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ETFP: A new fibre positioner concept for future Multi-Object Spectrographs

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ABSTRACT

Spectroscopy is a primary tool of ground-based and space-borne astronomy. It yields unique astrophysical insights across all contemporary astronomy, from mapping the chemical composition and radial velocities of stars in the Milky Way and nearby galaxies, to accurate redshifts and studies of the physical properties of distant galaxies (internal motions, stellar populations, outflows, etc) over cosmic time.

Multi-object spectroscopic surveys have become an essential tool to measure such properties across sufficiently large volumes to draw statistically significant conclusions. A key challenge in the design and construction of MOS instruments is the fibre positioning system. Here we present a new concept for a telescopic fibre positioner (the Edinburgh Telescopic Fibre Positioner: ETFP) in either a theta-r or theta-phi-r configuration. The positioner concept, being developed at UKATC, builds up from the technology of VLT-MOONS and VLT-KMOS and aims to provide a fast field reconfiguration, close packing for high-density targeting, and reliable fibre allocation to maximise the efficiency of observations for future multi-object spectrograph (MOS) facilities.

Keywords: Fibre positioner design, multi-object spectrograph, astronomical instrument design

1. INTRODUCTION

The importance of MOS is supported by a recent poll of the astronomical community's future priorities by the European Southern Observatory (ESO), which placed high-multiplex, high-resolution MOS facilities as the most essential new capability for their research in the 2030s. Facilities now in construction for 4-8m class telescopes will be capable of observing thousands of objects simultaneously (MOONS, 4MOST, WEAVE, DESI, PFS) at intermediate/high resolving power regimes (R~4,000-20,000). However, a new range of capabilities are required to continue to push the limits of our knowledge across all fields in astronomical research. For this reason, the community is now working in the development of a concept for a MOS with increased resolving power (R~80,000) to be installed at the VLT called HRMOS. Similarly, significant improvements on sensitivity at high multiplex can be gained via the design of dedicated 10m-class MOS survey telescopes (e.g. MSE, SpecTel).

A key challenge in the design and construction of MOS instruments is the fibre positioning system. MOS survey instruments must be capable of configuring a field:
1) accurately (sub-micrometre positioning accuracy and repeatability), to minimise throughput losses due to object-fibre misalignment,
2) quickly (from seconds to a few minutes) to maximise survey speed, and
3) reliably, to minimize failure and associated time losses.

These requirements become even more challenging when considering the need to bring fibres close to each other, either in pairs for subtraction of sky signal or in groups for efficient targeting of high-density sub-structures. In recent years, different combinations of hardware and software solutions have been developed to place thousands of optical fibres at the required positions in the focal plane. However, the technical requirements mentioned above have become increasingly difficult to meet. Priority should be given to the design of a flexible, yet reliable positioner solution that is suitable for the forthcoming facilities, while considering scalability as defined by the telescope field-of-view and high target density goals.

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2. MOTIVATION & CONCEPT

The use of independently driven fibre positioners allows for simultaneous movement of all the positioners during reconfiguration. This massively reduces reconfiguration time compared to a serial positioning, and so increases the proportion of time spent observing. This is achieved in VLT-MOONS via positioners which have two articulated arms (a theta-phi arrangement).

The reach of such a positioner is limited by the need to retract into a “home” position where the positioners can rotate about their primary axis without risk of collision with any other positioner (figure 1). If this was not achievable then the routing challenge would be massively more complex; there would be no “safe” state where no positioner could collide with its neighbours. Achieving such a safe state limits the combined length of the two arms to ~1 times the spacing between adjacent positioners. This results in 2 to 4 positioners being able to reach any given point in the field of view (figure 2).

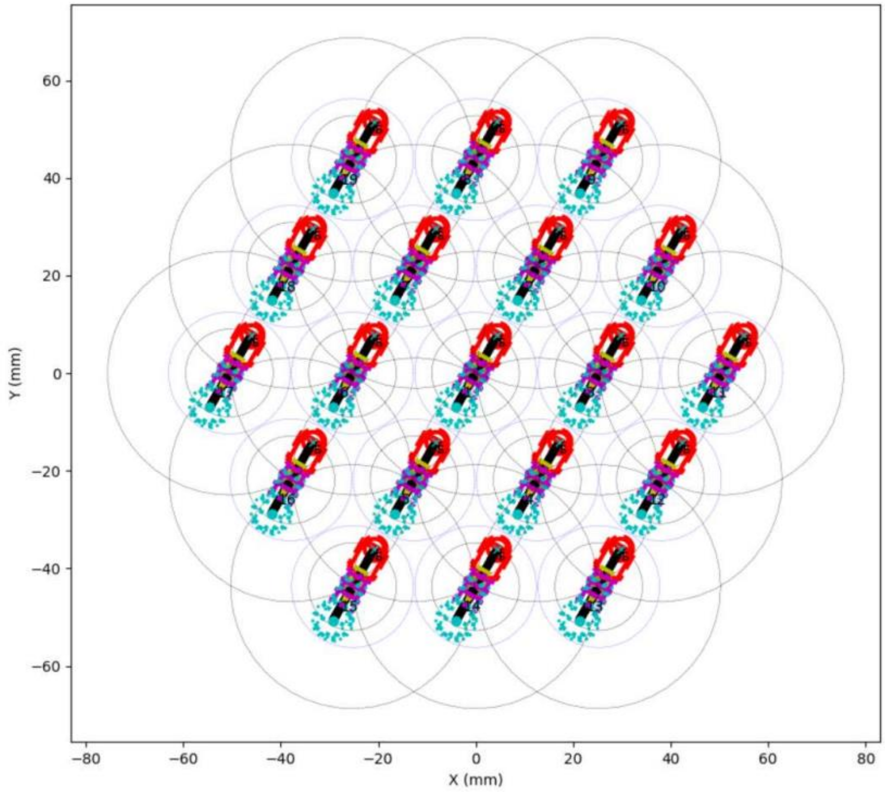
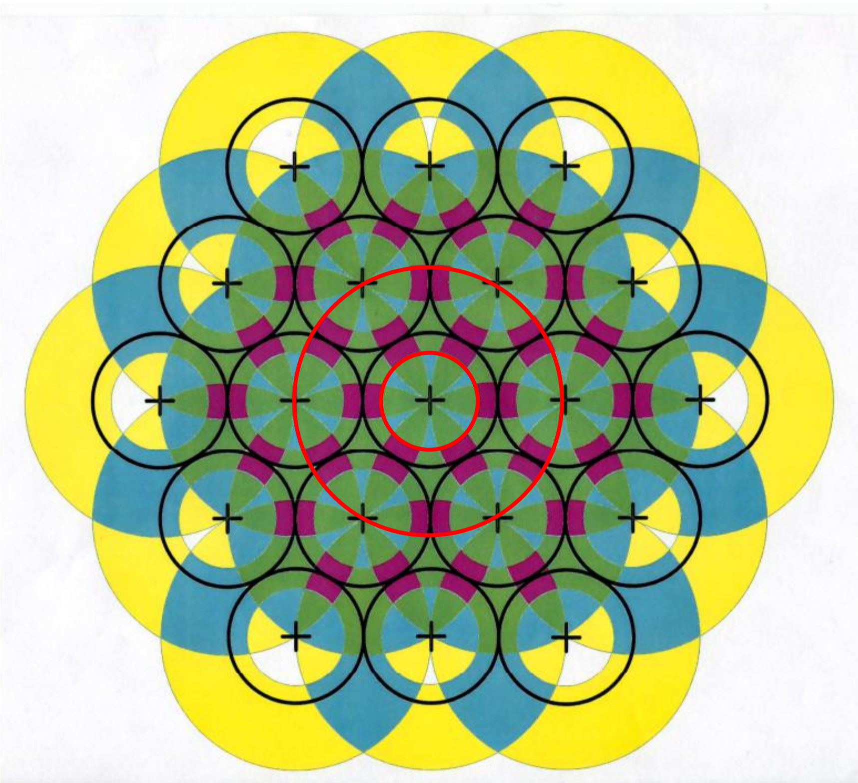


