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ROBO-AO: INITIAL RESULTS FROM THE FIRST AUTONOMOUS LASER GUIDE STAR ADAPTIVE OPTICS INSTRUMENT

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RESUMEN

Grandes sondeos están descubriendo miles de objetos para los que se requiere más caracterización en una resolución angular mayor. La demanda de los observatorios espaciales y telescopios grandes con sistemas de Optica Adaptativa (AO) los deja en general sin disponibilidad para sondeos grandes de alta resolución angular. Para abordar esta brecha, hemos desarrollado Robo-AO, el primer sistema robótico de AO láser, como un instrumento de imágenes económico y eficiente para telescopios de la categoría de 1.3 m. Observaciones de más de 200 objetos estelares por noche han sido realizadas rutinariamente, con tiempo de overhead entre targets de menos de 1.5 minutos. Programas científicos de varios miles de objetivos pueden ser realizados en apenas semanas, y Robo-AO ya ha completado los tres sondeos AO más grandes hasta la fecha.

ABSTRACT

Large surveys are discovering thousands of objects which require further characterization at high angular resolution. The demands on space-based observatories and large telescopes with AO systems leave them generally unavailable for large high angular resolution surveys. To address this gap, we have developed Robo-AO, the first robotic laser AO system, as an economical and efficient imaging instrument for 1-3 m class telescopes. Observations of over 200 stellar objects per night have routinely been performed, with target-to-target observation overheads of less than 1.5 minutes. Scientific programs of several thousands of targets can be executed in mere weeks, and Robo-AO has already completed the three largest AO surveys to date.

Key Words: instrumentation: adaptive optics — instrumentation: high angular resolution — techniques: high angular resolution

1. INTRODUCTION

Robo-AO is an autonomous laser guide star (LGS) adaptive optics (AO) instrument that robotically operates a telescope, laser, AO system, and science camera to observe several different classes of astronomical objects (Baranec et al. 2013). It is the first system that operates a laser guide star without human oversight. The software architecture for the Robo-AO system has been designed to be as robust as possible, but also as a system that is simple and flexible to manage and operate. Robo-AO is currently deployed on the 60-inch telescope at Palomar Observatory. Initial science results from the prototype system demonstrate visible-light imaging with angular resolutions approaching the diffraction limit of a 1.5 m telescope (≈0.12"). Robotic software automations keep target-to-target observing overheads of less than 1.5 minutes (including slew time) leading to the observation of about 20 targets per hour (Riddle et al. 2012), and the completion of the three largest AO surveys to date. Many other implementations of Robo-AO are under development.

2. SYSTEM HARDWARE

The Robo-AO instrument was installed on the Palomar Observatory 60-inch (1.5 m) telescope in 2011 for initial testing, with first science and robotic operations occurring in the summer of 2012. The P60 is a fully automated telescope, and includes a fully automated weather monitoring system to ensure telescope safety during operations (Cenko et al. 2006). The Robo-AO instrument is composed of three structures: the LGS system, the Cassegrain instrument (which includes the AO system, science instruments, and associated hardware), and the support electronics rack.

The core of the Robo-AO LGS system is a pulsed 10-W ultraviolet (355nm) laser (JDSU Q301-HD) mounted in an enclosed projector assembly on the side of the P60 telescope. The ultraviolet laser has

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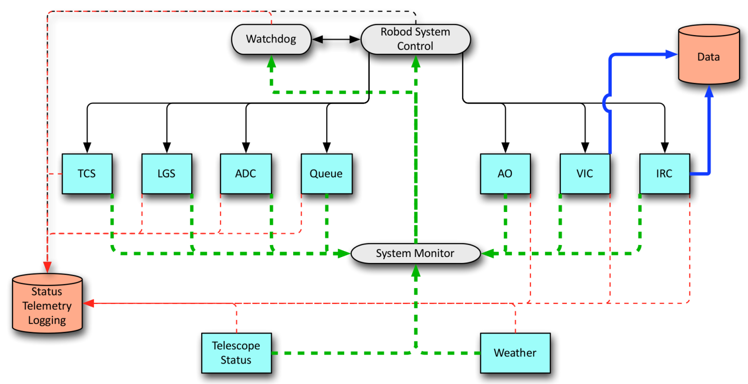

Fig. 1. The automation software architecture. Blue boxes are the hardware control subsystem daemons, gray boxes are control or oversight daemons, and red boxes are data file storage. Red lines with arrows show the paths for telemetry through the operating system, black the command paths, and blue the data paths.

the additional benefit of being invisible to the human eye; it is unable to flash-blind pilots, eliminating the need for human spotters located on site. High-order wavefront sensing is performed with an 11×11 Shack-Hartmann wavefront sensor. The detector is an 80×80 pixel format E2V-CCD39 optimized for high quantum efficiency at the laser wavelength (71.9%) and paired with a set of SciMeasure readout electronics. The high-order wavefront corrector within Robo-AO is a MEMS deformable mirror (Boston Micromachines Multi-DM). Robo-AO uses 120 of the 140 actuators to adjust the illuminated surface of the mirror.

