A Distributed Control System for Rapid Astronomical Transient Detection

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ABSTRACT

The Rapid Telescope for Optical Response (RAPTOR) program consists of a network of robotic telescopes dedicated to the search for fast optical transients. The pilot project is composed of three observatories separated by approximately 38 kilometers located near Los Alamos, New Mexico. Each of these observatories is composed of a telescope, mount, enclosure, and weather station, all operating robotically to perform individual or coordinated transient searches. The telescopes employ rapidly slewing mounts capable of slewing a 250 pound load 180 degrees in under 2 seconds with arcsecond precision. Each telescope consists of wide-field cameras for transient detection and a narrow-field camera with greater resolution and sensitivity. The telescopes work together by employing a closed-loop system for transient detection and follow-up. Using the combined data from simultaneous observations, transient alerts are generated and distributed via the Internet. Each RAPTOR telescope also has the capability of rapidly responding to external transient alerts received over the Internet from a variety of ground-based and satellite sources. Each observatory may be controlled directly, remotely, or robotically while providing state-of-health and observational results to the client and the other RAPTOR observatories. We discuss the design and implementation of the spatially distributed RAPTOR system.

Keywords: RAPTOR, robotic, automated, telescope

1. INTRODUCTION

Constructing an observatory that can run in a completely autonomous manner is a significant challenge. Not only must it be capable of scheduling its own observations, but it must robustly handle things such as changing weather conditions, software errors, and hardware failures. Recently, several projects have met this challenge admirably. The recent detection of a prompt optical flash from the gamma-ray burst GRB990123 by the Robotic Optical Transient Search Experiment I (ROTSE-I) at Los Alamos National Laboratory demonstrated the value of small robotic observatories.[1] The 80 second flash from GRB990123 was the brightest object ever observed in optical wavelengths at an absolute magnitude of -36.

The detection of GRB990123 also demonstrates how poorly the night sky is monitored for transient objects. Gamma-ray bursts occur every day, yet the ROTSE-I detection is still the only contemporaneous optical detection of a GRB. Undoubtedly many more events like this have been within the reach of small telescopes, yet few have been observed. The aim of the RAPTOR project is to develop a wide-field system for detecting these optical transients.[2] The system should have the greatest possible sensitivity for the given field of view and also be able to operate robotically. A fast analysis pipeline is also necessary if transients are to be identified in near real-time.

The ability to reject false triggers is an absolute necessity for any program that intends to do a wide-field search for transients that occur on the timescale of minutes. This was a significant problem in previous experiments such as the Explosive Transient Camera (ETC).[3] There can be many causes of false triggers in any astronomical imaging system; hot pixels, satellite glints, meteors, camera defects, cosmic rays, etc. One way to reduce the number of false triggers is to require that any object must be present in more than one image to be considered a valid detection. This technique can eliminate many false triggers, however things such as a glint from a geostationary satellite may still get through. An additional technique for eliminating false triggers is to use coordinated observations from spatially separated observatories. It is very unlikely that a camera defect

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will appear at the same location on two different telescopes. Additionally, if the observatories are separated by a sufficient distance, parallax can be used to eliminate nearby objects such as satellites and meteors.

Developing a set of telescopes that can operate in a coordinated manner further aggravates the challenge of building fully robotic observatories. Not only must each observatory be able to operate autonomously, they must also be able to communicate with each other and synchronize their observations. Further, if they are going to search for transients in real-time, they must be able to process and compare their observations with each other in a fast automated way. The goal of the RAPTOR project is to build just such a system.