Figure 1. Software representation of MOONS positioners in a home configuration

In order to bring significant numbers of fibres close together to view dense clusters of sky objects a much longer reach is needed. For this work a cluster of 10 objects has been considered. Thus a sky coverage of ~1000% (meaning 10 positioners can reach a given point) is required, vs 200% for MOONS (figure 2). This is achieved by having a reach of 1.7 times the spacing between positioners (figure 3). For example for the HRMOS proposal with a spacing between positioners of 65mm this would mean a reach of 110mm for each positioner.

To achieve this increased reach while maintaining the non-overlapping “safe” configuration we propose the use of a telescopic positioner arm. This could either be in a theta-r arrangement with a single rotation axis, or theta-phi-r with two axes plus the extending arm (figure 4).



White: zero

Yellow: 100%

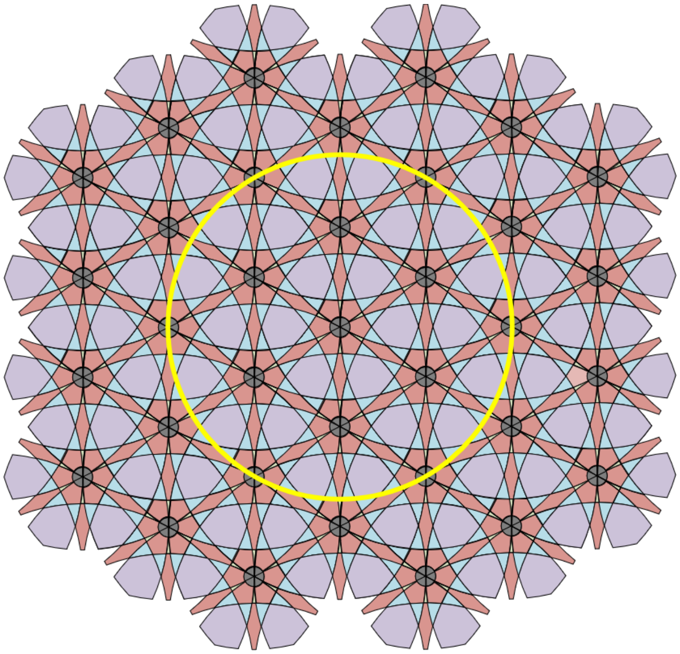
Green: 200%

Cyan: 300%

Magenta: 400%

A 200% coverage means MOONS can pick off object/sky pairs (needed for IR sky subtraction) anywhere on the sky.

Figure 2. MOONS sky coverage. Red circles show the minimum and maximum reach of a single positioner



Purple: 1200%

Blue: 1100%

Red: 1000%

Green: 900%

Figure 3. Sky coverage for 10 object clusters. Yellow circle shows the reach of a single positioner. Edge effects not shown.

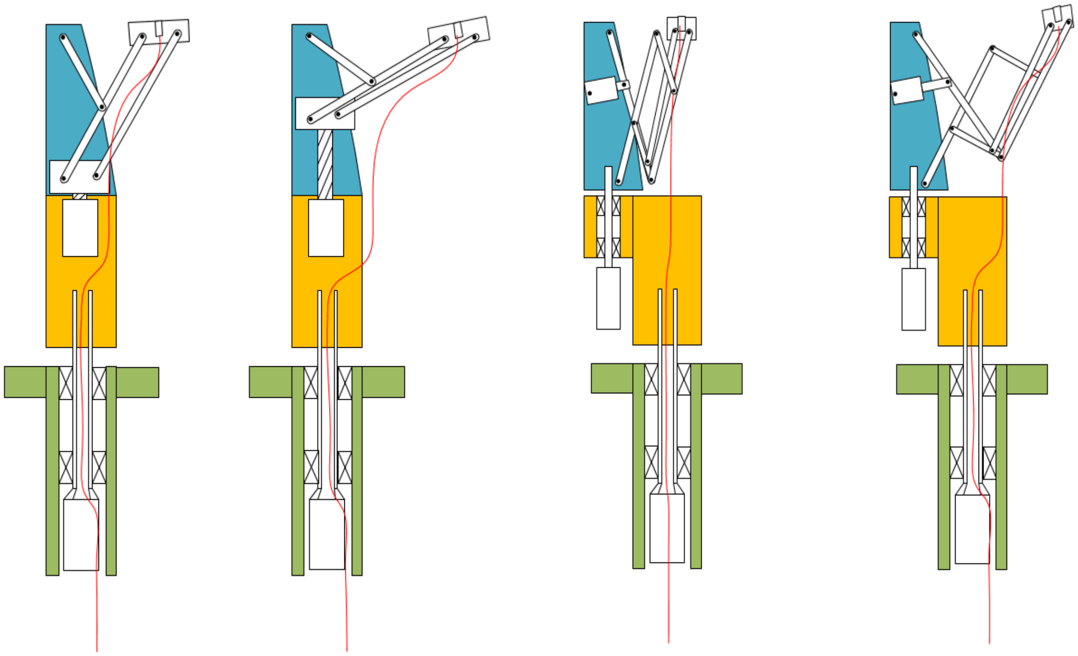


Figure 4. The two mechanical concepts in retracted and partially extended positions. Left is theta-r, right is theta-phi-r

2.1 Theta-r and theta-phi-r

A theta-r configuration has two degrees of freedom: the primary rotation axis and the linear extension. This is exactly sufficient to move the positioner around the 2D focal plane.