Individual Robo-AO science observations are currently made using the visible camera (an Andor iXon3 888 electron-multiplying CCD) with a 44" square field of view and 0.043" pixel scale. The camera is read out continually at a frame rate of 8.6 Hz during science observations, allowing image motion to be removed in software after observations with the presence of a $m_V < 16$ guide star within the field of view. A data reduction pipeline corrects each of the recorded frames for detector bias and flat-fielding effects, automatically measures the location of the guide star in each frame, and then shifts and aligns each frame to achieve an optimal image reconstruction (Law et al. 2009). During typical observing, we generally obtain residual wavefront errors in the 160 to 200 nm RMS range, leading to the ability to detect and characterize stellar companions at contrasts of > 5 magnitudes at separations of 0.25-1" at visible wavelengths. Initial science results demonstrating the capability of Robo-AO have already been published (Law et al. 2012; Muirhead et al. 2013; Terziev et al. 2013), with many more in preparation.

3. SOFTWARE ARCHITECTURE

The Robo-AO robotic control software was developed in parallel with the hardware, to avoid hardware choices that would limit software functionality and to enhance the efficiency of the final system (Riddle et al. 2012). Robo-AO is controlled by a single computer with a Fedora Linux 13 installation for the operating system. The system does not use a real time kernel; this choice was made to save on complication and increase portability of the software. All source code for the Robo-AO project is written in C++; at this time the software consists of more than 120,000 lines of documented source code.

The Robo-AO hardware interface software has been developed as a modular system, as shown in Figure 1. The software to control each hardware subsystem was developed as a set of individual modules; these subsystems are run as daemons in the operating system, each separately managing the hardware under its control and running a status monitor to sample subsystem performance and register errors that occur. Each daemon is able to manage operation of its associated hardware automatically and react internally to hardware errors. Communications between the daemons use a TCP/IP communications system developed for Robo-AO for command and control operations that pass continual status information and will automatically restart any daemons that lock up or crash. The daemons used to control subsystems in the Robo-AO instrument are:

LGS Laser guide star control
AO Adaptive optics control
TCS Telescope control system
ADC Atmospheric dispersion corrector control
VIC Visible instrument camera control

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IRC Infrared camera control
Queue Queue system
Telstat Telescope status
Weather Weather monitoring

The daemons are controlled by a central robotic control daemon that commands observation sequences, monitors the state and health of the subsystems, reacts to errors found by the subsystems, and manages all aspects of operation of the observing system. The modular design isolates problems, so that even major issues like daemon crashes result in procedural steps to resume normal operations (instead of system crashes and lost hours of operation), which creates a robust, efficient automated system that can successfully complete scientific observations throughout the night.

4. ROBO-AO AUTOMATED OPERATIONS

As a fully autonomous laser AO instrument, Robo-AO executes tasks that are generally performed manually. The robotic system operates multiple subsystems in parallel in order to increase efficiency; for example, to start an observation, the central robotic control daemon will point the telescope, move the science filter wheel, and configure the science camera, laser, and AO system, all before the telescope has settled onto a new science target. The automated laser acquisition process begins once the telescope has completed pointing at the new object. A spiral search algorithm automatically acquires the laser by moving the uplink steering mirror until 80% of the wavefront sensor subapertures have met a flux threshold of 75% of the typical laser return flux. A safety system manages laser propagation onto the sky, and stops laser operations if any errors occur.

Robo-AO uses a newly developed automated system for laser deconfliction that opens the entire area above 50 degrees zenith distance for observation by requesting predictive avoidance authorization for ∼700 individual fixed azimuth and elevation boxes of ∼6 square degrees every night. Areas of the sky below 50 degrees zenith distance can be observed as well if scientifically necessary.This gives Robo-AO the capability to undertake laser observations of any target overhead at almost any time, increasing observing efficiency by removing the need to preselect targets of observation. This method can be implemented for all laser AO observatories to reduce bookkeeping and make immediate target of opportunity observations possible. A fully automated queue system was developed for Robo-AO that integrates the laser predictive avoidance authorization into the decision making process for which science object to observe next (Hogstrom et al., in preparation). This queue ensures that only objects that are cleared for lasing will be observed at all times.

