It's Alive! – Performance and control of prototype Starbug actuators

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ABSTRACT

As part of the Starbug development, a range of actuator technologies have been prototyped and trialled in the quest to develop this novel focal plane positioning system. The Starbug concept is a robotic positioning system that deploys multiple payloads, such as pickoff optics, optical fibres and other possible devices to micron level accuracy over a flat or curved focal plane. The development is aimed at addressing some of the limitations of other positioning systems to provide a reliable, cost effective way of positioning multiple payloads in ambient and cryogenic environments. In this paper we identify the specification and required characteristics of the micro-robotic actuators as applied to the MOMSI instrument concept, present descriptions of some of the prototypes along with the results from characterisation and performance tests. These tests were undertaken at various orientations and temperatures as well as using different actuator concepts.

Keywords: Starbug, robotic positioner, micro-actuators, multi-object imaging and spectroscopy, focal plane positioning.

1. INTRODUCTION

There appears to be a strong development trend in the science drivers and instrumentation for many of the world's leading optical/infrared telescopes. Many of these started out with relatively simple programs targeting single or small numbers of sources, but with time the instruments and science programs for the telescope become more complex and highly multiplexed. This has resulted in a large number of wide field multi-object spectrographs in the visible region that have become workhorse instrumentation for 1 to 10m class telescopes, for example: SDSS (Sloan) [1], 2dF (AAT) [2], GMOS (Gemini) [3], DEIMOS (Keck) [4], VIMOS [5] and OzPoz for FLAMES (VLT) [6]. For ground based instrumentation, the wide field requirement adds a significant air-mass dependant field distort constraints and as one moves towards diffraction limited observations, many addition constraints [7] such as second order atmospheric chromatic dispersion across the field.

Furthermore, much of the early science is targeted at the technically "easier" optical wavelengths and then grows to encompass the more challenging "infrared" regime. As many of the easier optical science "cherries" are picked and as cosmology pushes to higher redshift, many of the key diagnostic features shift into the infrared. A further driver is the desire to reveal objects otherwise obscured by dust extension at optical wavelengths, hopefully providing insights into key processes and our understanding of stellar and galaxy formation. These trends, and the requirement to improve observing efficiency, mandate greater multiplex advantage, greater spatial resolution and a shift to infrared wavelengths, all of which are clearly reflected in much of the recent and planned 4-10m telescope instrument development program such as: IRIS2 (AAT) [8], Flamingos-2 (Gemini) [9], CIRPASS (Cambridge) [10], FMOS-Echidna [11] and MOIRCS (Subaru) [12] and KMOS [13]. In this regime, the potential large thermal background from "warm" surfaces imposes the further requirement that much of the optical train of the instrument be cooled well below standard telescope operating temperatures.

These characteristics introduce a large number of technical challenges, many of which cannot be simply solved using conventional positioning technologies. The Starbug concept* has been developed as a generic positioning systems aimed addressing each and all of the above instrument constraints as part of a larger development into the next generation Smart Focal Plane for current and future telescope instrumentation systems and is able to simultaneously deploying large

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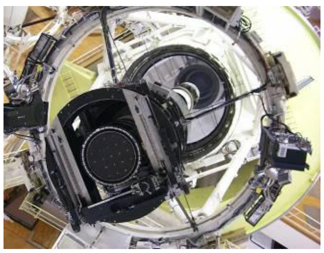
numbers of arbitrary payloads over a focal surface with extremely high accuracy, potentially in a low temperature vacuum environment.

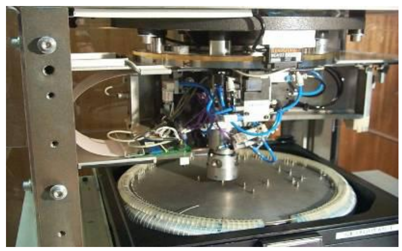
The Starbug concept was first described in 2004 [14] and the Starbug concept primary features and possible applications are discussed in these proceedings [15]. In this paper we summaries the progress made and current status of the Starbug concept as constrained by MOMSI instrument concept [16], part of the Opticon-funded Smart Focal Plane Technologies program [17].

2. THE STARBUG HERITAGE

The Starbug concept is one of the latest of many positioning concepts developed at the AAO (Fig. 1) to deploy multiple payloads in a telescope focal plane. The 2dF system was a development of earlier systems such the Autofib series [18] and so these requirements are clearly not new.

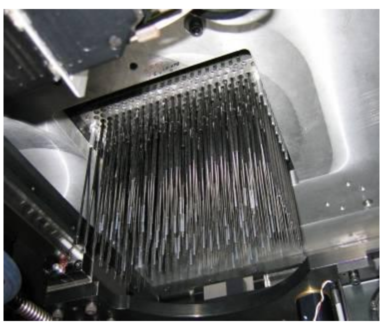


2dF System

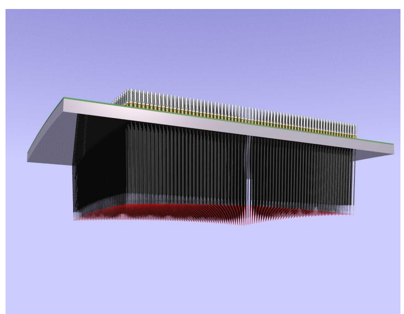


6dF Positioner and field plate

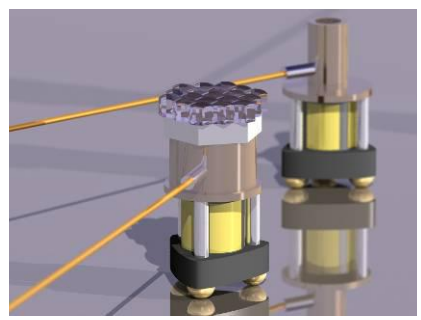
OzPoz positioner and field plate



FMOS-Echidna positioner



WFMOS positioner concept



Starbug positioner concept

Fig. 1. Multi-object positioning systems developed at the Anglo-Australia Observatory in chronological order.