To meet these goals, we have decided on a system similar to human vision. Humans use two eyes not just for depth perception, but also to filter out artifacts that appear in only one eye. We have a central fovea which has greater resolution and color sensitivity. Our vision process operates in a feedback loop which can quickly identify a transient object at the edge of the field of view and "slew" our eyes to center the object in the foveas to study the object with greater sensitivity. Following this example, we have decided to construct two telescopes, RAPTOR A and B, which will operate simultaneously. Each telescope will have a set of four wide field cameras and a central "fovea" camera. A real-time image processing pipeline will identify transients in the wide field system. If a transient is present in both telescopes at the same location and the same time, each telescope will re-center the object in the fovea camera. Additionally we are constructing a third system, RAPTOR S, which will consist of a single 12 inch telescope with a transmission grating allowing low resolution spectroscopic follow-up of any transients identified by the RAPTOR A-B system.

2. THE RAPTOR OBSERVATORIES

The RAPTOR A and B telescopes are located at Los Alamos National Laboratory (LANL) and consist of two identical systems separated by approximately 38 km. The RAPTOR A telescope is located at the Fenton Hill site of LANL at an elevation of $\sim$8700 ft. The RAPTOR B telescope is located at the Los Alamos Neutron Science Center (LANSCE) site which is just southeast of Los Alamos itself at an elevation of $\sim$7000 ft. The RAPTOR S telescope is located next to RAPTOR A at the Fenton Hill site. The 38 km separation of RAPTOR A and B generates sufficient parallax to filter out objects in Earth orbit even out to geostationary altitudes.

2.1. Cameras and Optics

The wide-field cameras on the RAPTOR A and B telescopes consist of an 85 mm f1.2 Canon FD lens mounted on an Apogee AP-10 CCD camera[*]. The AP-10 uses a 2000 x 2000 pixel Thompson chip measuring 28 mm on a side. This camera/lens combination provides a 19^o x 19^o field to a limiting magnitude of 13. The fovea cameras consist of a 400 mm f2.8 Canon FD lens mounted on a Finger Lakes 1000 x 1000 pixel CCD camera[†]. The fovea systems should provide a 2^o x 2^o field of view to a limiting magnitude nearing 17. Both of the CCD cameras are thermoelectrically cooled and provide a fast readout of $\sim$5 seconds. Focus on all of the cameras is controlled using a 1/4-80 threaded screw which is adjusted by hand. Temperature variations do cause focus shifts, but seasonal re-focusing is adequate to maintain satisfactory performance of the cameras.

The RAPTOR S optical system consists of an Apogee AP-6 CCD camera mounted on a 12 inch aperture f/7 Richey-Chretien telescope. The telescope and camera rest in the exact same mount as the RAPTOR A and B telescopes. The telescope itself has motorized focus control; however it also has invar spacers which should reduce the need to re-focus as the temperature changes.

Each camera has its own dedicated dual-processor 1 GHz Pentium III computer running the Red Hat Linux distribution[‡]. The camera computers run a server which accepts commands over a socket connection. The resulting images are stored locally on hard disk until they are transferred to the LANL tape storage system at a later time. The network connection at RAPTOR B is fast enough that we simply transfer processed images over the network to the tape storage system. For RAPTOR A and S the network connection is slow enough that transferring over the network is impractical. For those telescopes we visit the site on a regular basis and

[*]Apogee Instruments Inc., www.ccd.com
[†]Finger Lakes Instrumentation, LLC, www.fli-cam.com
[‡]Red Hat Inc., www.redhat.com

download the images to portable hard drives which we then bring back to LANL headquarters to be loaded on to the tape system.

2.2. Mounts

All RAPTOR optical systems are attached to a rapidly slewing mount custom built for this project by The Pilot Group§. These mounts employ a servo-motor control system using encoders consisting of a precision ruled tape with 10 micron spacing in close proximity to opto-electronic sensors that detect relative motion. This encoder system can provide arcsecond pointing accuracy relative to the home position of the mount. The mounts are capable of slewing at a speed of nearly $100^o/s$ and accelerating to this velocity in less than one second. Emergency braking is accomplished using a pneumatically driven caliper which clamps on to a thin steel disk located on each drive axis. The mounts are controlled by an independent PC running Windows NT 4.0 which accepts simple text based commands over the serial port.