Robo-AO requires ∼35-50 seconds, on average, from the end of a telescope slew to the beginning of integration with the science camera; many nights of 200+ observations have already been achieved (with a current record of 240). As of this writing, Robo-AO has completed ∼479 hours of fully robotic operations during 83 nights of allocated telescope time, of which ∼261 hours (54%) were open-shutter science observing time. In total, almost 10,000 observations were made, which comprise some of the largest high-angular resolution surveys ever performed, as indicated in Table 1 (table citations are: 1 - Law et al., I'm preparation; 2 - Riddle et al. 2014; 3 - Janson et al. 2012; 4 - Hartkopf, Tokovinin, & Mason 2000; 5 - Metchev & Hillenbrand 2009; 6 - Kraus & Hillenbrand 2012; 7 - Law et al. 2014a; 8 - Adams et al. 2012; 9 - Lillo-Box, Barrado & Bouy 2012). Robo-AO is able to complete these large surveys much faster than other AO systems, such as having observed ten times the number of Kepler Objects of Interest (KOI) than larger telescope facilities in half of the observing time.

5. THE FUTURE OF ROBO-AO

The Robo-AO collaboration is currently in the process of constructing a low-noise wide-field imager using a 2.5 μm cutoff Teledyne HAWAII-2RGTM detector which was delivered to Caltech in September 2012. The Robo-AO instrument has an IR camera port designed to accommodate the expected 70-kg mass of the infrared camera. As part of our integration plan, we will develop automated routines for configuring the high-speed infrared tip-tilt sensing and recording of infrared science data in much the same way as has been done with the visible Robo-AO camera, and then integrate the IR camera into the automation and queue system software.

A clone of the current Robo-AO system is currently being developed for the 2-m IUCAA Girawali Observatory telescope in Maharashtra, India. The system is expected to see first light in 2014. In addition to this clone, Pomona College has used the Robo-AO design and software to develop an AO instrument, built mainly by undergraduate students, that has already achieved on-sky AO correction (Severson et al. 2013), and the Minerva project is basing their robotic control software on the Robo-AO system (Hogstrom et al. 2013). The modular design of Robo-AO and the relative simplicity of the instrument make it straightforward to replicate or adapt the system to other observatories and instruments.

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TABLE 1

THE LARGEST GROUND-BASED DIFFRACTION-LIMITED SURVEYS PERFORMED WITH TELESCOPES GREATER THAN 1 M IN DIAMETER.

Survey	Instrument	Method	Targets	Time
Binarity of the solar neighborhood[1]	P60 (Robo-AO)	LGS AO	3,081	172 hours
Solar-type dwarf multiplicity[2]	P60 (Robo-AO)	LGS AO	1,115	49 hours
M-Dwarf multiplicity[3]	Calar Alto 2.2-m (AstraLux), NTT (AstraLux)	Lucky	761	300 hours
Washington Double Star Catalog[4]	SOAR (HRCam)	Speckle, AO+Speckle	639	16 nights
Young Solar analogs[5]	KeckII (NIRC2), Hale (PHARO)	NGS AO	266	47 nights
Multiplicity at the bottom of the IMF[6]	KeckII (NIRC2)	LGS AO	78	10 nights
Kepler KOI validation[7]	P60 (Robo-AO)	LGS AO	1,800	112 hours
Kepler KOI validation[8]	MMT (Aries), Hale (PHARO)	NGS AO	90	12 nights
Kepler KOI validation[9]	Calar Alto 2.2-m (AstraLux)	Lucky	98	19 nights

The prototype Robo-AO at Palomar has been crucial in validating the current sample of KOIs, having observed over three-quarters of the 2,036 host stars (from the January 2013 release). A complementary follow-on mission to Kepler is the Transiting Exoplanet Survey Satellite (TESS). TESS will execute a shallower survey compared to Kepler, with the majority of objects $m_V < 16$, but over the entire sky. It is estimated that there may be as many as ten or more times as many transit signals discovered by TESS during its mission lifetime, which could all be validated by Robo-AO in less than a year. To make this happen, we are planning to deploy such systems at either or both of the 2.2 m UH and 3 m IRTF telescopes on Mauna Kea and are looking for partners for a facility-class Robo-AO in the southern hemisphere. Eventually, a network of globally linked Robo-AO systems could observe the night sky at high resolution operating as one unified robotic instrument (Riddle 2011).

The next generation large telescopes all will require an automation of tasks of the same order of magnitude as the Robo-AO robotic system in order to achieve their operational requirements. The lessons learned from developing and operating Robo-AO can inform the process of developing the next generation of astronomical instruments.

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