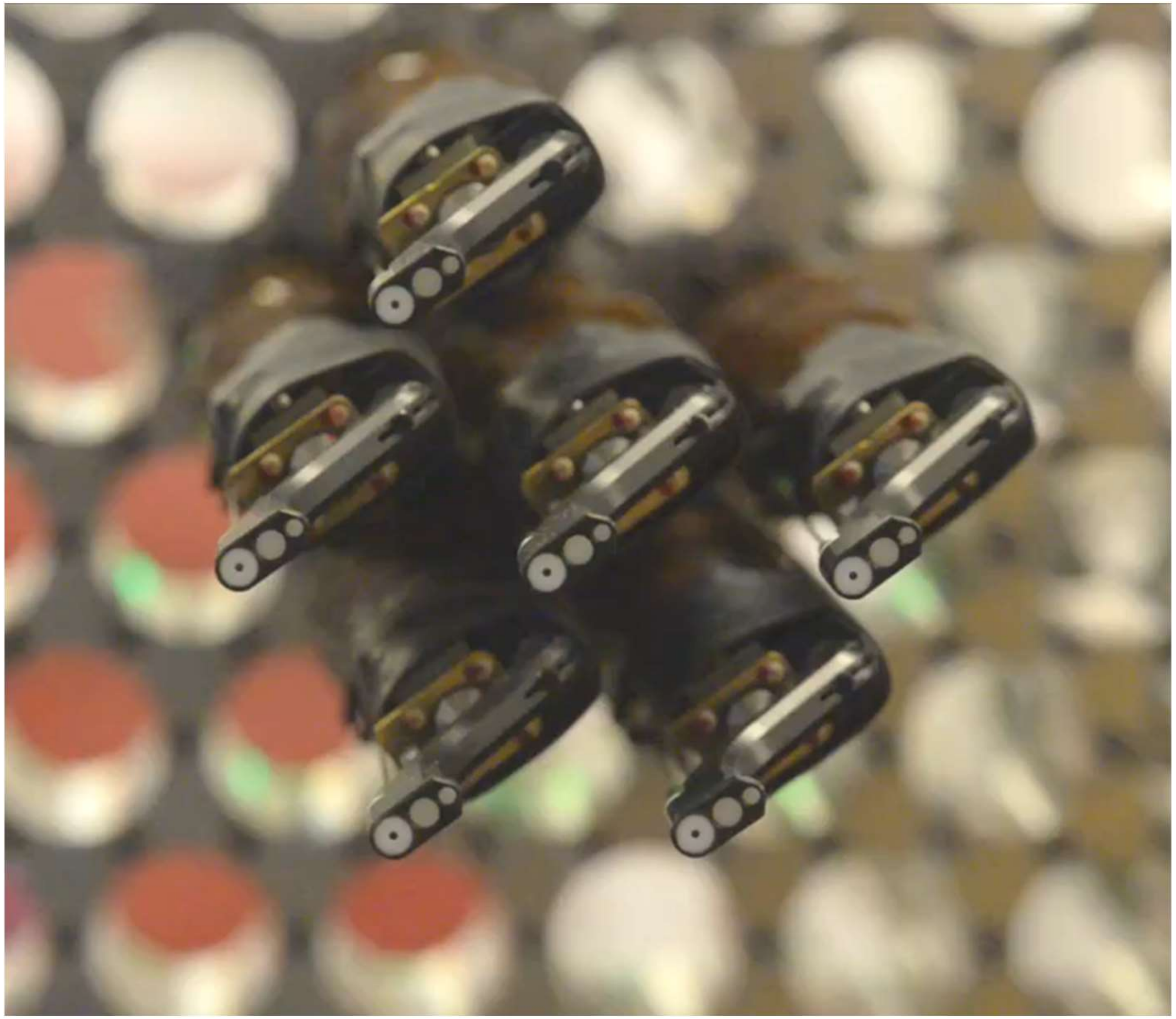
“Tiptoe” Algorithm (simplified)

```
For each path element
   For each fibre positioner
      Move slowly towards the target
      For each neighbouring positioner
         If collision zones closer than tolerance
            Request to stop the positioner
      Adjust motor demands to meet constraints
   Next fibre positioner
Next path element
```