A theta-phi-r configuration has an extra degree of freedom: the secondary rotation axis, making it more complex. This introduces an opportunity in that it allows the positioner to be in any of a range of positions while accessing a given point in the focal plane which increases the options to avoid clashes. In particular it allows a positioner to reach around its immediate neighbour (figure 5).

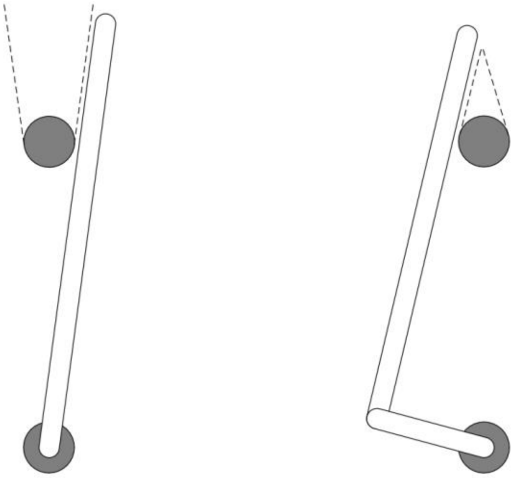


Figure 5. Comparison of exclusion zone caused by the axis of adjacent positioner for theta-r (left) and theta-phi-r (right)

2.2 Object Selection & Routing

As the number of positioners increases (e.g. from ~1 000 on MOONS to ~20 000 on HST) the task of assigning positioners to sky objects, and moving them into position, gets exponentially harder. For a given number of positioners an increased reach results in more potential clashes (figure 6) and more potential configurations. Existing routing algorithms require non-negligible computing time [1], and result in solutions that are not 100% efficient. This means that not every fibre is assigned to an object, or not every high priority object is assigned a fibre.

Our partners at the RAL Scientific Machine Learning Group are investigating opportunities to make use of machine learning to develop improved algorithms. Specifically these would use reinforcement learning and simulations to train black box algorithms. Currently object selection is separated from routing; fast, efficient routing algorithms based on machine learning would allow routing to be used directly as a scoring metric for object selection, and should result in solutions that have shorter reconfiguration times between observations.

Specific areas of exploration include:

- Determining whether algorithms can be robust to different instrument configurations or whether the models must retrain for each instrument
- Exploring robustness to small numbers of failed positioners during the lifetime of an instrument
- Using the models to explore the parameter space when designing new instrument architectures

This last point is of particular interest. Fast routing algorithms would allow many embodiments of a design to be simulated against potential observations and so score the capability of the designs to reach sets of objects. This would allow the designer to find the sensitivity of their concepts with respect to various design variables, and to find optimal solutions. A simple example would be to vary both the reach of a telescopic arm and its thickness, and score this against the density and size of clusters of objects that can be reached. This was carried out as an initial “toy model” with a simple object selection algorithm and fixed cluster size of 10 objects (figure 7). As expected thicker arms cannot reach as high a proportion of dense clusters because the fibres cannot be brought as close together (figure 8).

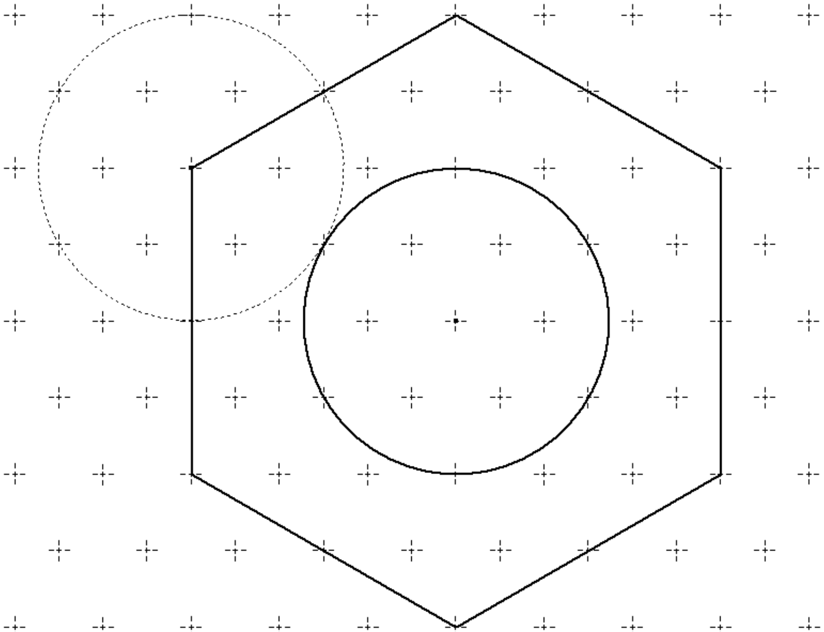


Figure 6. Diagram of potential collisions. Solid circle is the reach of a single positioner, hexagon is the set of positioners that can collide with it, dashed circle is the reach of a positioner at the limit of collisions

