March of the Starbugs: Configuring Fibre-bearing Robots on the UK-Schmidt Optical Plane

Nuria P. F. Lorente\textsuperscript{1}, Minh Vuong\textsuperscript{1}, Christophe Satorre\textsuperscript{1,2}, Sungwook E. Hong\textsuperscript{3}, Keith Shortridge\textsuperscript{1}, Michael Goodwin\textsuperscript{1} and Kyler Kuehn\textsuperscript{1}

\textsuperscript{1}Australian Astronomical Observatory, PO Box 915, North Ryde, NSW 1670, Australia
\textsuperscript{2}Laboratoire de Systèmes Robotiques (LSRO), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 9, 1015 Lausanne, Switzerland
\textsuperscript{3}Department of Physics, Korea Institute for Advanced Study, Seoul 130-722, Korea

Abstract. The TAIPAN instrument, currently being developed for the Australian Astronomical Observatory’s UK Schmidt telescope at Siding Spring Observatory, makes use of the AAO’s Starbug technology to deploy 150 science fibres to target positions on the optical plane. This paper describes the software system for controlling and deploying the fibre-bearing Starbug robots. The TAIPAN software is responsible for allocating each Starbug to its next target position based on its current position and the distribution of targets, finding a collision-free path for each Starbug, and then simultaneously controlling the Starbug hardware in a closed loop, with a metrology camera used to determine the position of each Starbug in the field during reconfiguration. The software is written in C\texttt{++} and Java and employs a DRAMA middleware layer (Farrell et al. 1995).

1. Introduction

Multi Object fibre Spectroscopy (MOS) is a well-established technique for efficiently carrying out spectroscopy on a large number of targets in the field of view. The AAO’s 2dF instrument (Lewis et al. 2002) has facilitated spectroscopic studies of many thousands of objects in the 17 years since it began operation — e.g. 2dFGRS (Colless et al. 2001), 2QZ (Boyle et al. 2000), WiggleZ (Drinkwater et al. 2010), GAMA (Driver et al. 2011) and GALAH (De Silva et al. 2015).

Due to its single robot arm and the sequential nature of its operation, the field configuration time of 2dF increases linearly with the number of fibres. This and other limitations (such as diversity of payload and non-planar focal planes) are resolved by the AAO’s new Starbugs technology, which consists of one independently positionable robot per science fibre. The initial phase of TAIPAN, the first instrument to make use of this technology, will have 150 science fibres and therefore consist of 150 Starbugs. This will allow the field configuration process to be carried out in parallel, and thereby decrease the configuration time from around 60 min for 2dF to the order of 5 minutes.
2. The TAIPAN Instrument and Survey

A Starbugs positioner is currently being developed for the TAIPAN instrument (Kuehn et al. 2014) on the AAO’s 1.2m, 6 FoV UK-Schmidt telescope, located at Siding Spring Observatory in New South Wales, Australia, and is scheduled to commence on-sky observations in early 2016.

The TAIPAN survey will obtain visible band spectra for $5 \times 10^5$ Southern Sky galaxies (~70% completeness) at $R=2200$ in $14 < r < 18$ at SNR=5–10 (30 min exposures). The related FunnelWeb stellar survey will obtain spectra for $2 \times 10^6$ Southern stars (~99% completeness) in $5.7 < v < 12$ at SNR=100 (30 min exposures).

The primary scientific aims of the 5-year survey include providing a measurement of $H_0$ to within 2% and improving by a factor of 2 the measured accuracy of the local growth rate, resulting in stronger tests of General Relativity. Additionally TAIPAN will carry out a precision peculiar velocity survey and engage in studies of galaxy evolution, transition, environment and fuelling studies.

TAIPAN will also serve as a prototype instrument for MANIFEST (Many Instrument Fibre System) (Lawrence et al. 2014) on the Giant Magellan Telescope (GMT), scheduled for completion in 2021.

3. Starbugs

A Starbug (Brown et al. 2014) consists of two concentric piezo-electric ceramic tubes which are made to move over a glass field plate by the alternate deformation of the inner and outer tubes. This is done by applying a voltage in a given sequence to generate a “walking” motion, with which the Starbug is positioned to within a few microns of the target. The 8-mm diameter Starbug carries an optical fibre payload and three back-illuminated metrology fibres. Adhesion to the field plate is provided by a vacuum system which keeps the Starbug on the plate whilst allowing freedom of motion.

4. The TAIPAN Positioner Software System

The positioner software is responsible for open– and closed–loop control and monitoring of the 150 Starbugs on the field plate. It determines the current location of each Starbug, assigns its next target position, calculates a valid trajectory and sends the appropriate control commands via the electronics firmware layer to move it to its new position. Secondary to this the software system collects and displays monitor information to allow the user to ascertain the health of the instrument. Finally, the software also stores monitoring data for the long-term characterisation and evaluation of the instrument’s performance. The software system comprises the following modules:

- Master Controller: responsible for starting up and shutting down the software system and ensuring that all components are operational. It also looks after the archiving of Starbug operational properties and monitor data.
- Positioner: this is responsible for the motion of the 150 Starbugs, both in a field reconfiguration (expected to occur on average once per hour and take ~5 min) and in position adjustment during an observation. Reconfiguration is carried out in closed-loop control, with the Metrology module providing position updates.
on the Starbugs whilst they are in motion. Given a target field (a list of sky positions) the Positioner allocates a Starbug to each target position, determines a route for each Starbug and iteratively moves the Starbugs to their new positions while receiving position updates from the metrology module, until the Starbugs are within the target tolerance.