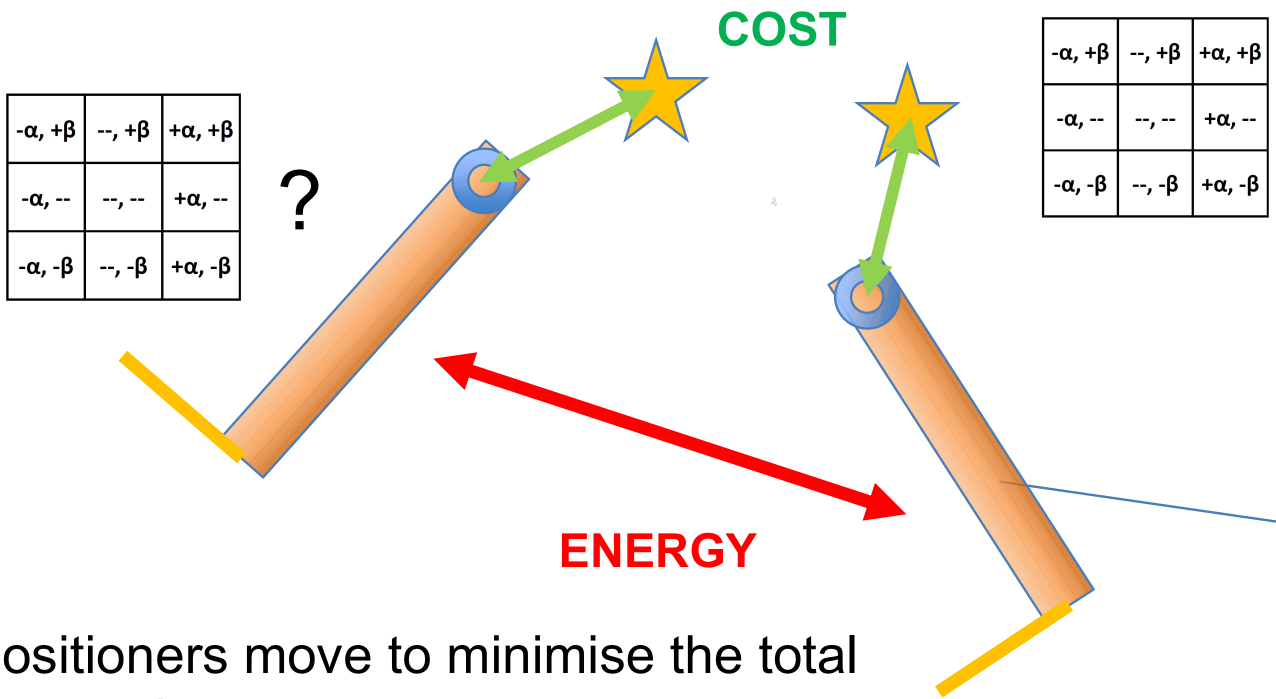
DNF algorithm in action







How does the GC/MC algorithm work?



-α, +β	--, +β	+α, +β
-α, --	--, --	+α, --
-α, -β	--, -β	+α, -β

-α, +β	--, +β	+α, +β
-α, --	--, --	+α, --
-α, -β	--, -β	+α, -β

9 choices per path step: 3 choices per motor.

Positioners represented by rectangles

Positioners move to minimise the total cost and energy.

GC: A positioner always attempts to minimise its own cost.

MC: A positioner can decide at random whether to minimise its cost or help another positioner by minimising its energy.

COST: Distance between fibre and target (in motor coordinates).

ENERGY: Sum of inverse square distances to neighbours.

