FINAL REPORT

NASA Grant No. NCC 2-977

THE ASSOCIATE PRINCIPAL ASTRONOMER FOR AI MANAGEMENT OF AUTOMATIC TELESCOPES

Submitted to:

NASA Ames Research Center
Moffett Field, CA 94035-1000

Project Period: March 1, 1997 to September 30, 1998

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I. INTRODUCTION

This document is the final report summarizing the results of NASA Grant NCC 2-977 to Tennessee State University, which began March 1, 1997 and ended September 30, 1998. This project was a continuation of a collaboration between NASA Ames and TSU, funded previously under NASA Grant NCC2-883. This report summarizes the entire project. Section II briefly summarizes the objectives of the project, Section III describes the accomplishments, and Section IV lists all publications and presentations.

II. RESEARCH OBJECTIVES

This research program in scheduling and management of automatic telescopes had the following objectives:

1. To field test the 1993 Automatic Telescope Instruction Set (ATIS93) programming language, which was specifically developed to allow real-time control of an automatic telescope via an artificial intelligence scheduler running on a remote computer.

2. To develop and test the procedures for two-way communication between a telescope controller and remote scheduler via the Internet.

3. To test various concepts in AI scheduling being developed at NASA Ames Research Center on an automatic telescope operated by Tennessee State University at the Fairborn Observatory site in southern Arizona.

4. To develop a prototype software package, dubbed the Associate Principal Astronomer, for the efficient scheduling and management of automatic telescopes.

III. RESEARCH ACCOMPLISHMENTS

The goals of this project have been accomplished and documented in the literature. A brief summary of the activities associated with the project is given below with references to the literature produced.

a. Background

Research quality telescopes located at prime observing sites have always been a scarce resource, and astronomers have had to contend with limited access to these telescopes. Typically, observing time is allocated to an individual astronomer a few times per year in short contiguous blocks of a few nights each. Furthermore, the astronomer has needed to be physically present at the telescope in order to operate his instrumentation for data acquisition. Thus, limited access, block allocation, and local operation all have restricted both the amount of data that can be gathered and the type of observational campaigns that can be accomplished. These same factors make acquisition of astronomical data expensive and difficult to obtain and also often limit the precision of the resulting data (Henry 1995a).

More recently, sophisticated network and communication technologies have enabled a number of new approaches where astronomers may participate in an observation program from a remote location. These approaches range from remote verbal communications with the on-site telescope operations staff to actual remote control of a telescope with real time video feedback (Emerson, 1993). Such remote observations provide flexibility by allowing the observer to be physically distant from the telescope yet remain in direct control. However, even in this remote observing paradigm, the astronomer must still be involved during the execution of the observing program, and human presence at the observatory is often still required.

Fully automatic telescopes represent an extension to the remote observing paradigm, allowing an astronomer to be removed from the telescope both temporally as well as spatially. For example, Fairborn Observatory (Arizona) has designed and built software and hardware systems for the control of modest-aperture telescopes equipped with photoelectric photometers to measure stellar brightness (Genet & Hayes 1989). These systems make it possible for a remotely located telescope to operate unattended for significant periods (up to a number of months). These telescopes execute commands provided by an astronomer in such a way that the astronomer is not required to participate in the execution of the observing program. It is in this sense that these telescopes are fully automatic. While the majority of existing ground-based automatic telescopes are used for aperture photometry, development efforts for automated imaging and spectroscopy have been increasing (Boyd et al. 1993, Treffers et al. 1995, Eaton 1995).

Astronomers at Tennessee State University (TSU) operate several of these automatic photoelectric telescopes (APT's) at Fairborn Observatory in support of long-term observational programs that would be impossible to accomplish with traditional manual telescopes (Henry 1995a). These telescopes include (1) a 10-inch telescope dedicated to long-term observations of semi-regular variable stars in collaboration with the Harvard-Smithsonian Center for Astrophysics as well as a project in education in collaboration with the TSU Department of Education, (2) a 16-inch telescope dedicated to observations of chromospherically active (magnetic) stars in collaboration with Vanderbilt University, (3) a 30-inch telescope dedicated to lower-main-sequence stars in collaboration with the Harvard-Smithsonian Center for Astrophysics, and (4) a 32-inch telescope dedicated to solar duplicate stars in collaboration with the Center for Astrophysics. In addition to these existing telescopes, a 24-inch automatic imaging telescope (AIT), three new 32-inch APTs, and an 80-inch automatic spectroscopic telescope (AST) are under construction.