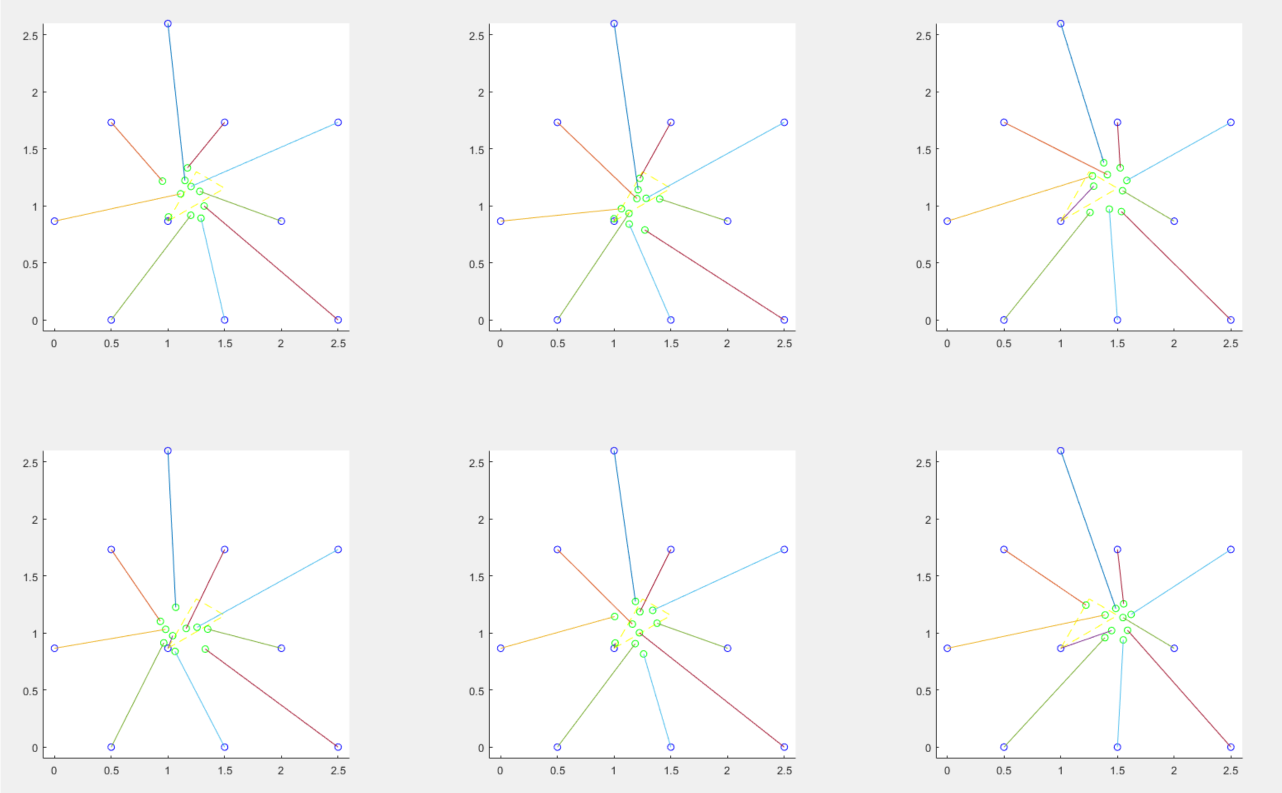


Figure 7. Examples of positioners reaching to clusters of sky objects

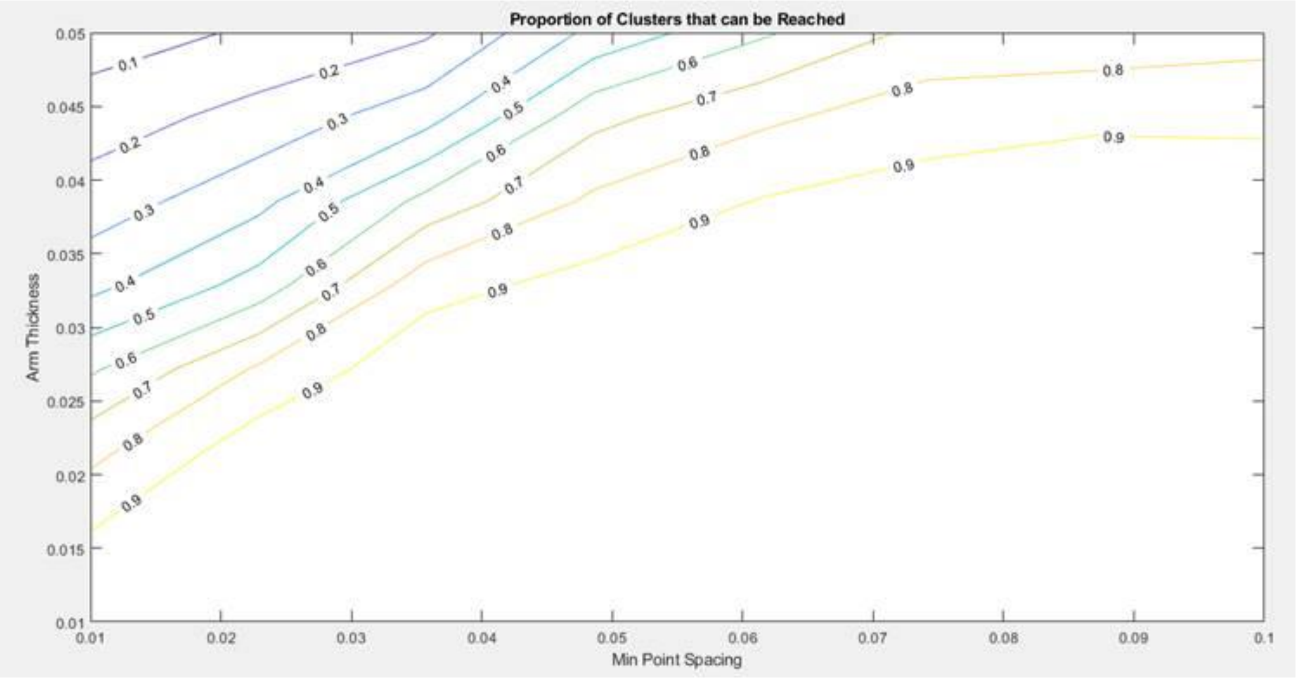


Figure 8. Tradeoff between arm thickness and cluster density (expressed as the spacing between objects) for clusters of 10 objects

3. MECHANICAL DESIGN

The focal plane of a MOS is actually a large radius spherical surface, and the fibres must be moved to given positions on this surface, with the fibre itself pointed towards the centre of the sphere (figure 9). The telescopic arm therefore comprises of two linkages:

- A modified straight line linkage which approximates the spherical surface
- A modified parallel linkage which controls the angle of the fibre carrier