"Pick and Place" positioning systems such as 2dF addressed positioning up to 400 objects with a single robot positioning magnetic buttons (in this case carrying optical fibres) on a flat focal plate. 2dF was followed by 6dF and OzPoz, designed to operate with a curved focal surface. With these "Pick and Place" systems the configuration time is essentially proportional to the number of deployable payloads and could potentially lead to unacceptable delays between observations. However this was overcome, at the expense of mass and mechanical complexity, by using multiple exchangeable field plates. This allows preparation of one field configuration while another is observing and so minimizing or eliminating the configuration "dead time".

The FMOS-Echidna system, based on thin fibre-carrying spines operating within specific patrol areas, was developed to address the packing density associated with systems at the fast prime foci of 8-10m and ELT class telescopes (~f/2). Each spine in the FMOS-Echidna system can be simultaneously and independently moved, effectively freeing its field configuration time from its former proportional dependence on the number of deployable payloads. Fast configuration times eliminate the large "dead times" between observations without the need for multiple field plates. This can have large space/mass/cost savings and reduce system complexity; all can be of particular value in cryogenic environments. Also the single field plate design has the added bonus of limiting the required number of buttons/pucks over that required by twin plate systems. The time taken to re-configure the focal surface for the next science field, when employing the simultaneous and independent movement, might easily be absorbed in the time taken to slew to and acquire the next field centre with the telescope. Furthermore, even over moderately wide fields, the ability to make small adjustments to spine positions in "real time" (micro-tracking) can be used to compensate the change the relative position of target objects of the focal surface as a result of differential atmospheric refraction effects, a function of air-masses. To a limited extent, this effect may be accommodated in a suitably designed twin plate "pick and place" system by anticipating when the target shifts would reach unacceptable levels, and configure a "tweaked" field on the second plate with the positional adjustment included, then swapping field plates. The "pick and place" systems have been shown to be very effective as a key component of large survey facilities. However, this is not ideal as the field plate might only be optimally configured for a relatively short length of time and also has to include the overhead of changing plates and re-acquiring the field. Furthermore, in swapping plates the some optical path components change and this can lead systematic errors being introduced in the data. For massively multiplexed systems such WFMOS it would be quite impractical to position up to 4500 fibres using a pick and place system. The Echidna concept, where all the fibres might be configured simultaneously, is well matched to the problem.

3. STARBUG CONCEPT

3.1 Starbug concept and requirements

Worldwide, a variety of micro-robotic developments provide very useful insights into design possibilities for Starbug actuators, however none of these appear to adequately fulfil the specific requirements visualised for application in astronomical instrumentation. Starbug is a general concept aimed at providing a relatively simple, cheap, scalable, reliable, and multiply-redundant system for positioning arbitrary payloads in warm or cryogenic[†] environments, requiring positioning accuracies and stabilities typically around the micron level. It takes advantage of the simultaneous configuration nature of FMOS-Echidna, allowing both fast reconfiguration and micro-tracking[‡], along with positioning versatility of "pick and place" systems that can be unconstrained by zonel placement of the payloads. These payloads can be positioned on a curved, flat, or arbitrarily shaped focal surfaces, however, unlike "pick and place" systems the Starbugs moved simultaneously and independently in the manner of Echidna spines. Of course there is no requirement that a single actuator technology fulfil the requirements for more than a single instrument, although there are clear advantages in the reuse of designs that do this.

Two fundamentally different Starbug approaches have been investigated; the first with active bugs patrolling over a passive focal surface, and the second with passive bugs being positioned on and by an active surface. Both schemes should remain cost effective and readily scaleable. Schemes such as the pick-off arm system employed by KMOS may be effective when target numbers are small, but become impractical for large number of targets in a field. This is analogous to the MX "fishermen around a pond" positioning technology [19], which was pretty much superseded by "pick and place" system in the drive to increase the multiplex advantage of wide field systems.

3.2 Active Starbugs scheme

The active Starbug concept employs self propelled units, which are controlled to move themselves to any point on a field plate and orientate themselves in rotation should that functionality be required. This scheme and possible applications are discussed in much greater detail in these proceedings by Andrew McGrath [15].

An example of a generic concept for subfield imaging (also suitable for the MOMSI Instrument concept) is shown in Fig. 2, in which Starbug mirror-based optical relays be pointed towards the base station optics that relaying the target light from the focal surface into the main instrument units, in the case of MOMSI this would be integral field spectrographs.