When the system begins operations each night, the mount finds its absolute home position by slewing to the hard limits in both Right Ascension and Declination. The absolute home position can vary by several arcminutes so a single image is taken at the start of the night and processed to find the position of the image center in sky coordinates. The relative mount coordinates are then adjusted to correspond to the sky coordinates from the test image. The resulting accuracy is a few arcseconds, well below our pixel scale.

2.3. Observatory Enclosures

The RAPTOR telescopes are housed inside 10 ft diameter welded steel cylindrical enclosures built for us by D & R Tank Co. in Albuquerque, New Mexico (Fig. 1). The roof of the enclosure is covered by an aluminum clamshell attached to a linear actuator. The clamshell is large enough that the telescope may be moved freely underneath it when the clamshell is closed. When the telescope is ready for observations after sunset, the actuator drives open the clamshell providing the telescope with an unobstructed field of view. The telescope mount sits on a 30 inch diameter steel pier make of 1/4 inch thick welded steel. Both the cylindrical tank and the pier are bolted to a 10 ft x 12 ft steel truss composed of 10.5 inch thick welded I-beams.

Control of the clamshell is provided by a custom built I/O Box which, using the SNAP Ethernet I/O control system from Opto 22¶, accepts commands over a socket connection (Fig. 2). The I/O Box accepts commands to turn on AC power to open or close the clamshell, reads the open and close limit switches, controls 4 extra AC outlets, and has a 4 channel analog-to-digital (ADC) converter. Additionally, the I/O Box has a watchdog mechanism which will automatically close the clamshell if it has lost contact with the host computer. The I/O Box draws its power from an uninterruptable power supply (UPS) with enough power to close the clamshell in the event of a power outage.

The weather station is composed of a Davis Weather Monitor II‖ which senses temperature, humidity, dew point, barometric pressure and wind speed and direction. Additionally we use a Vaisala DRD11A** precipitation detector which is read out through one of the ADC channels in the I/O Box. If any of the weather variables exceed limits, the control software will issue an alarm and the system will be put into a standby state with the clamshell closed.

3. THE RAPTOR DATA ACQUISITION SOFTWARE

RAPTOR is different from its predecessors in two significant ways. First, the scientific goals of the project require the operation of multiple observatories in synchronization with each other. As stated in the introduction, this is not a trivial task. We require the observatories to be able to image the same location on the sky within a second of each other. Simply scheduling coordinated observations beforehand does not work due to the fact that our system schedules the observations dynamically. For instance, observations at one observatory

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¶Opto 22 Inc., www.opto22.com

‖Davis Instruments Inc., www.davisnet.com

**Vaisala Inc., www.vaisala.com

may be interrupted by a weather alarm while the other observatory has perfectly good weather. To maintain synchronization between the observatories, we have implemented a client/server mechanism which allows one observatory to act as the master scheduler and control other "client" observatories. The master will wait until all the client observatories are ready to execute the next command, so that none of the clients will ever fall behind the rest. If a client observatory loses its connection to the master, it must then return to scheduling its own observations.

The second way in which the RAPTOR system is different from its predecessors is the need for a real-time analysis pipeline to meet our scientific goals. This means that images must be processed and searched for transient events on the timescale of our typical exposure, 30 seconds. If a transient is found by one observatory, the results must be compared to the data from the other observatory to reject false positives, hence the need for synchronized observations. In this way we establish the feedback loop where the observatories generate and respond to their own transient alerts.

To facilitate the goals listed above, we are developing a new software system for running the RAPTOR telescopes. This data acquisition (DAQ) software is composed primarily of a set of three UNIX daemons which schedule the observations and also monitor and control the hardware (Fig. 3). These daemons run asynchronously and communicate via TCP/IP sockets. The first daemon, *controld*, represents the brain of the system and schedules the observations, listens for transient alerts, and provides commands to the hardware daemons. The second daemon, *telescoped*, provides the hardware interface to the telescope mount and cameras. It executes commands from *controld* that it receives over the socket connection. The third daemon is *observatoryd* which is responsible for monitoring the weather and executing commands to open and close the clamshell.