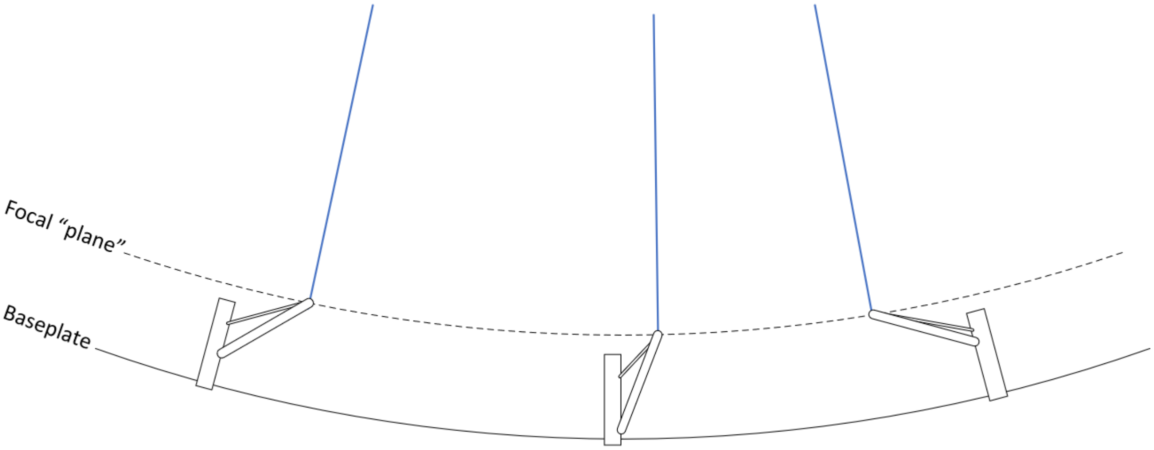


Figure 9. Spherical focal plane showing ideal fibre alignment to incoming light rays

3.1 Modified Straight Line Linkage

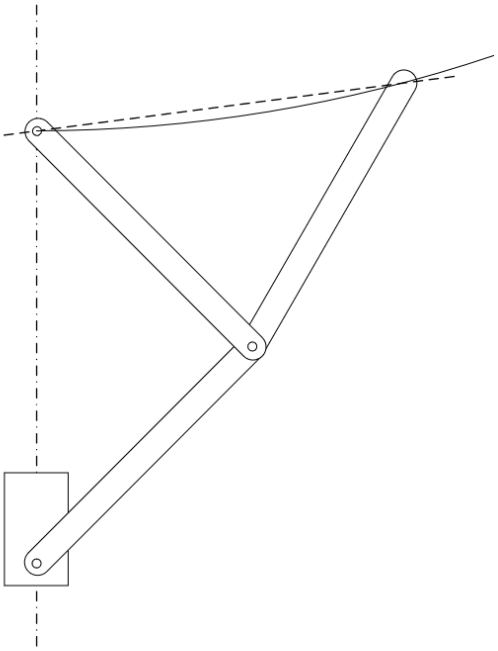
There are a number of true straight line linkages which can be modified to give true circular motion. Unfortunately they typically consist of 6 or more links, each of which increases flexibility and mass, and each connection between links introduces friction that must be overcome by the drive system. One advantage of a system with more links is that a greater range of motion can be achieved in a smaller space.

There are also approximate straight line linkages, and true straight line linkages, that can be modified to give approximate circular motion. The ones of interest consist of 4 links which results in a considerable improvement in overall stiffness and complexity. The challenge is that the path is only a good approximation of circular through a portion of the total range of motion of the mechanism. Long links which achieve the desired reach within a small portion of their range of motion will be heavier and less stiff (and take up more space), so a compromise must be reached depending on the needs of a given instrument.

The straight line mechanism that has been analysed is a Scott Russel linkage which converts linear motion through 90°, so a driven linear motion parallel to the positioner axis is converted to linear motion across the focal plane. Adding an offset angle between the front and rear halves of the long link results in a conical tip path, which is the first approximation to circular motion (figure 10).

Adjusting the relative lengths of the links results in a curved path. The closest approximation of a circular path is achieved by extending the rear portion of the long link (figures 10, 11). Combining the two above modifications gives a path that more closely matches the ideal spherical focal "plane" surface than either independently (figure 12).

Further degrees of freedom in the design are available and may allow for closer approximations of a circular path in combination with those already studied. A full optimization study is needed.



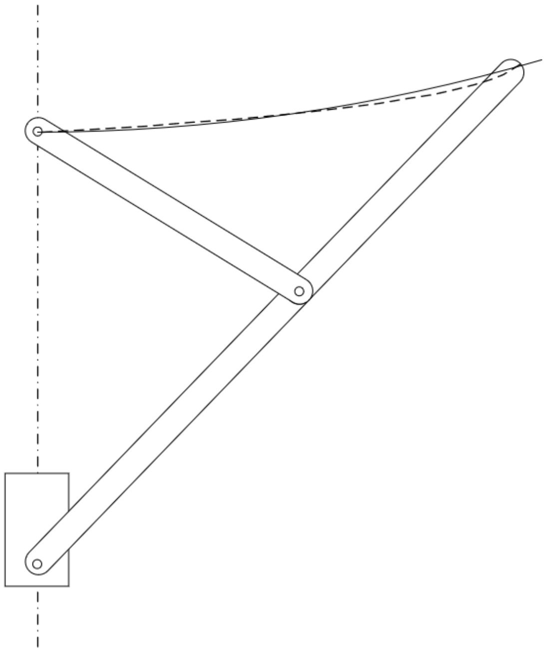


Figure 10. Offset Scott Russel linkage showing conical swept path vs circular focal “plane” (left), and linkage with extended rear part of long link showing curved swept path (right). Curvature of the focal “plane” and so deviations from the original straight line mechanism are exaggerated