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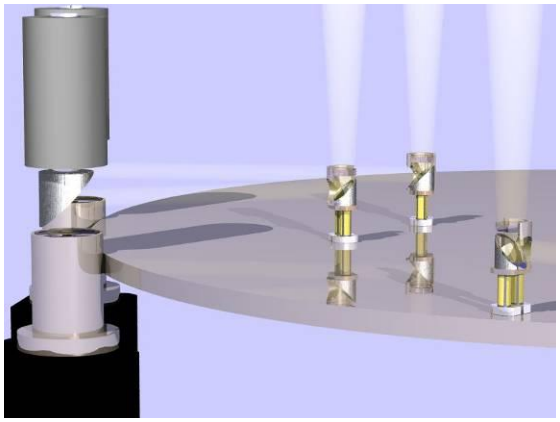
† Low temperature system environments are often required for infrared instrumentation.

‡ Micro-tracking is the ability to tweak the position of the Starbug in order to track the micro scale motion of the object introduced by atmospheric refraction effects for example.



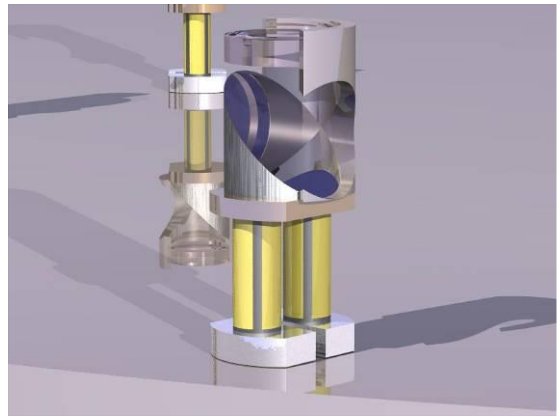
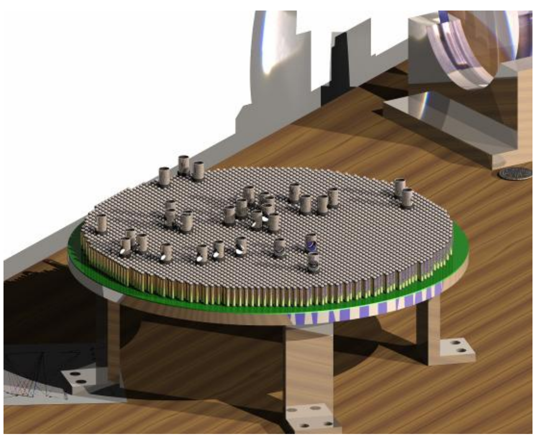


Fig. 2. Left; A representation of a generic Starbug concept for a focal plane pickoff system with Starbugs and base station unit pairs, this basic concept is also applicable to the MOMSI instrument concept. Right; A detailed representation of a Starbug unit carrying a mirror and lens payload.

3.3 Active focal surface scheme

An active focal surface Starbug scheme has been pursued via what is known as the "Crowd Surfer" concept (Starbug-CS) illustrated in Fig. 3. In this arrangement, a flat field plate is made up of an array of actuators, each with magnetic contact at the top. The passive bugs are magnetically secured to the spherical tips of the actuators and are sized such that at least three contact points are under each, wherever they are on the surface. By "flexing" and "flicking" the actuators in an action similar to cilia (small whip like appendages of many living cells that are used to move fluid or to propel the cells along, with an oar-like motion), the bugs can be moved anywhere over the surface. Each actuator can be addressed and controlled individually, or in groups, enabling X, Y and rotational motion of every bug, individually or simultaneously.



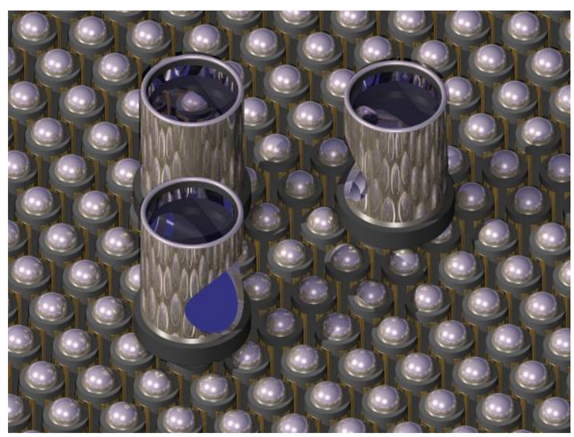


Fig. 3. Left; Starbug-CS, with passive bugs on an active field plate comprised from a "field" of quadrant piezo tubes. Right; Detail of the passive Starbugs of the "Crowd Surfer" concept, each with a lens and fold mirror payload.

3.4 Concept development

By far the majority of the AAO Starbug development effort has been directed at the active Starbug scheme as the unit cost and system complexity tend to scale fairly directly with Starbug numbers, while the active plate of the passive-bug Starbug-CS scheme means instrument cost is largely independent of bug number. The performance of the Starbug prototypes is discussed below.