3.1. Controld

The control daemon, *controld*, is the heart of the RAPTOR DAQ system. *Controld* is capable of running in four different modes: normal, server, client, and manual. When running in "normal" mode, *controld* generates commands for the hardware daemons. The manner in which it decides which command to execute next is configurable, but generally consists of a predefined sky-patrol scheme. This sky-patrol scheme can be interrupted by transient alerts, weather alarms, and the sun passing the elevation threshold. Additionally, *controld* must evaluate each patrol position for factors such as field elevation and lunar distance.

To facilitate coordinated operations of separate observatories, *controld* can operate in both "server" mode and "client" mode. To accomplish this, *controld* has a socket port available for a client mode connection. If a socket connection is made on this port, *controld* will relay commands from another *controld* running at a separate observatory. If *controld* loses the connection, it will return to normal mode operation. To run in server mode, *controld* simply performs the same tasks that it does in normal mode operation but then forwards these commands to the clients. To run in server mode, *controld* must be properly configured before the DAQ system is started.

A stand-alone program provides the manual interface by making a socket connection to *controld*. Using this program, the user may check the status of the system at any time. If the user then enters the command to put the system into "manual" mode, *controld* will stop sending any automatic commands and will simply relay commands from the user to the hardware daemons, *telescoped* and *observatoryd*. Manual mode operation also overrides client mode commands to *controld*. Manual mode commands do not, however, propagate to the *controld* of client observatories.

Another stand-alone program provides alert notices to *controld* at the various observatories. This program acts as a clearinghouse for alert notices by accepting multiple connections and forwarding an alert coming from one location to all the other clients connected to the alert server. The alert server also relays alert notices coming from the gamma-ray burst coordinate network (GCN)[4] to the various observatories. This is necessary because RAPTOR-A and RAPTOR-S are behind the LANL firewall and can not make a GCN connection themselves.

3.2. Telescoped

The telescope daemon, *telescoped*, is responsible for controlling the telescope mount and cameras. It was decided to combine these two hardware elements due to the fact that they are highly interdependent. Having a single daemon control both elements allows easier management of timing issues such as preventing an exposure from starting while the mount is still in motion. Also mount status information such as encoder and sky position are more easily incorporated into the fits headers of the images.

Telescoped has a socket port that will accept a connection from *controld* over which commands are transmitted. *Telescoped* accepts commands to sync, slew, park and halt the mount. It also accepts commands to sync and move the focus if the telescope has that capability. To operate the CCD it accepts commands to take dark and light exposures and also abort an exposure. Finally, it accepts a general query command and responds with the current status of the telescope.

Communication to the mount is made via a serial connection to the dedicated mount computer. The mount computer runs custom software from the Pilot Group which, in addition to handling the communication with our DAQ system, also monitors the mount status such as limit switches, encoders, and so forth. The mount computer only accepts commands to move to raw encoder positions. The task of converting these to sky positions falls on our software. To do this we have implemented the TPoint[††] software system to generate a pointing model. This only needs to be done when the telescope is initially installed or the telescope base has been physically moved. After the model is created, the only necessary parameter for transforming sky positions to encoder positions is the current time.

Communication to the cameras is accomplished via another client/server mechanism. Each CCD camera has its own dedicated computer which runs a small server program that accepts commands for that camera. When *telescoped* receives a command from *controld* to take an exposure, the command is parsed and passed to the appropriate camera servers. The reason for this client/server setup for the cameras is two-fold. First, each camera requires a computer card slot and, in the case of RAPTOR A and B, a single computer cannot hold them all. Secondly, this setup allows us to transparently have different types of cameras operating together on a single system. The camera servers all accept commands in a standard syntax and then translate them to the hardware specific commands for that particular type of camera.