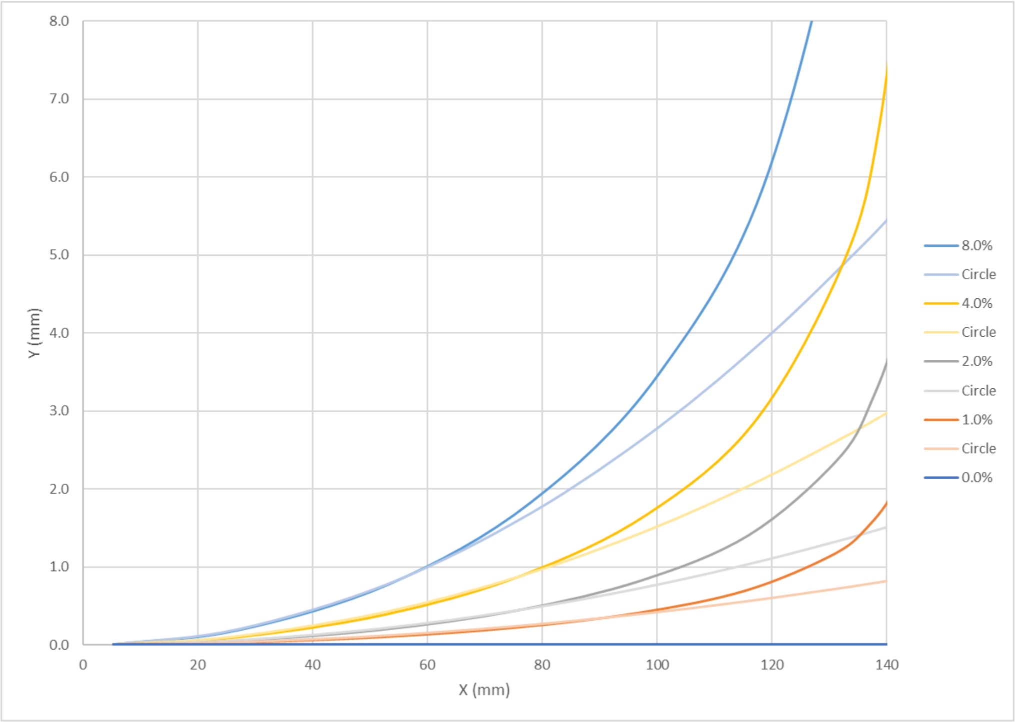


Figure 11. Effect of increasing the rear part of the long link by a given percentage of the original length. Note how a greater increase gives a more pronounced curve, but deviates from the circular path sooner. Vertical displacement is exaggerated

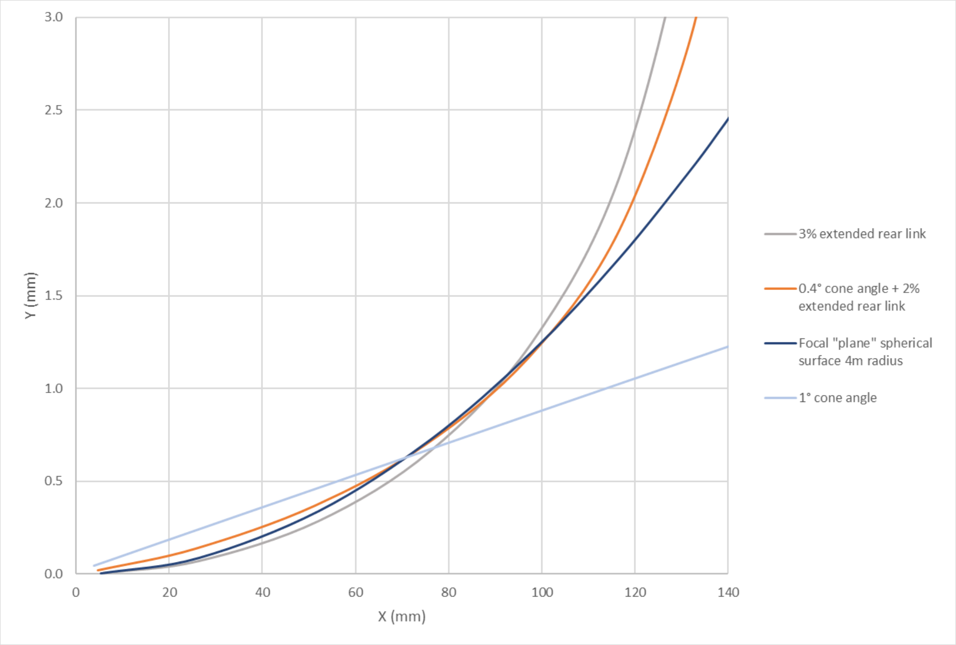


Figure 12. Effect of combining offset and extension. Vertical displacement is exaggerated

3.2 Modified Parallel Linkage

As the positioner moves around the focal plane the fibre must point directly towards the centre of the incoming optical beam. This maximises the light that is transmitted into the downstream spectrograph. As the telescopic arm extends it is therefore necessary for the tip to tilt slightly relative to the positioner's primary axis. This is achieved by using a modified parallel link (figure 13), reducing the spacing between the long links at the tip causes rotation in the correct direction.

The relative position of the two long parallel links is chosen to keep them separated throughout the range of motion of the linkage. This is important because the rotation effect is exaggerated as the links get close together which would not permit the fibre to point at the centre of the optical path through the desired range. Additionally, the stiffness of the arrangement is greatest when the links are well separated, and of course they must not clash.

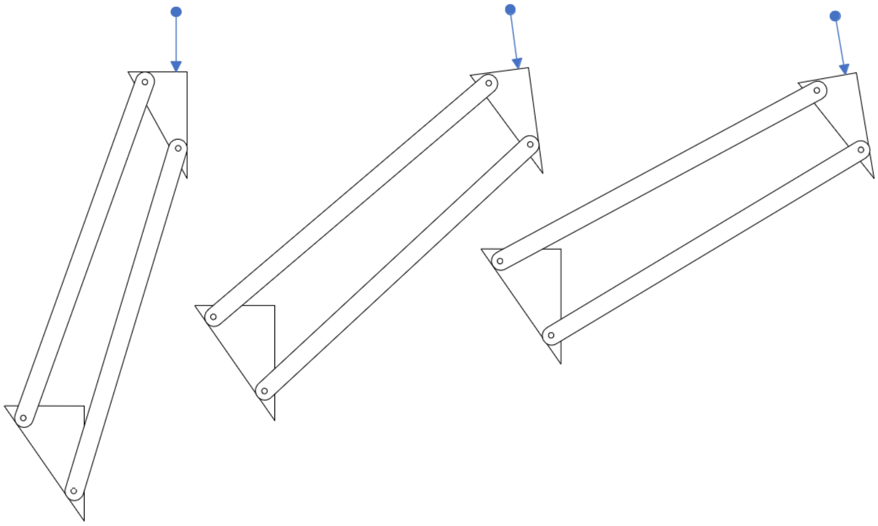


Figure 13. Modified parallel linkage showing orientation of incoming light rays

3.3 Reduced On-Axis Height

One challenge of the Scott-Russel mechanism is that it requires a pivot on the primary axis, at the same height as the tip of the mechanism. The structure to support this pivot would create an exclusion zone around the axis of each positioner, preventing other fibres from accessing this space. We can make use of a parallel linkage (which we already need) to move the offending link and so the pivot on the centreline downwards (figure 14). This allows any fibre that is within reach to be positioned above or close to the centreline of each positioner.