4. STARBUG PROTOTYPES AND PERFORMANCE

4.1 Base MOMSI-Starbug requirements

As much of the Starbug funding has come from the Opticon Smart Focal Planes program the program has been directed towards the requirements of the MOMSI instrument for a 30-100m aperture European ELT. The base requirements were that the Starbugs should;

- have a footprint of less than 10mm
- operate under closed loop control
- attain positional accuracies of around 1μm or better
- accommodate micro-tracking to correct for field distortions (e.g. atmospheric refraction effect)
- orientate a Starbug payload to point to the optical relay pick-off stations
- deploy freely over a possibly curved focal surface
- operate at varying gravitational orientation from 0-90º
- operate in a low temperature and vacuum environment.

4.2 Starbug prototypes

4.2.1 Kickbot

The earliest of the Starbug prototypes, known as Kickbot, served to demonstrate the feasibility of the Starbug concept (Fig. 4, left) and was showcased at the Glasgow SPIE instrumentation meeting in June 2004. Kickbot, based on a quadrant piezo tube, is an inertial stick-slip device with a footprint of ~6mm achieving a sub-micron step size and moving at a rate of a few mm per minute over a field plate tilted up to 20º. It is able to move in x and y in a predictable manor, but is not capable of rotation. Kickbot lends itself readily to micro-tracking and has a good payload potential. It has 4 electrical connections to high voltage, low current and low frequency drive electronics. The main limitations for Kickbot in terms of a MOMSI implementation are slow movement and inability to rotate.

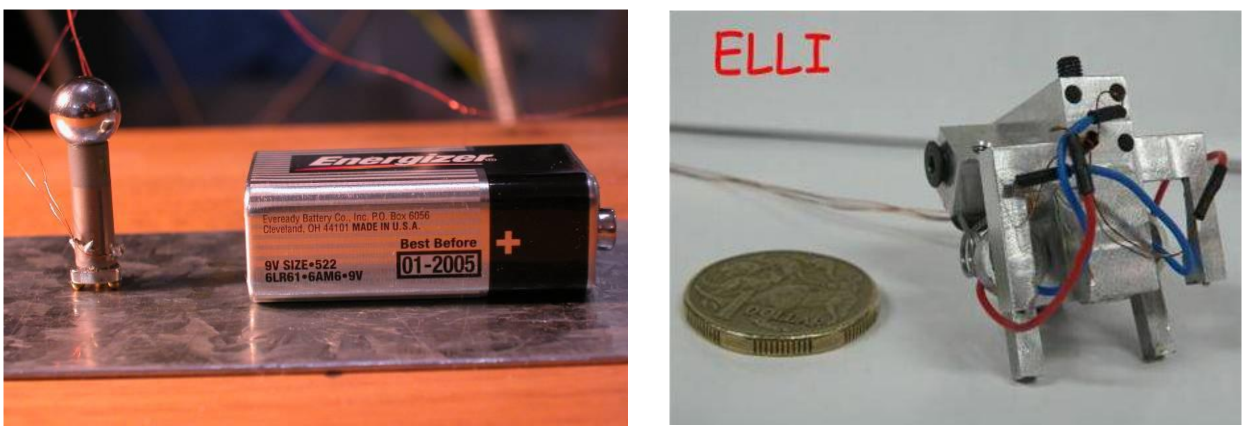


Fig. 4. Left; the "Kickbot" Starbug prototype next to a PP3 battery, Right; one of the "Elli" Series of Starbug prototypes next to an Australian dollar coin (~24mm in diameter).

4.2.2 Elli Series

The Elli series (see example in Fig. 4, right) were the second generation Starbug prototypes and where primarily aimed at increasing the speed of the devices. They are based on a pair of Elliptec[§] resonant actuators, to act as resonant stick-slip devices. The footprints of the Elli series bugs are typically around 25mm square. As they are based on resonant

§ Elliptec Resonant Actuator are based on Piezo technology, see www.elliptec.com drives the step size has little meaning and was not determined, however, they all move at rates of several centimetres per second (up to tens of cm/s) over a horizontal field plate and continue to operate, though at reduced speed, with the field plate tilted at angles up to and including vertical. They are able to move forwards and backwards and have some rotation capability, but this was typically limited to moving in an arc and not a true rotation. Potential for micro-tracking is limited as they are not able to move in well-defined steps, but they do have a good payload potential being able to exert a pulling force of up to ~1N. These devices each require drive electronics with 4 electrical connections (one pair for each actuator), operating with to low voltage drive frequencies in the kHz range. The main limitations for Elli in terms of a MOMSI implementation are the somewhat poor determinism of the movement, the limited rotation capability and the size.

4.2.3 Rez Series

Most of the Rez series of prototypes are based on low-voltage piezo stack devices, the exception being Rez-J that is based on a quadrant piezo tube. All of the Rez series operate by a resonantly enhanced inertial stick-slip action.

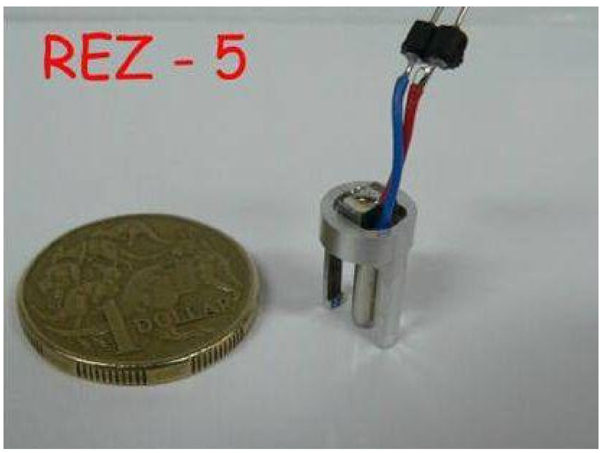


Fig. 5. Left; Rez-5, a late generation piezo stack resonance based Starbug prototype next to an Australian dollar coin (~24mm in diameter). Right; Rez-J, a quadrant piezo tube resonance based Starbug prototype next to an Australian dollar coin.

