Real-time control developments for the CANARY MOAO instrument at Durham

Alastair Basden[1a], Richard Myers[1], Nigel Dipper[1], and Tim Morris[1]

Department of Physics, Durham University, South Road, Durham, DH1 5XR, UK

Abstract. The CANARY instrument is an MOAO demonstrator instrument for the E-ELT EAGLE instrument, fielded on the William Herschel Telescope. We present the CANARY real-time control system, both as used on-sky for the NGS only phase in 2010, and also as will be used on-sky in September 2012 with tomographic LGS capability and four LGSs. This system is based on the Durham AO Real-time Controller (DARC), for which we provide details of the main features. The challenges that we encountered will be presented as a learning experience, including camera synchronisation issues, and problems with a reliable telemetry on a loaded network. We will also present recent progress made in implementing a real-time control system for EAGLE in the laboratory in Durham, and the implications that this design has. By using a system comprised of a small number of high end GPU accelerators, theoretical performance is enough to perform matrix-vector based wavefront reconstruction for EAGLE, and we investigate whether this is a practical solution.

1 Introduction

The next generation of optical ground-based Extremely Large Telescopes (ELTs) is currently in the design phase, with plans for primary mirror diameters of over 30 m [4,5]. These facilities will allow astronomers to probe the universe with unprecedented sensitivity and very high resolution. A suite of instruments for these telescopes is planned, allowing many different observation goals to be met.

The EAGLE instrument for the planned 42 m European ELT (E-ELT) is currently in the design phase [3]. It is a multi-object integral field unit spectrograph using adaptive optics (AO) with a multi-object AO (MOAO) system to correct incoming wavefronts in open-loop, using wavefront sensors which do not sense the corrections made to the science fields. A wide-field correction can be obtained. Baseline designs for EAGLE include up to 11 wavefront sensors, using laser and natural guide stars. It is envisaged that there will be 20 science field pick-offs, allowing good AO correction in 20 separate fields, each 1.5 arcseconds diameter, simultaneously across a five arc-minute field. The use of a multi-object AO system allows good atmospheric correction to be achieved for selected objects across a wide field of view.

CANARY (a name, not an acronym) is a technology demonstrator instrument for EAGLE. It is designed to test a single MOAO channel on-sky, fielded on the William Herschel Telescope on La Palma. The first stage of CANARY was operated in the Autumn of 2010, and involved three off-axis natural guide star wavefront sensors which were used to correct an on-axis deformable mirror (DM). This DM operates in open-loop, i.e. the wavefront sensors are not sensitive to changes on the DM. Tomography is performed using a Learn and Apply algorithm [6].

Further stages of CANARY include the use of multiple Rayleigh laser guide stars, and a Woofer-Tweeter system for multiple DM control, as well as increasing the wavefront sensor order.

Real-time control for CANARY is provided by the Durham AO real-time controller (DARC). DARC is a freely available software package, which can be downloaded from sourceforge, and provides a powerful, yet flexible and configurable real-time control system for AO. The learning curve with DARC is fairly straightforward, and help can be provided in Durham for anyone considering using DARC if required.

[a] a.g.basden@durham.ac.uk

2 DARC details

DARC is primarily a central processing unit (CPU) based real-time control system. It is highly optimised, and also very optimisable, being well suited for adaption to different requirements. It is based around a modular design, with modules being created to perform specific parts of the processing pipeline. As a result of this, DARC is easy to extend and develop. New algorithms can easily be added and tested in DARC by writing an appropriate module, using the well defined DARC module interface. New cameras and DMs can also easily be added, again by writing an interface module, meaning that DARC is well suited to laboratory requirements, and can quickly and easily be configured to work with a given AO bench.

As well as being highly customisable, DARC can also provide very high performance, and is suitable for use with almost any current and future proposed AO system. This performance is achievable because DARC can easily be optimised for different AO system requirements, allowing the user to select the optimum number of CPU processing threads, whether hardware acceleration should be used, and making other optimisations too. It has been shown [1] that DARC can provide low latency and jitter, particularly when used with real-time Linux kernels.

2.1 DARC components

DARC as a package has several main components. The most important of these is the core real-time pipeline, which is responsible for all of the real-time processing from wavefront sensor data to DM commands. There is also a DARC control interface, which acts a server that is used to control the core real-time pipeline. This uses a CORBA middleware to provide the control, allowing DARC to be controlled from any computer language for which a suitable CORBA binding exists. The DARC package also contains a telemetry component, responsible for handling diagnostic data, making it available to users for processing and real-time display, and for logging to disk. Finally, the DARC package also contains a client package. This includes an application programming interface allowing users to develop their own clients and control scripts. It also provides a powerful command line tool as well as graphical user interfaces for display and control, as shown in Fig. 1.