GC/MC Algorithm (highly simplified)

```
For each path element
    For each fibre positioner
        Compute cost from distance to target
        If the cost is zero (target reached)
            If no neighbour nearby
                Stay at target. Next positioner.
        Compute energy from distances to neighbours
        For each of the 9 options
            If the option doesn't risk a collision
                Compute the change in cost and energy
        Randomly choose to minimise cost or energy.
        Choose option which minimises cost or energy.
        Adjust motor demands to meet constraints
    Next fibre positioner
Next path element
```

Summary

- MOONS is an instrument with 1000 fibre positioners with a high degree of overlap.
- The positioners need to be moved from a known starting position to targets without colliding.
- We communicate with the fibre positioners using CANBus and have solved the synchronisation issue with a custom “EtherCAN” card designed at ESO.
- Each positioner can be pre-loaded with a <=256 element waveform which is can execute on demand.
- Path planning uses either DNF (EPFL) or GC/MC (Sloan) algorithms.
  - DNF is faster and more flexible. Can be used for fault recovery.
  - GC/MC is inflexible but has a better outcome. Better for science targets.
- We can achieve target acquisition efficiencies of
  - 75-90% in 5 minutes (DNF)
  - 98% in 30 minutes (GC/MC)

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Any Questions ?

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Frequently Asked Questions - 1

- **Q: What is the field of view of MOONS?** A: About half a degree on the sky.
- **Q: How closely can fibres be placed?** A: The MOONS plate scale is 1.718 arcseconds per millimetre. The fibre holders are 4mm in diameter so they will touch when placed 6.87 arcseconds apart. In reality we add a 0.5mm safety buffer, so they can safely pick off objects 8.59 arcseconds apart. In XSWITCH mode, MOONS needs to place object and sky fibres between 10 and 30 arcseconds apart.
- **Q: What kind of target allocation efficiencies can be achieved with the path planning algorithms?** A: The DNF algorithm works much better in STARE mode, where it can achieve 90%. Its worse case is 10 arcsecond XSWITCH mode where it manages only 75%. By contrast, Scrooge can achieve ~98% (at the cost of less flexibility and more processing time).
- **Q: How long do the algorithms take to generate paths for 1000 positioners?** A: It depends on your workstation, but the DNF algorithm typically takes about 5 minutes and the Scrooge algorithm about 30 minutes. DNF can be run at the telescope when needed. Scrooge takes too long to run in real time.
- **Q: Can you mix and match the algorithms?** A: It would be great if we could run the DNF algorithm first and then complete the motion using the Scrooge algorithm, but Scrooge cannot start from an arbitrary location. This is why we usually finish DNF with the Tiptoe algorithm.
- **Q: What happens if a fibre positioner breaks?** A: Both algorithms can cope with one or more “locked” positioners, which are treated a stationary obstacles.

Frequently Asked Questions - 2

- **Q: How accurate are the FPUs?** A: They are repeatable to 10 microns but repeatability doesn't equate to accuracy. After calibration, all installed FPUs have 95th percentile accuracy of less than 50 microns in open-loop operation, with most around 30 microns.

- **Q: Why do the FPUs need to be calibrated?** A: We operate open loop for efficiency reasons. Although the antibacklash gearboxes are very repeatable, form errors in the gear wheels and teeth result in a non-linear response through the drivetrain. The magnitude of the non-linearity is ~10x the headline repeatability, so we need to calibrate and correct for this to achieve the required accuracy of movement.

- **Q: How do you know where the positioners are?** A: Normally we just rely on the calibrated motion. However, we do have an external metrology systems with an accuracy of about 15 microns to verify this if needed.

- **Q: How do you detect collisions?** A: A pattern of voltages are applied to the beta arms so that any collisions result in a voltage difference and a detectable current flow. The aluminium beta arms need to be matte black but also conductive, thus black anodizing is unacceptable. They are roughened using micro shot-peening before being coated with black chromate. To isolate the arms from the main body of the positioner and each other via the baseplate, the alpha arm shaft is made from ceramic. The voltage is applied to the alpha arm and travels to the beta arm via the beta motor bearings and shaft.

- **Q: Can you replace them?** A: Yes but with difficulty! There is a balance to be struck between the performance loss of a non-functional FPU and the risk of collateral damage during replacement.

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