Rez-5 (Fig. 5, left) is a resonant device with a footprint of 10mm that has a step size much less than 1μm and move at a rate of many mm/s over a field plate at orientations from 0 - 90º. It is able to move in several directions, and can rotate both clockwise and anticlockwise without significant lateral movement. Rez-5 appears to be capable of small motions and so should be able to micro-track. Rez-5 has been shown to operate both at room temperature in air, and down to temperatures below -100ºC in a vacuum. It has 2 electrical connections to low voltage, moderate current and high frequency (100s kHz) drive electronics. Rez-5 is appears to fulfill the initial MOMSI requirements, but the controllability and load capacity need improving.

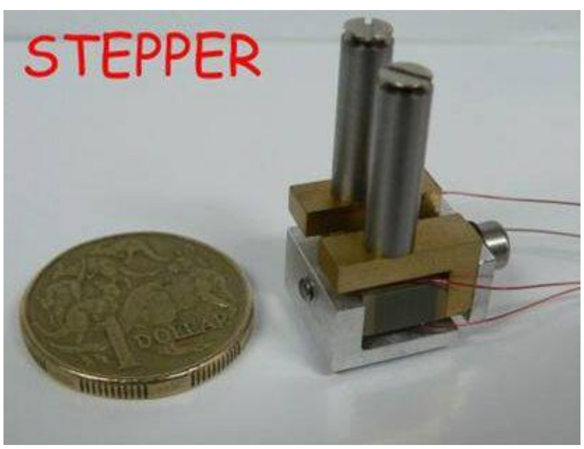
Rez-J (Fig. 5, right) is a resonant device with a footprint of 6mm that has a minimum step size of less than 1μm and moves at a rate around 1mm/s at room temperature over a field plate at orientations from 0 - 90º. It is able to move in several directions and can rotate both clockwise and anticlockwise without significant lateral movement. Rez-J should be able to micro-track. Rez-J has also been shown to operate down to temperature below -100ºC, and although the speed is reduced to around 0.25mm/s at low temperature, it is likely that a full instrument specification would not exceed such a figure. It has 4 electrical connections to high voltage, low current, moderate frequency (kHz) drive electronics. Rez-J is capable of fulfilling the initial MOMSI requirements, but the controllability and load capacity need improving. The performance of the Res-J prototype is compared to the MOMSI deployable pickoff requirements benchmark in Table 1. It has been demonstrated to reach most of these, but further development and testing is required against a more thorough set of instrument requirements.

Table 1: Performance of Res-J prototype against target specification for the MOMSI deployable pickoff units

Parameter	Target Specification	Achieved Performance
Size	Footprint <10mm diameter	6mm diameter
Number of pickoff units	Minimum 100, Goal 1000	1 demonstrated, 100s in principle
Motion	X and Y	X and Y
Speed of Motion	>1mm/s	>5mm/s at ~20ºC, <1mm/s at -100ºC
Minimum step size	<1µm	<2µm at ~20ºC
Minimum operational temperature	-100ºC	-100ºC
Gravitational orientation	Arbitrary	Horizontal and vertical surfaces

4.2.4 Stepper

The Stepper prototype (Fig. 6, left) is the second in a generation of inertial stick-slip devices that have been designed to improve the determinism of the Starbugs. Stepper has a footprint of ~18mm that has a step size less than 1µm and moves at a rate of around 0.5mm/s over a horizontal field plate. It has not been tested on tilted field plates or in cold environments. It is able to move backward and forward as well as rotate. Stepper lends itself readily to micro-tracking and has a good payload potential. It has 4 electrical connections to low voltage, moderate current, and low frequency (100s Hz) drive electronics. The main limitation for Stepper in terms of a MOMSI implementation is its size, and possibly its speed under load.



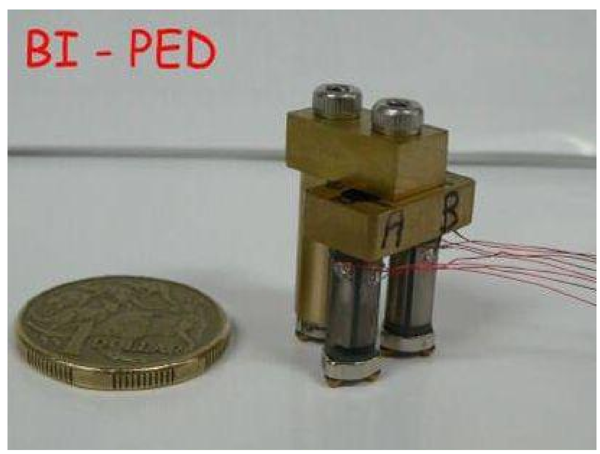


Fig. 6. Left; Stepper, a piezo stack inertial stick-slip based Starbug prototype, photographed next to an Australian dollar coin. Right; Bi-Ped, a quadrant piezo tube inertial stick-slip based Starbug prototype photographed next to an Australian dollar coin.