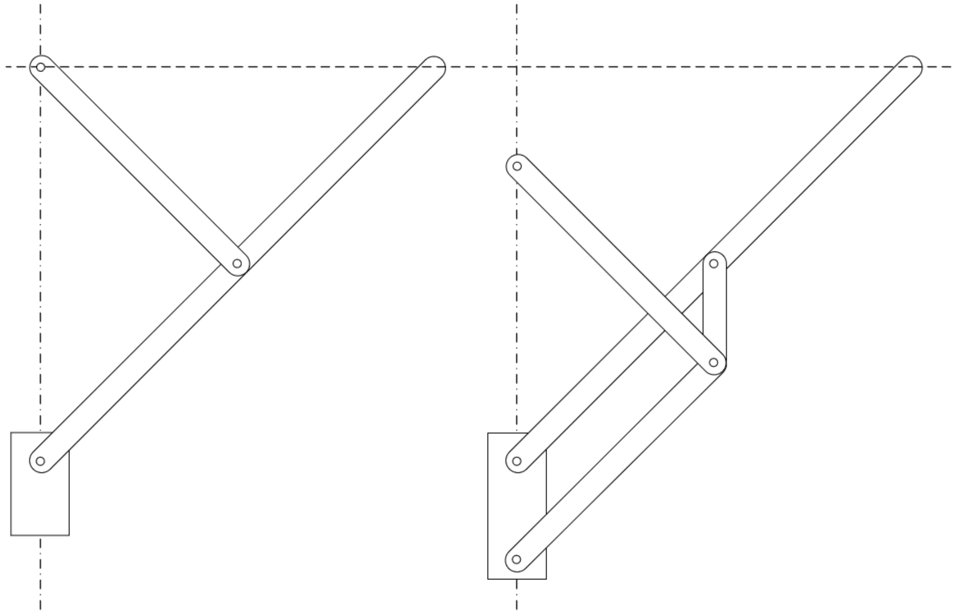


Figure 14. Standard Russel-Scott linkage (left), and modified linkage with identical motion

4. MECHANICAL EMBODIMENT

The overall architecture of the proposal is independent of the physical scale of a given instrument, but in order to explore issues of physically realizing the design it is necessary to consider specific scales (table 1). For this work we have used the scale of the HRMOS instrument proposal, specifically a positioner spacing of 65mm, and VLT focal plane curvature of 4000mm.

Table 1. Key geometry values

Embodiment Geometry	
Positioner Spacing	65mm
Positioner Reach	120mm
Tip Diameter	8mm
Focal Plane Radius	4000mm

The purpose of creating a simple embodiment was primarily to investigate the mechanisms and drives, so structural elements have not been optimized in any way (figure 15).

The primary axis motor is a Faulhaber 1016K SR DC motor, in combination with a Faulhaber 10-1K 4 stage reduction gearbox. This gives a maximum torque of 200mNm which is sufficient to drive against the imbalance of the arm at any position in its range of motion, and at a maximum velocity of ~3 radians per second. Of particular relevance to reconfiguration time is the achievable angular acceleration. This depends on drive torque and moment of inertia of the rotating structure. This latter factor varies with extension of the telescopic arm. It may be favourable to do most or all of the rotation with arms fully retracted, and then extend to the final position with minimal angle adjustment.

The secondary linear drive consists of a Faulhaber AM0820 stepper motor driving a leadscrew with pitch 0.4mm. This gives a linear precision of 20micron at full steps. The linear motion is constrained using a T track which will need to be considered in detail. In particular such a mechanism must not cause backlash nor stick-slip.

The linkages are shown with pin joints; in reality a pin and V groove joint or flexure would give a more precisely defined axis. This would need to be developed to fit in the small footprint required while constraining the necessary degrees of freedom and avoiding stick-slip behaviour.

Deflection of the links is detrimental to performance so they must have a high stiffness to weight ratio. The most promising material for this use case is carbon fibre reinforced composite (CFRP). Ideally this would be uniaxial to give best performance, but it may be preferable to use parts cut from stock material such as sheet or rod.

Compared to a theta-phi arrangement the telescopic arm occupies considerable space in the direction parallel to the rotation axis. A more efficient packaging of the linkage and linear drive with respect to the primary axis drive motor could reduce this dimension considerably. This would reduce the overall cantilever length from the baseplate and so improve stiffness as well as minimising overall instrument volume.