The RAPTOR analysis pipeline runs on each camera computer and automatically processes images as they are taken. The processing involves subtracting a dark frame and dividing by a flat frame. The resulting image is then processed by the SExtractor[5] program which reduces each image to a list of objects with relative brightness and positions. The resulting object list is then calibrated against a catalog to get an absolute position and brightness for each object. Each resulting calibrated object list can contain 10,000 to 50,000 sources depending on the instrument and the variations in crowding for different galactic latitudes. All of the above operations take place within 30 seconds allowing one image to be processed while an exposure is under way for the next image.

The calibrated object lists are then compared with calibrated object lists from previous observations (Fig. 4). Any object that appears in only a single image is assumed to be non-astronomical and discarded. Any object which passes the above cut and shows sufficient variability is then flagged as a possible transient. If both RAPTOR-A and RAPTOR-B detect a transient at the same location at the same time a notice is sent to the alert server. After this occurs, all three telescopes center on the candidate and begin taking images in rapid succession to exhaustively monitor the object. We believe this four-way coincidence requirement (at least two images in two telescopes) will greatly reduce the number of false positives.

3.3. Observatoryd

The observatory daemon, *observatoryd*, is responsible for operating the clamshell and the weather station. Like *telescoped*, *observatoryd* accepts commands via a socket from *controld*. Only three commands are accepted, open and close the clamshell and a status query. The response to the status query is to send the state of the clamshell and the current weather conditions. The reason for combining the functionality of the clamshell and the weather station into a single daemon is to allow the fastest possible reaction time for closing the clamshell in the event of a weather alarm. Also, in the absence of a weather alarm, the clamshell should only move twice every night, once to open at sunset and once to close at sunrise. Therefore, normal operation of *observatoryd* consists almost entirely of monitoring the weather station.

[††]Patrick Wallace, TPoint Software, www.tpsoft.demon.co.uk

4. SUMMARY

The RAPTOR project is a group of robotic telescopes that will search for optical transients. Each system will operate in a completely autonomous manner. Additionally, each telescope will communicate with the others allowing them to operate in synchronization. Using this technique, we will be able to eliminate false transient detections with high efficiency. To accomplish the task of synchronized observations, we are developing new data acquisition software which will coordinate the activity of the RAPTOR telescopes. Three telescopes are currently under construction; RAPTOR A, B, and S.

In late February 2002, RAPTOR A had first light and began limited operation in manual mode. Since that time, construction has finished on RAPTOR A and RAPTOR B. We also expect construction of the RAPTOR S telescope to be completed by the end of August 2002. Initial testing on all three telescopes indicate that they all will perform within expectations. Several scientific observations have been made with the RAPTOR A telescope, including monitoring the eclipsing binary W Ursae Majoris and photographing the comet Ikeya-Zhang (Fig. 5).

RAPTOR A and B are currently able to operate in a limited robotic mode using an early version of the RAPTOR DAQ system. This early version of the DAQ system allows for simple sky patrols and alert responses. The client/server capability of *controld* is not yet implemented, nor is the transient alert feedback loop. However, the automated processing pipeline is running on all of the camera computers. We expect the DAQ system to be fully functional in the coming months.

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Figure 1. The RAPTOR-B enclosure with the clamshell open. The weather station and power distribution panel are visible on the side of the enclosure.

Figure 2. The RAPTOR I/O box. The Opto 22 components which control most of the functionality are on the bottom.

Figure 3. The RAPTOR data acquisition system. Each box represents a specific process. The three in bold are the primary control processes of the system. The arrows represent socket connections.

Figure 4. The RAPTOR transient alert feedback loop. Each telescope must observe a transient at the same time and location for it to be considered a valid detection.

Figure 5. An 60 second exposure of comet Ikeya-Zhang (C/2002 C1) taken with the RAPTOR-A fovea camera on 3 April 2002.

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