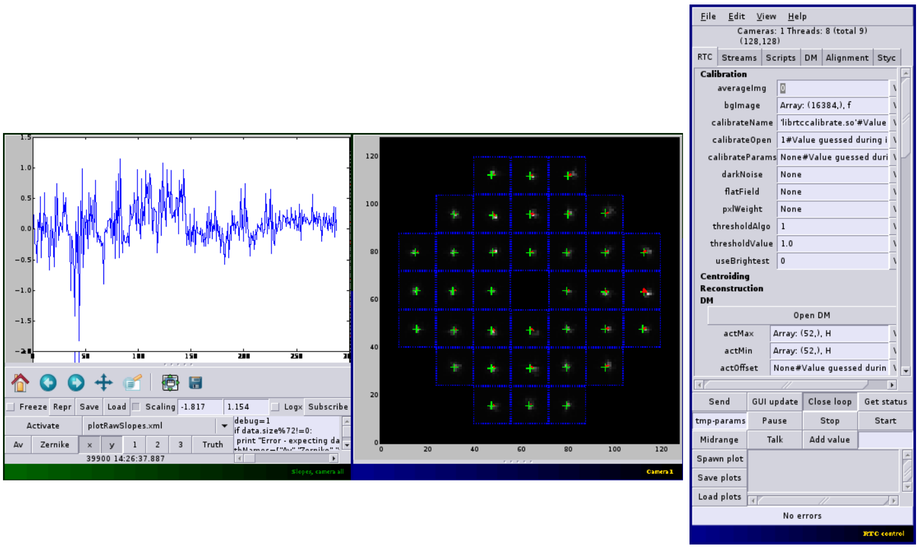

Fig. 1. A figure showing the DARC real-time display and control graphical user interface.

2.2 The core real-time pipeline

The core real-time pipeline in DARC is responsible for all of the real-time data processing. It is built up with a number of processing modules, which can be inserted and removed while the system is running. These modules include hardware interfaces (wavefront sensors and DMs), image calibration, wavefront slope calculation and wavefront reconstruction. Standard modules exist, and more advanced algorithms can be implemented by replacing an existing module (dynamically, if experimenting with an algorithm).

Processing in DARC is carried out using a horizontal processing strategy [1], which allows computational workload to be spread evenly between computer cores. This should be taken into account when developing a new module, and the provided module interface definition helps to ensure that modules are written in a suitable way. If DARC is being used in a non-real-time environment, for example with a slow test bench, then the horizontal processing strategy is not essential, and modules can be written in a more simplified way. However this is not advisable, because if the algorithm is ever required to operate in real-time, the module would need to be re-written.

A benefit of a horizontal processing strategy over a more conventional vertical strategy is that less thread synchronisation is required, resulting in a lower latency and making good use of available computing resources. It also naturally leads to processing beginning as soon as pixels arrive, rather than waiting for an entire camera frame to be made available.

2.3 Hardware acceleration

Since DARC is modular, it is possible to develop modules that provide hardware acceleration, for example for more demanding high order, high frame rate AO systems. Two such modules already exist, and can readily be used with DARC.

A field programmable gate array (FPGA) based pixel processing module, similar to the ESO SPARTA design is available. Here, wavefront sensor pixel data is sent directly to an FPGA, which performs image calibration, and optionally, slope calculation, based on a weighted centre of gravity algorithm. It uses a streaming architecture, and has sub-microsecond latency with negligible jitter. The calibrated pixels or wavefront slopes are then sent to DARC using a serial Front Panel Data Port (sFPDP) interface.

A graphical processing unit (GPU) based wavefront reconstruction module is also available, which offloads matrix-vector multiplication based wavefront reconstruction to a NVIDIA GPU. This operates piecewise, performing partial multiplications as wavefront slope data becomes available. It can be used with or without the FPGA pixel processing module. The GPU code has been developed specifically for DARC, and provides significantly better performance than the standard CUDA libraries. To our knowledge, this is the first instance of GPUs being used on-sky for adaptive optics correction (November 2010).

Other hardware acceleration capabilities can easily added, allowing hybrid hardware and CPU systems.

3 CANARY real-time implementation

DARC was selected to provide real-time control for CANARY after a commercial offering failed to demonstrate the ability to meet CANARY requirements, which were easily met by DARC. A large number of algorithms were implemented in DARC, as befitting a test-bench instrument. These included the ability to perform slope calculation by weighted centre of gravity, by correlation and using a matched filter. Shack-Hartmann, pyramid and YAW wavefront sensors are supported. DARC has the ability to perform adaptive windowing (spot tracking), allowing sub-aperture windows to follow spot motion, thus reducing the number of pixels required for each sub-aperture, and hence reducing the impact of CCD readout noise. This is particularly important for open-loop AO systems, where spot motions can be large. Sub-aperture size can also be adjusted dynamically by the user.