- Metrology: this controls the 29M-pixel camera which images the Starbugs’ back-illuminated metrology fibres and processes the resulting 6576×4384 pixel images to find the position of the science fibre for each Starbug, based on the measured position of its 3 metrology fibres. Together with the Positioner, the Metrology module forms part of the Starbug control closed loop, which keeps track of Starbug locations at a given time, detects lost Starbugs (e.g. if a bug’s metrology fibres fail to illuminate, a bug falls off the plate due to vacuum failure, etc.) or unusable Starbugs (e.g. one which does not respond to movement commands, has faulty metrology fibres or has otherwise been marked as bad by the system). This module is also crucial in Starbug initialisation and position calibration.

- User Interface: will provide two degrees of control over the system, for engineering and observing uses, and give operational feedback.

- Instrument Simulator: simulates the behaviour of the Starbugs, the firmware layer and the Metrology system. It allows the software to be tested with no hardware present.

5. Route Finding and Position Allocation

For each Starbug a collision-free path must be found which minimises the time to target, the amount of Starbug rotation (to avoid focal ratio degradation in the science fibre) and the tangling of fibres between Starbugs. Additionally the path assigned to a Starbug must not render another’s target position unreachable.

Because optimum path determination can be computationally expensive for some field configurations, route finding for the TAIPAN instrument is designed to be carried out either “live” during the plate reconfiguration process, or off-line (e.g. during the day) allowing one to set up a series of observations ahead of time. The off-line process calculates 3 separate routes for each Starbug: 1) the path between the current (configuration n-1) and next (configuration n) targets; 2) the path between the current target and the home position; and 3) the path between the home position and the next target. Because there is always a pre-calculated path to the Starbugs’ park position recovering from a fault or skipping one or more configurations (e.g. due to bad weather) can be done quickly and with a minimum of path recalculation.

Although the Starbugs can be controlled independently, due to constraints imposed by the electronics system the movement mode (rotation or translation) must be the same for all Starbugs driven by a given electronics rack. Because of this, the routing software divides the reconfiguration process into a series of Ticks, each defined as an interval (not necessarily of equal duration) during which all the Starbugs either rotate on their central axes, translate, or wait.

The positioner uses three stages of increasing complexity in determining a valid path for each Starbug. If a path cannot be found using the earlier (computationally
cheaper) methods, an attempt is made with the more complex and expensive methods until a valid path is found or the target is flagged as unreachable:

1. **Simple Vector**: This is a priority-based positioner. It detects crossings and possible collisions between pairs of Starbug paths in the current Tick, and prioritises those with no crossings, calculating their paths first. Once these simplest paths are done the positioner calculates the path for one of the Starbugs of each crossing pair, then the second of each pair and finally any remaining routable bugs. Unroutable bugs progress to stage 2.

2. **Traffic Light**: This introduces the option for a Starbug to wait at a position along its path for one or more Ticks, so as to avoid a collision. As before, unroutable bugs progress to stage 3.

3. **Traffic Light + Cooperative A**: The A algorithm determines the minimum-cost path using a combination of the geometric (past) cost and the heuristic (future) cost. However, it is grid-based (we require continuous positioning of Starbugs on the field plate) and does not avoid moving objects (the Starbugs themselves are dynamic obstacles). We are using a modification of this algorithm, the Cooperative A, which adds a time dimension to avoid the paths of other Starbugs by reserving a path through the grid in a given Tick. The grid used is 4-dimensional consisting of 2 cartesian axes, a Tick axis and a reserved path axis. This approach finds a path for a significant number of Starbugs, but is expensive, and so is only used for Starbugs which are otherwise unroutable.

Although a successful strategy in a large number of use-cases, tests so far show that some cases remain unresolved by this 3-phased approach. Work on further refining the Traffic Light + Cooperative A method continues, together with improvements to the algorithm which allocates Starbugs to target positions, with the aim of avoiding the occurrence of deadlocks and improve overall efficiency.

**References**

Boyle, B. J., Shanks, T., Croom, S. M., Smith, R. J., Miller, L., Loaring, N., & Heymans, C. 2000, MNRAS, 317, 1014

Brown, D. M., et al. 2014, in Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation, edited by R. Navarro, C. Cunningham, & A. A. Barto, vol. 9151 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 91511A

Colless, M., et al. 2001, MNRAS, 328, 1039

De Silva, G. M., et al. 2015, MNRAS. In preparation

Drinkwater, M. J., et al. 2010, MNRAS, 401, 1429

Driver, S. P., et al. 2011, MNRAS, 413, 971

Farrell, T. J., Bailey, J. A., & Shorridge, K. 1995, in Astronomical Data Analysis Software and Systems IV, edited by R. A. Shaw, H. E. Payne, & J. J. E. Hayes, vol. 77 of Astronomical Society of the Pacific Conference Series, 113

Kuehn, K., et al. 2014, in Ground-based and Airborne Instrumentation for Astronomy V, edited by S. K. Ramsay, I. S. McLean, & H. Takami, vol. 9147 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 35

Lawrence, J. S., et al. 2014, in Ground-based and Airborne Instrumentation for Astronomy V, edited by S. K. Ramsay, I. S. McLean, & H. Takami, vol. 9147 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 94

Lewis, I. J., et al. 2002, MNRAS, 333, 279