TSU astronomers have collaborated with Fairborn to develop precision photometers, software, observing techniques, and quality control procedures that have culminated in the automatic acquisition and reduction of high volumes of photometric data of incomparable precision and at extremely low cost (Henry 1995b). The scientific return from these automatic telescopes has been profuse (e.g., Henry et al. 1995a, Kaye et al. 1995, Cristian et al. 1995, Henry et al. 1995b, Henry & Newsom 1996, Henry et al. 1997).

A language used to define observation requests for the Fairborn APT's was developed at Fairborn in 1989 and named the Automatic Telescope Instruction Set, or ATIS (Genet & Hayes 1989). This new ATIS language allowed APT users to tailor the exact specifics of their observing programs and communicate them to the telescopes via ASCII file transfers over telephone lines or the Internet and to retrieve the resulting observations the next day. In ATIS, a group is the primitive unit to be scheduled and executed. A group is a sequence of telescope commands and instrument commands composed by an astronomer to accomplish the observation of an object of interest. The group contains commands to move the telescope, to control the filters, and to make integrations in a defined sequence.

In addition to specifying the syntax and semantics for observation requests and results, the ATIS standard provides a set of group selection rules that are used to determine the execution order of groups during the night. The group selection rules provided by ATIS essentially implement a first-to-set-in-the-west policy: at any given point in time the telescope observes the group that will next move out of its observation window. By implementing a set of user-input parameters to define group types, group priorities, probabilities of execution, date and local sidereal time limits, number of observations requested, etc., this ATIS dispatch scheduling method allows APT users to define any desired observation sequence as well as to intersperse standard star observations and other quality control checks throughout the night and have them all scheduled automatically.

However, in spite of the revolutionary improvements to the long-term scientific programs being conducted at Tennessee State University and elsewhere that have resulted from the use of automatic telescopes running the ATIS control language, the 1989 version of ATIS is not without its limitations. There is no look-back or look-ahead capability that might help the telescope decide when to make a given observation, perhaps to fill in a variable star's phase curve automatically or make an observation that got missed on a previous night. Many situations can arise, particularly on multi-user telescopes, where more intelligent scheduling is needed than the simple ATIS default group selection rules can provide in order to help ensure that the highest priority observations are made at scientifically appropriate times and that all users are treated fairly in the allocation of telescope time. Also, since ATIS allows access to the telescope only before the beginning of the night and after the end of the night, no information is available during the night about the current status of the observing program, the quality of the data being obtained, or about the performance of the telescope and detector that might allow appropriate modifications to the observing program in real time. Henry (1996) has shown that substantial gains could be made over ATIS dispatch scheduling even for the case of an APT dedicated to a single long-term observing program.

b. The APA Project

Several years ago, the NASA Ames Research Center initiated a project to develop artificial intelligence scheduling techniques and apply them to the problems of scheduling and managing the operation of automatic telescopes like the ones being operated at Fairborn Observatory by Tennessee State University. Up to that time, automatic telescopes, whether single or multi-user instruments, had been managed by a single Principal Astronomer (PA) whose responsibilities included scheduling scientific observations from all users on the telescope, scheduling and examining quality control observations to ensure proper operation of the complete system, retrieving, reducing, and parsing out the nightly observations to all observers, and ensuring fair access to the telescope for all participating observers (see e.g., Seeds 1994). The Ames project sought to simplify the management of these telescopes through the creation of a software package, later dubbed the Associate Principal Astronomer (APA), containing routines for automatically receiving observational requests from users, generating the ATIS commands needed to execute these requests, selecting the appropriate mix of observations to schedule on each night (the loading process, based on a detailed set of group specification parameters that define each user's scientific goals), finding a satisfactory, detailed, minute-to-minute schedule for the night's observations (the scheduling process), downloading this schedule to the remote telescope's control computer at the beginning of the night, monitoring the schedule during the night and dynamically rescheduling when appropriate, retrieving the resulting data the following morning, applying quality control checks to the data and telescope performance, reducing the data, and parsing and sending each user's data to his home computer.

In 1992, an informal collaboration began that included NASA Ames, Fairborn Observatory, TSU, and other interested users and builders of APTs. Workshops were held at Ames and in Phoenix in May and November of that year to address the limitations of the original ATIS control language, especially those that precluded real-time control by an external scheduler. By the end of the year, a new group selection advice statement had been developed that had the capability to override the default ATIS group selection rules in real time through the use of partial input and output files. This new capability would make it possible to implement a non-native scheduler that could effectively drive an APT controller to give better schedules than could the ATIS default rules. A host of other enhancements were developed for a new version of ATIS, called ATIS93, including a set of commands for making CCD imaging observations. The ATIS93 specification was published by Boyd et al. (1993) in hopes of its becoming an international standard language for automatic telescope control.