A brightest pixel selection algorithm is available [2], which performs background subtraction by selecting a user defined (on a sub-aperture basis) number of brightest pixels in each sub-aperture, and ignoring the rest, thus reducing the impact of CCD readout noise.

Slope linearisation can be performed using a user defined look-up table. Measured wavefront slope is not directly proportional to true wavefront slope due to the discrete nature of pixel based detectors. For closed loop AO systems, this does not matter because spot offsets are usually small. However, for open loop systems such as CANARY, this non-linearity can result in a significant reduction in performance. Therefore, being able to correct for this can be important.

Wavefront reconstruction can currently be performed using a matrix-vector algorithm, using a Linear Gaussian Quadratic (LQG) control formulation, and also using a preconditioned conjugate gradient algorithm. Other algorithms could of course be added by creating a new reconstruction module.

DARC has the ability to perform actuator oscillation to help mitigate the effect of DM hysteresis, which can benefit both open and closed loop AO systems. Here, when a set of DM commands have been computed, they are placed onto the DM with (typically) a decaying Sine wave, oscillating the actuators for a short period of time until they have reached the desired shape. DARC also has the ability to be used as an open-loop figure sensor, allowing DM demands to be fed into an instance of DARC, which then adjusts a DM in closed loop using a figure sensor. This figure sensor interface has been used on-sky.

DARC parameters can be changed on a frame-by-frame basis, with the details of how these parameters are changed being left to a buffer interface module. This, for example, could allow reference slopes to be adjusted in real-time, every camera frame.

The flexible nature of DARC also allows many extra capabilities to be added, for example an interface to a telescope control system, to offload mean slope measurements, or to produce audible warnings for DM saturation. Many other possibilities also exist.

3.1 Initial challenges and solutions

We encountered several challenges, unsurprising given the complexity of CANARY and short timescales, when developing the real-time control system. Each of our four natural guide star wavefront sensors was found to lose a partial image frame every four minutes. As a result, an innovative front-end camera module was developed for DARC which was able to handle this. It is not as simple as simply discarding partial frames, since we interleave pixel processing with camera readout, and so by the time we know that a frame is incomplete, a large amount of processing has already been done. Our solution was, once a partial frame had been detected, to freeze the DM, discarding all intermediate processing, and this approach worked well.

We also encountered problems with the CANARY telemetry system which was based on CORBA, and was found to be unsuitable for high bandwidth data transfer. As a result, we now use the native DARC telemetry system instead, which is based on TCP/IP, and offers far higher performance.

3.2 Trigger signals

Triggering of CANARY is fairly complex. There are up to eight wavefront sensors, additional cameras, two pulsed lasers (for Rayleigh laser guide star creation) and an electronic range gate shutter (based on Pockel cells). Trigger pulses for these components must be synchronised but with different delays, and different frequencies. For this, we have developed a trigger unit based on custom FPGA hardware (Fig. 2). This allows multiple trigger outputs to be created, each with a unique frequency, delay and pulse width. Trigger pulses can be derived from internal or external clock sources, meaning that the trigger unit itself can also be triggered.

We use this trigger unit to trigger our lasers at between 10-20 kHz (with slightly offset trigger pulses, due to internal delays in the laser electronics). We also trigger a Rayleigh range gate, either a gated CCD, or a Pockel cell system, at the same rate as the lasers, but with a different pulse width and delay. Four natural guide star wavefront sensors, up to four laser guide star wavefront sensors, a

Fig. 2. A picture showing the CANARY trigger unit

science camera and an open-loop figure sensor are also triggered, at a rate of between 100-500 Hz for the wavefront sensors (synchronised with the lasers), up to 1 kHz for the figure sensor, and up to 70 Hz for the science camera.

3.3 Future real-time requirements

CANARY is a very flexible instrument. There are plans to test many different forms of AO with CANARY, including LTAO, MOAO, SCAO, GLAO, MCAO and semented MCAO. There are also plans to test many different AO related technologies, including woofer-tweeter configurations, LQG control, conjugate gradient reconstruction, the use of asynchronous camera frame rates, the use of hybrid Sodium/Rayleigh laser beacons, NGS sharpening, different wavefront sensor technologies, test of a complex amplitude sensor, spot elongation studies and Sodium layer profile studies.