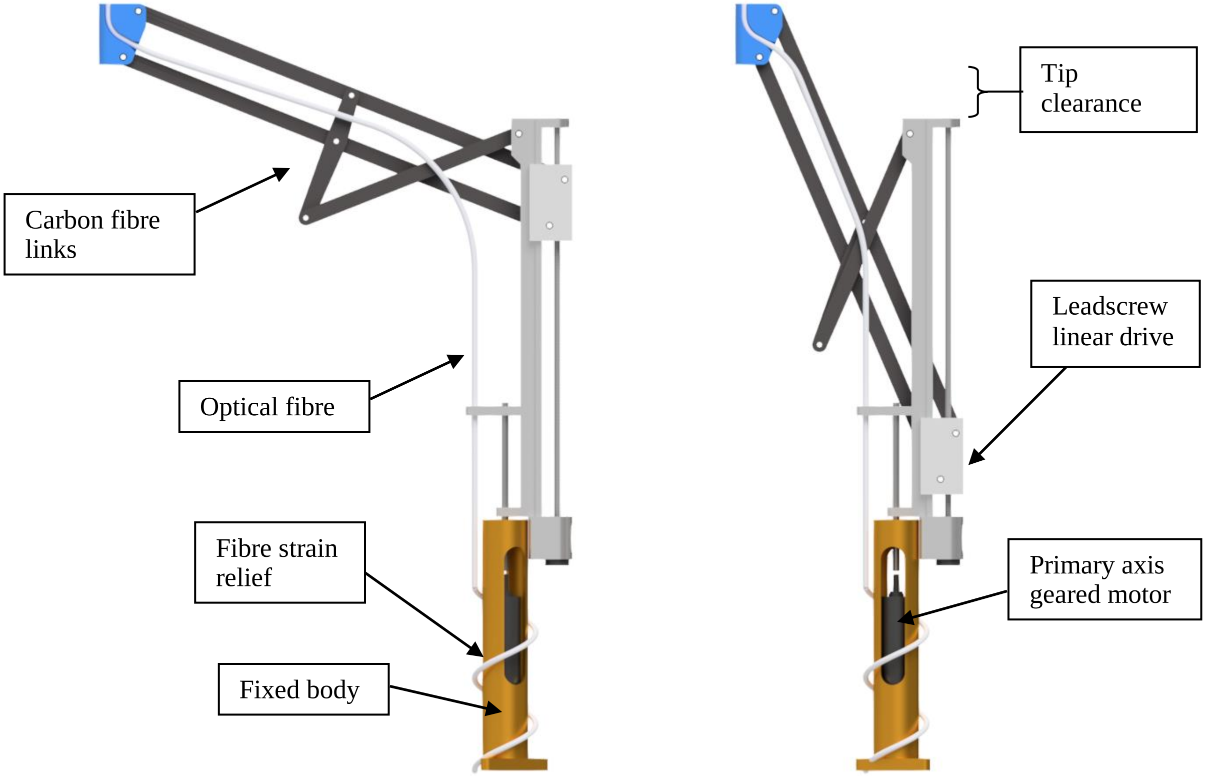


Figure 15. Example theta-r embodiment

Figure 16. Example theta-r embodiment, additional view

4.1 Structural Analysis

The long reach of the fibres presents a challenge for the stiffness of the structure. Predictable static deflections can be compensated for, but dynamic deflections necessitate larger clearances between arms, and hysteresis and non-predictable deflections contribute to the error budget. As such minimizing tip deflection is important. This is primarily achieved by minimising tip and arm mass, and by making the links out of stiff materials. We propose using carbon fibre (CFRP).

Preliminary structural analysis of the concept model suggests that at full extension the tip will deflect under self weight by 0.4mm, and when fully retracted will deflect by 0.3mm (figure 17).

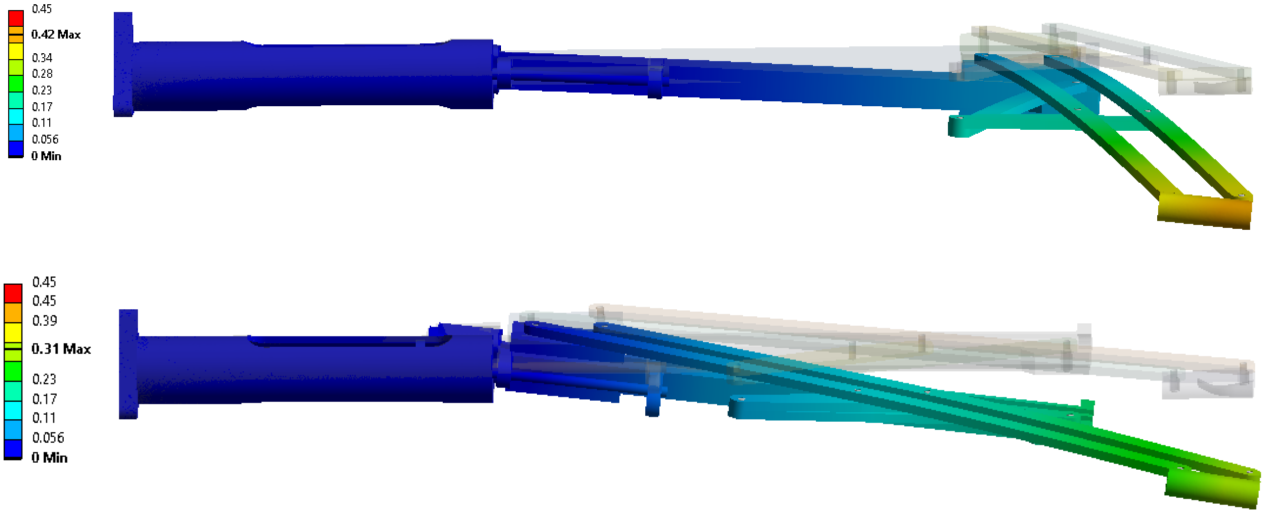


Figure 17. Plots from FEA showing tip displacement: extended (top) and retracted (bottom). Deformation exaggerated

A considerable contribution to the overall deflection comes from the primary axis shaft (figure 18). There is a significant weight projected forward from this and so any bending or twisting of the shaft is amplified. How this rotation axis is supported and constrained should be a focus for future design effort to minimise these effects.

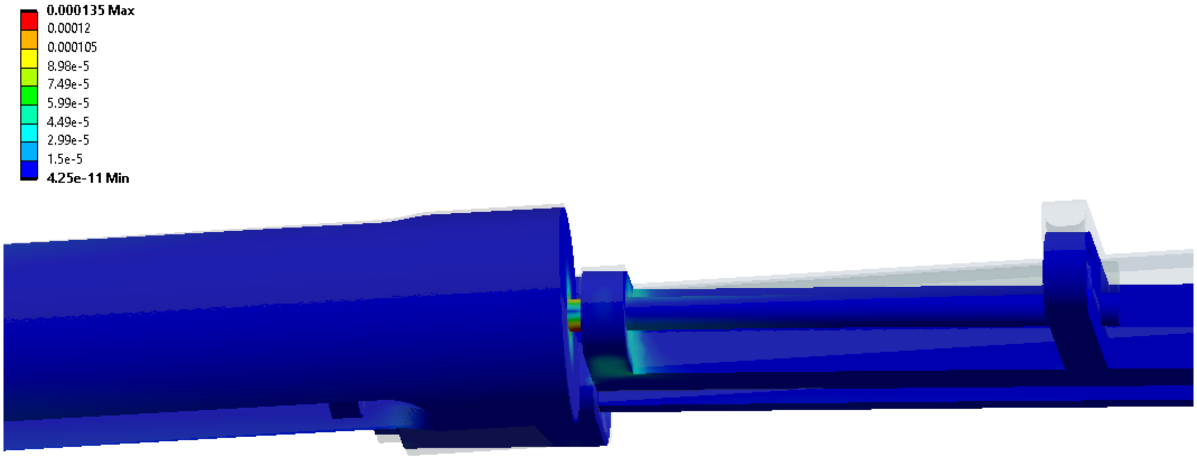


Figure 18. Strain plot from FEA showing high strain of the primary axis shaft. Deformation exaggerated

5. CONCLUSIONS

This initial exploration of the concept is promising and does not throw up any immediate reasons to believe it is non-viable. The solution appears to offer improvements over current positioners for certain use cases, notably those involving long reach positioners to access dense clusters of sky objects.

Further work will cover several streams:

- Full implementation of machine learning to the object selection and routing challenges
- Further optimization of linkages, including consideration of 6 link options. This should specifically address errors introduced by the approximation to circular swept path, and fibre tilt
- Tolerance analysis
- Development of the embodiment design and initial prototyping
- Design of pin and V groove link pivots

5.1 References

[1] Beard S. et al, “MOONS fibre positioner control and path planning software” This conference, 12189-35

[2] Watson S. et al, “MOONS fibre positioning module: instrument build overview” This conference 12188-79