4.2.5 Bi-Ped

The Bi-Ped prototype is based on a two quadrant piezo tubes and was initial tested as a true biped device, but as part of the development program a third inert leg was added as shown on the right hand side of Fig. 6. Bi-Ped is an inertial stick-slip device with a footprint of ~18mm, has a step size less than 1µm and moves at a rate of a few mm per minute over a horizontal field plate. It was not tested on tilted field plates or in cold environments. It is able to move in x and y and is capable of rotation. Bi-Ped lends itself readily to micro-tracking and has a good payload potential. It has 8 electrical connections to high voltage, low current, and low frequency (100s Hz) drive electronics. The main limitations for Bi-Ped in terms of a MOMSI implementation are its large size and slow movement.

4.2.6 Crowd Surfer

The Crowd Surfer prototype differs significantly from the previous devices in that it uses an active focal surface scheme. Quadrant piezo tubes both form the field plate and provide the motion. Crowd Surfer is an inertial stick-slip based scheme with a minimum passive Starbug unit footprint of ~6mm that has a step size around 1μm and moves the Starbug at rates of about ½mm/s over a horizontal active surface. It is able to move bugs in x and y in a predictable manner, but low temperature operation has not been attempted. The current simple prototype drive electronics are not sophisticated enough to drive the actuators in the required sequence to achieve rotation although modelling suggests this is achievable. Crowd Surfer is well-capable of micro-tracking and has a very good payload potential. It has 4 electrical connections for each actuator from high voltage, low current, and low frequency (100s Hz) drive electronics. The main limitations for Crowd Surfer in terms of a MOMSI implementation are the very limited development this concept has received, the potential cost and complexity of the active plate and control systems for small numbers of Starbugs.

Fig. 7. A photograph of the Crowd Surfer active plate, a quadrant piezo tube based active focal surface. The passive Starbug units that sit on top of the quadrant tubes are not shown in this photograph.

4.3 Starbug metrology system

The Starbug prototype metrology and closed loop control system (Fig. 8) is based on an overhead camera/lens, similar to that used for the FMOS-Echidna system, and demonstrated centroiding performance locates the Starbug metrology targets to better than a 1/30th Pixel (3 sigma). This arrangement and was used to control the Res-J prototype Starbug under closed loop control to within 10μm (i.e. to the imposed resolution limit for the feedback control system) of the ideal target position.

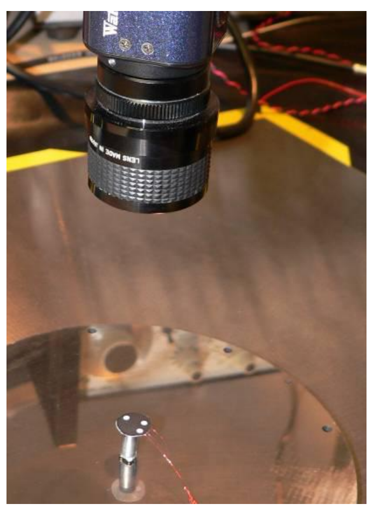


Fig. 8. Metrology and feedback control system for the Starbug prototype. The camera/lens combination is at the top of the photograph and in the lower part of the photograph Res-J has a positioning target attached on top sitting on the test field plate.

4.4 Starbug allocation efficiency

In the context of a MOMSI implementation of Starbug a series of simulations where carried out to determine the efficiency with which Starbugs (designed to conform to the MOMSI minimum requirement of 10mm of less in size) to randomly distributed targets over the MOMSI field of view. One such simulation is shown in Fig. 9 in which 200 Starbugs are available to be allocated to any of 800 randomly distributed targets. In this example it was possible to allocate 178 out of the 200 Starbug to targets without infringing on the "clear line of sight" requirement between the Starbug pickoff mirror and base station located at the edge of the field plate and is reasonably representative of the simulation result.