In 1994 September, Tennessee State University submitted a formal proposal to NASA Ames entitled "Artificial Intelligence Scheduling of Automated Telescopes" in which they agreed to make their APTs available for field testing of the Ames AI scheduling techniques and to work further with Ames to develop the APA project. The proposal was approved (NCC 2-883) in 1995January. During the course of the project, TSU worked with Ames to develop ATIS93-based tools for quality-control monitoring of photometric data from the APTs, participated in the development of various loading and scheduling techniques for improving the performance of the APTs, worked with Fairborn Observatory to develop the ATIS93-based controller that would interface with the APA scheduler, and installed and debugged this controller on TSU's new 32-inch APT.

The project culminated in the spring of 1996 with several weeks of real-time scheduling of the 32-inch APT via an Internet connection to a prototype scheduler running at NASA Ames. Details of the work were published in the literature and can be found in Drummond et al. (1994), Swanson et al. (1994), Bresina (1994), Bresina et al. (1994), Drummond et al. (1995), and Edgington et al. (1996). The most recent work on scheduling techniques for the APTs was summarized by Bresina (1996) and Bresina et al. (1996).

During the course of this project, the Center of Excellence at TSU received funding from NASA Headquarters to establish a new University Research Center within the Center of Excellence called the Center for Automated Space Science (CASS). This enabled TSU to begin construction of a new 24-inch automatic imaging telescope (AIT) with a CCD detector and an 80-inch automated spectroscopic telescope (AST) with a fiber-fed, high-resolution, echelle spectrograph to complement the capabilities of the existing APTs. In addition, construction began on three new 32-inch APTs. However, the existing Fairborn Observatory site on Mt. Hopkins had insufficient room to accommodate these new telescopes, so Fairborn purchased and developed a new site at the 5700-foot level in the Patagonia Mountains near Washington Camp, Arizona. All existing APTs were moved to the new site during the summer of 1996 and resumed operations in November. A new computer was installed at the site with the capability to run the APA directly over a local area network.

All of the major research results of this project have been published in the literature and/or presented at national and international conferences (see the publications and presentations lists given below). Some of the recent highlights of the project include the following:

1. The development of the an ATIS93 simulator to debug problems with the APA/APT communications interface. Earlier tests of the remote scheduler on the 32-inch APT revealed a number of difficulties in real-time Internet communication between the scheduler and the APT that resulted in often repeated as well as missed observations. The ATIS93 simulator was developed to run on the computers at Fairborn. The remaining communication difficulties were solved and continued alpha-testing of the scheduler were accomplished with the simulator.

2. The installation of a dedicated computer at Fairborn Observatory to run the APA. To avoid the apparently inevitable problems with long-distance, real-time Internet communication between the scheduler and the APT controllers, Fairborn Observatory installed a local platform for running the APA package on-site at Fairborn. This computer ran the Linux operating system and connected to all the Fairborn telescopes via a local network. When APA scheduling of the 32-inch telescope resumed, far fewer difficulties were encountered by having the APA machine connected to the telescope control computer vial the local area network rather than via the Internet connection to NASA Ames.

3. Tests of several of the new scheduling methods developed at NASA Ames were tested via the

APA/APT simulator and/or in live scheduling tests on the 32-inch APT. The most successful field tests resulted when the APA control computer was placed on the local network at Fairborn. Technical details of the various scheduling methods are given in the literature cited in the final section of this report.

4. Pursue development at TSU of analytical techniques to find the *optimal* schedule. The robust controls group (Keel, Sathananthan, Tantaris) within the Center of Excellence at TSU explore alternative analytical methods for *computing* the *optimal* schedule for an APT. Here, the optimal schedule is defined as the one that successfully includes all of the observations for a night passed to the scheduler by the loader and orders the observations in a way that minimizes the nightly average airmass. New Discrete Event Systems (DES) approaches were used that dealt with a time-dependant cost function as well as Optimal Control Formulation approaches would be attempted to solve this complex optimization problem. This work resulted in the successful completion of a Master's Thesis by TSU Electrical Engineering student Richard Tantaris entitled "Development of an Optimal Scheduling Algorithm for a Multi-User, Multi-Tasking Automatic Telescope."

5. New search techniques, such as HBSS and GenH, were further evaluated by John Bresina at Ames for finding high-quality schedules. The GenH technique automatically generates a multi-attribute search heuristic specialized to a particular scheduling problem. HBSS stochastically explores the space of possible schedules biased by heuristic advice. This work led to a number of new publications (see below) as well as to a Ph.D. dissertation by Bresina.

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IV. PUBLICATIONS AND PRESENTATIONS

A total of 28 papers were published in the astronomical and artificial intelligence literature with support from NCC 2-883 and NCC2-977. In addition, 23 presentations related to the project were given at various regional, national, and international meetings. These publications and presentations are listed below:

Publications

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