We hope to test most or all of these on-sky (given enough telescope time), and so the real-time control system needs to be highly capable and flexible. Fortunately, DARC is able to handle all of these situations.

It is also interesting to consider how well DARC can perform when applied to other AO systems. We have therefore configured DARC to be used in configurations similar to some existing and proposed demanding AO systems. These performance tests are made in a full real-time system configuration, as would be used on-sky, with thread synchronisation, interleaved pixel processing and readout, etc. However, they do not include the time to read pixels in from a camera (since we do not have suitable cameras), or time taken to send DM commands (since we do not have a suitable DM). These extra operations would only reduce performance by a minimal amount.

3.3.1 VLT Sphere configuration

A planet-finder instrument is currently being developed by ESO. The AO system, SPHERE, has a 40×40 sub-aperture Shack-Hartmann wavefront sensor, operating at a desired frame rate of 1.2 kHz. Using DARC on a recent server class computer (two Intel E5645 processors at 2.4 GHz), we are able to operate at a frame rate greater than 3 kHz, using the 12 CPU cores.

Performance is measured using the Linux real-time clock averaged over ten million consecutive frames, and a real-time Linux kernel (2.6.31-10.rt) was used. The frame computation time was $323 \pm 11\ \mu$s. It should be noted that more recent stock Ubuntu kernels (2.6.35 and 2.6.38) give far worse performance, almost doubling the frame computation time. The reasons for this are currently unclear.

3.3.2 Palm 3000 configuration

When using DARC in a configuration similar to that of the Palm 3000 AO system, which is an XAO system with about 64×64 sub-apertures, we are able to achieve a frame rate of 2 kHz when using three GPUs (NVIDIA Tesla 2070) for acceleration, with the aforementioned server. This is equal to the desired frame rate, showing that DARC is suitable to be used with the most computationally demanding AO system currently commissioned.

3.3.3 EAGLE configuration

EAGLE is an E-ELT MOAO instrument, with 11 84×84 sub-aperture wavefront sensors, and 20 science arms, each with a 84×84 actuator DM. It is specified to have a desired frame rate of 250 Hz. Each science arm is independent, meaning that real-time control can be partitioned into the individual arms. With our available hardware (3 GPUs in a server), we are able to demonstrate operation of four wavefront sensors and one science arm at 300 Hz, with near-linear scaling. Therefore, adding GPUs to this system, it should be possible to operate each EAGLE science channel (processing 11 wavefront sensors, controlling one DM) using a server containing eight GPUs, at a cost of less than £10000. Therefore, it can be seen that DARC is suitable to be used as the real-time control system for EAGLE, with currently available hardware and software.

3.4 Future studies for CANARY

We are currently investigating technologies to give a high performance and reliable telemetry system for CANARY and future ELT instruments. Suitable candidates include the Data Distribution Service, and 10 gbit Ethernet. We are also developing a real-time simulation front-end for DARC that will allow DARC to be operated with simulated inputs and outputs. Much of this work will be performed on our DRAGON test bench.

4 Conclusion

We have provided details of real-time control system developments at Durham, focused on use with CANARY. The Durham Adaptive optics Real-time Controller (DARC) is a powerful and flexible system which, as well as being well suited for CANARY, is also suitable for use with most proposed E-ELT instruments.

References

1. A. Basden, D. Geng, R. Myers, and E. Younger. Durham adaptive optics real-time controller. *Applied Optics*, 49:6354–6363, November 2010.
2. A. G. Basden, R. M. Myers, and E. Gendron. Wavefront sensing with a brightest pixel selection algorithm. *MNRAS*, page 1744, October 2011.
3. C. J. Evans, M. D. Lehnert, J. G. Cuby, S. L. Morris, A. M. Swinbank, W. D. Taylor, D. M. Alexander, N. P. F. Lorente, Y. Clenet, and T. Paumard. Science Requirements for EAGLE for the E-ELT. In *Adaptive Optical Components II. Edited by Holly, Sandor ; James, Lawrence. Proceedings of SPIE, Volume 141, pp. 120-124*, volume 7014 of *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, pages 1–2, 2008.
4. J. Nelson and G. H. Sanders. The status of the Thirty Meter Telescope project. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 7012 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, August 2008.
5. J. Spyromilio, F. Comerón, S. D'Odorico, M. Kissler-Patig, and R. Gilmozzi. Progress on the European Extremely Large Telescope. *The Messenger*, 133:2–8, September 2008.
6. F. Vidal, E. Gendron, M. Brangier, A. Sevin, G. Rousset, and Z. Hubert. Tomography reconstruction using the Learn and Apply algorithm. In *Adaptative Optics for Extremely Large Telescopes*, 2010.