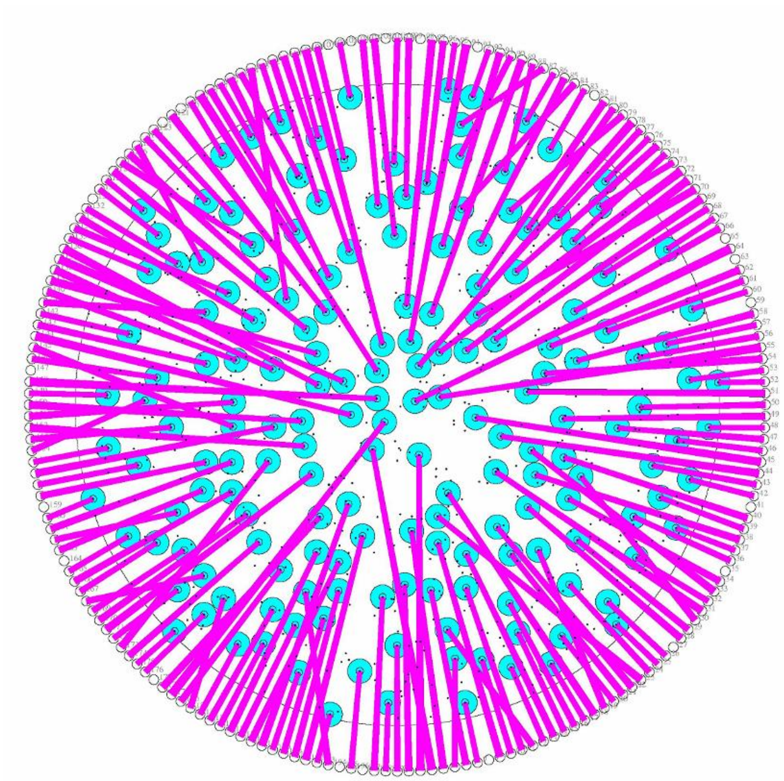


Fig. 9. Simulation of a Starbug allocation given 800 possible targets over field plate 260mm across, with 2mm collimator lenses, 4mm pick-up lenses, 10mm bug diameters. In this case 178 out of 200 Starbugs are allocated.

5. FURTHER DEVELOPMENT

At the current stage of the Starbug development we believe that the basic feasibility of the technology has been demonstrated, however, there is still significant work required in order to develop sufficiently mature actuator technologies achieving a suitable "technology readiness level" (to use NASA-speak) such that the Starbug concept could be considered for a full instrument development system. As the Starbug currently stands, some system components are at TRL2 and some are closer to TRL3 (such as some of the Starbug units). In order to seriously consider incorporating the system into an instrument build it would be highly desirable that the concept be developed to at least TRL6 for the higher risk components of the system. All that said, much of the basic Starbug system control architecture can be adapted from other AAO positioning systems such as FMOS-Echidna (which are currently being acceptance tested - equivalent to TRL8 - prior to shipping and commissioning on the Subaru telescope) and 2dF that has been in operation on the AAT from ~10 years. This enable the AAO to recycle previous a massive amount of previous investment these systems, reducing much of the development to the Starbug units and control electronics.

<u>Summary of Technology Readiness Levels</u>

TRL 1 Basic principles observed and reported
TRL 2 Technology concept and/or application formulated
TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4 Component and/or breadboard validation in laboratory environment
TRL 5 Component and/or breadboard validation in relevant environment
TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7 System prototype demonstration in a space environment
TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9 Actual system "flight proven" through successful mission operations

6. CONCLUSION

The Starbug concept, as applied to the MOMSI instrument requirements, has been jointly funded by the Australian Government Innovation access program and the Smart Focal Plane Technologies development program as part of the European Union Framework 6 program. It addresses some of the weaknesses of current positioning systems and providing a reliable, cost effective way of positioning multiple payloads, the Starbug concept employs micro-robotic actuators (either using active bugs or an active field plate) that can independently and simultaneously position multiple small payloads accurately across arbitrarily sized and/or curved surfaces. One significant advantage over most conventional pick and place schemes is the ability to make small positional adjustments in "real time" during an observation correcting for residual atmospheric refractive effects and instrument flexure.

The Starbug development has already achieved significant successes, and at the time of writing, has demonstrated; Starbug prototype units with minimum actuator step size at the sub-micron level, and can operate under closed loop control and at temperatures down to -100ºC, using a variety of low cost technologies and approaches. However, significant further development is required to key areas of system before some of technologies employed can be regarded as being at a sufficiently mature level (or "Technology Readiness Level" to use NASA speak) to provide a low risk, reliable, cost effective, highly flexible focal plane positioning for applications in astronomical instrumentation.

REFERENCES

1. D. G. York, et al., "The Sloan Digital Sky Survey: Technical Summary", *The Astronomical Journal,* Volume 120, Issue 3, 1579-1587, 2000.

2. I. Lewis et al., "The Anglo-Australian Observatory's 2dF facility", *Mon. Not. R. Astron. Soc.* **333 issue 2**, 279-299, 2002.

3. D. Crampton, R. Murowinski, "Scientific and technical performance of GMOS: the Gemini Multi-Object Spectrograph", *Ground-based Instrumentation for Astronomy, ed. A. Moorwood and M. Iye,* Proc SPIE **5492**, 181-189, 2004.

4. DEIMOS Webpage, http://loen.ucolick.org/Deimos/deimos.html.

5. O. Le Fevre et al. "Commissioning and performance of the VLT-VIMOS", *Instrument Design and Performance for Optical/Infrared Ground bases Telescope, ed. M. Iye, A. Moorwood*, Proc. SPIE **4841**, 1670-1681, 2003.

6. P. Gillingham et al., "The performance of OzPoz, a multi-fiber positioner on the VLT", *Instrument Design and Performance for Optica/Infrared Ground-based Telescopes, ed. M. Iye & A. Moorwood*, Proc. SPIE **4841**, 1170-1179, 2003

7. A. Russell et al., "Instruments for a European Extremely Large Telescope: The challenges of designing instruments for 30-100m telescopes", *Ground-based Instrumentation for Astronomy, ed. A .Morwood & Mice*, Proc. SPIE **5492**, 1796-1809, 2004.

8. C. G. Tinney, S. D. Ryder, S. Ellis, V. Churilov, J. P. Dawson, G. A. Smith, L. G. Waller, J. D. Whittard, R. Haynes, A. F. Lankshear, J. R. Barton, C. J. Evans, K. Shortridge, T. J. Farrell, J. A. Bailey, "IRIS2: a working infrared multi-object spectrograph and camera" *Astronomical Telescopes and Instrumentation,* SPIE Proc. **5492**, 998-1009, 2004.

9. Eikenberry, Stephen S.; Elston, Richard; Raines, S. Nicholas; Julian, Jeff; Corley, Richard J.; Hanna, Kevin; Hon, David; Julian, Roger; Rashkin, David; Leckie, Brian; Gardhouse, W. Rusty; Fletcher, Murray; Dunn, Jennifer; Wooff, Robert, "FLAMINGOS-2: the facility near-infrared wide-field imager and multi-object spectrograph for Gemini, Ground-based Instrumentation for Astronomy, ed. A. Moorwood and M. Iye. Proc. SPIE **5492**, 1196-1207, 2004.

10. Parry, Ian; Bunker, Andrew; Dean, Andrew; Doherty, Michelle; Horton, Anthony; King, David; Lemoine-Busserole, Marie; Mackay, Craig D.; McMahon, Richard; Medlen, Steve; Sharp, Robert G.; Smith, Joanna, "CIRPASS: description, performance, and astronomical results", *Ground-based Instrumentation for Astronomy, Ed. A. Moorwood and M. Iye,* Proc. SPIE **5492**, 1135-1144, 2004.

11. Gillingham, Peter R.; Moore, Anna M.; Akiyama, Masayuki; Brzeski, Jurek; Correll, David; Dawson, John; Farrell, Tony J.; Frost, Gabriella; Griesbach, Jason S.; Haynes, Roger; Jones, Damien; Miziarski, Stan; Muller, Rolf; Smedley, Scott; Smith, Greg; Waller, Lew G.; Noakes, Katie; Arridge, Chris, "The Fiber Multi-object Spectrograph (FMOS) Project: the Anglo-Australian Observatory role", *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes. Edited by M. Iye, A. Moorwood,* Proc. SPIE **4841**, 985-996, 2003.

12. Tokoku, Chihiro; Suzuki, Ryuji; Ichikawa, Takashi; Asai, Ken'ichiro; Katsuno, Yuka; Omata, Koji; Yamada, Toru; Sasaki, Atsuo; Nishimura, Tetsuo, "MOIRCS: Multi-Object Infrared Camera and Spectrograph for the Subaru Telescope", *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes. Edited by M. Iye, A. Moorwood,* Proc. SPIE **4841**, 1625 – 1633, 2003.

13. R. Sharples et al., "KMOS: an infrared multiple-object integral field spectrograph for the ESO VLT", *Ground-based Instrumentation for Astronomy, ed. A. Morwood & M. Iye*, Proc. SPIE **5492**, 1179-1186, 2004.

14. A. McGrath and A. Moore, "Starbug: enabling the smart focal plane", Astronomical Structures and Mechanisms Technology, ed. J. Antebi & D. Lemke, Proc. SPIE 5495, 600-610, 2004

15. A. McGrath and R. Haynes, "Deployable payloads for Starbug", Optomechanical Technologies for Astronomy, ed. E. Atad-Ettedgui, J. Antebi & D. Lemke, Proc. SPIE 6273, paper 70, 2006.

16. S. Ramsey-Howat, www.mpia-hd.mpg.de/ELT/PPTs/Ramsay-Howat/ELT_Instrumention2.ppt

17. Colin Cunningham, “Smart Focal Planes” http://www.astro-opticon.org/presentations/misc_downloads/JRA5_18_month_report.pdf

18. Lewis, Ian J.; Sharples, Ray M.; Parry, Ian R.; Jones, Lewis R.; Watson, Frederick G.; Barker, Stuart A.; Rees, P. C., “Autofib-2: commissioning results of a robotic multiobject fiber system for the William Herschel Telescope”, *Optical Telescopes of Today and Tomorrow ed. Arne L. Ardeberg,* Proc. SPIE **2871**, 1318-1324, ,1997.

19. J. M. Hill, M. P. Lesser, “Deployment of the MX spectrometer”, *Instrumentation in astronomy VI,* Proceedings of the Meeting, Tucson, AZ, Mar. 4-8, Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 303-320, 1986.

20. J. Bland-Hawthorn, M. Englund, and G. Edvell, “New approach to atmospheric OH suppression using an aperiodic fiber Bragg grating”, *Opt. Express 12*, 5902-5909 (2004).

21. J. Bland-Hawthorn & A. Horton, “Instruments without optics: an integrated photonic spectrograph”, *Ground-based and Airborne Instrumentation for Astronomy, ed. I. McLean & M. Iye*, Proc. SPIE **6269**, paper 23, 2006.

22. A. Russell et al., “Instruments for a European Extremely Large Telescope: The challenges of designing instruments for 30-100m telescopes”, *Ground-based Instrumentation for Astronomy, ed. A. Morwood & M. Iye*, Proc. SPIE **5492**, 1796-1809, 2004.

23. J. Bland-Hawthorn et al., “Honeycomb: a concept for a programmable integral field spectrograph”, *Ground-based Instrumentation for Astronomy, ed. A. Morwood & M. Iye*, Proc. SPIE **5492**, 242-250, 2004.