Session 4

Automatic Photoelectric Telescopes and Extinction

Robotic Observatories: Past, Present and Future

Russell M. Genet and David R. Genet

AutoScope Corporation, PO Box 2560, Mesa, Arizona 85214, USA

Abstract

We briefly describe the history of robotic observatories, give details on an example of the current state-of-the-art in robotic observatories, and suggest several key areas for future development.

1. Past

The first fully automatic electrical measurements of starlight were made at the University of Wisconsin (McNall, et al, 1968) and at Kitt Peak National Observatory (Meinel and Meinel 1990, and Maran 1969) about 25 years ago. These pioneering, fully automatic photoelectric telescopes (APTs) were mainly technological demonstrations, and were little used for scientific research. The Wisconsin group went on to develop automated space telescopes, which were very useful scientifically although outside the scope of this Earth-bound review. KPNO quickly reverted to manual operation, however, never to return to automatic operation. As Aden B. Meinel, KPNO's innovative first Director, mentioned to me, "Astronomers just weren't ready for automation yet." It also seems likely that robotic telescopes were not really ready for astronomers yet either. The Wisconsin system only had 4K of RAM, punched paper tape as an input, and a printer as an output, while the computer for the KPNO system was not very reliable.

About 15 years were to transpire before automatic photoelectric measurements were to be made on a regular basis. The next fully automatic system was able to take advantage of the much more capable (and less expensive) microcomputers that had been developed in the interim. This first really useful APT was developed by Louis J. Boyd, with some assistance from one of us (RMG). This system, the "Phoenix-10", saw first operation in October of 1983, and has been producing useful science ever since. One of us (RMG) developed a somewhat similar system, the "Fairborn-10" APT, which began operation in September of 1984, eight months after the Phoenix-10 APT began its operation. The Fairborn-10 APT was transferred from Fairborn, Ohio, to Mt. Hopkins in southern Arizona in 1985, and has been operating there ever since. The Phoenix-

10 and Fairborn-10 APTs have been described by Boyd and Genet (1984), and in more detail by Trueblood and Genet (1985). The history of all four pioneering systems mentioned above, as well as that of a semiautomatic system developed by David Skillman, have been discussed in detail by Genet (1986) and by Genet and Hayes (1989). Genet and Hayes (1989) also discuss the development of the Automatic Photoelectric Telescope Service on Mt. Hopkins, jointly run by the Fairborn Observatory and the Smithsonian Institution. With some five APTs in operation (and two more about to begin operation), the APT Service now serves some four dozen institutions world wide, and is a primary source of photoelectric measurements of variable stars.

There have been a number of mainly independent developments of APTs elsewhere. An outstanding example is the 0.5-meter "Danish APT" at the European Southern Observatory, described elsewhere in these proceedings by its developer, Ralph Florintien-Neilson. Russell Robb developed a nearly automatic system that has been used to observe faint X-ray binaries at the University of Victoria. The Bulgarians recently brought a system on line that is being used to observe flare stars. R. Kent Honeycutt, and his associates at Indiana University, developed a fully automated APT that utilizes a CCD camera as the detector and is able to make automatic photometric observations of very faint stars. Edwin Budding and his colleagues in New Zealand are using a modified C-14 to make automated observations. There are also many other APTs under development but not yet operational, such as those by James O'Mara in Australia, David Killkenny in South Africa, by an Irish amateur astronomer, and by a group in India, etc.

Five years ago, one of us (DRG) founded AutoScope (a contraction of *auto*matic tele*scope*) to commercially produce robotic observatories. Both of us thought that the astronomical community should now be ready for robotic telescopes and, more importantly, thanks to technological advances across a wide front, that robotic telescopes should, at last, be ready for astronomers. A number of complete observatories or telescopes have now been purchased from AutoScope by various institutions. The Jet Propulsion Laboratory purchased three complete observatories that are being used in a network in the southwestern US. The Lawrence Berkeley Laboratory purchased a 30-inch aperture telescope for use in their supernova search. Tennessee State University and the Smithsonian Institution have teamed up to place a 32-inch system on Mt. Wilson in southern California. The University of California at Berkeley is placing a 32-inch aperture system at Lick Observatory for faint object CCD photometry. Catania Observatory placed a 32-inch system on Mt. Etna. Its primary use is the observation of flare stars. The Fairborn Observatory operates a system in Mesa, Arizona. Buhl Science Center, in Pittsburgh, operates a system with a video wall display in their public science center of the live output from a CCD camera. A 40-inch system is nearing completion for the Korean Astronomical Observatory, and is described in some detail below. Systems are also being built for the University of California at Irvine, NASA Ames Research Center, and New Mexico State University. The latter is a 40-inch alt-az system with an autoguider.

2. Present

We thought that the best way to provide the reader with a feel for the current state-of-the-art in robotic observatories was to describe a recently-produced system in some detail. We have chosen, as the example state-of-the-art system, the 1-meter (40-inch) aperture telescope, instruments, and observatory manufactured for the Korean Astronomical Observatory (KAO) by AutoScope. Unlike some earlier AutoScope systems, whose intended use was strictly just for aperture photometry, the "KAO-40" was intended to also be used to obtain long-exposure CCD images and, perhaps later on, for fully automated spectroscopy. The KAO-40, as well as all currently built AutoScope systems, are now general-purpose automatic systems with highly precise optics and very accurate pointing and tracking, and are *not* just automatic photoelectric telescopes (APTs). As these systems usually include, besides an automatic telescope, automatic instruments and an automatic enclosure (with weather station, etc.), we often refer the them as *robotic observatories.*

AutoScope systems have made a sharp break with past tradition in terms of their size and especially their weight. Research telescopes have, in the past, been rather gargantuan in proportions, and have been generously fabricated from steel with weights measured in the tens or hundreds of tons. Their design philosophy was somewhat akin to that of battleships and bridges. Our telescopes, however, are unusually compact, and they primarily utilize aluminum alloy in their construction. They are philosophically similar to aircraft or spacecraft in conception (we are both airplane pilots, so such thinking comes naturally), and are very lightweight. Lightweight telescopes, other things being equal, have higher natural resonant frequencies and are thus less effected by wind buffeting than heavier telescopes. Furthermore, their moments of inertia are an order of magnitude less than conventional telescopes, allowing very rapid acceleration, deceleration, and settling. Such "crispness" is well suited to the inhumanly rapid and precise robotic nature of these systems.

Lightweight automatic telescopes demand lightweight mirrors, as well as lightweight and compact (or off-telescope) automatic, instruments. The KAO-40 and all other AutoScope systems now use primary mirror blanks manufactured for us by HexTek. For apertures up to 1 meter, these HexTek blanks use a gas fusion process that sandwiches vertically stacked Pyrex tubes between fairly thin horizontal Pyrex front and back plates. The entire assembly is then brought to fusion temperature, slumped over a mold and, at the right moment, gas is forced, under pressure, through holes in the bottom plate into each of the Pyrex tubes. This causes all the tubes to simultaneously expand until they are in contact along their entire surfaces, forming hexagonal patterns (hence the company's name, HexTek).

Not only are these blanks light in weight, but they are very stiff. Also, with only 20% of the mass of solid mirrors of the same thickness, HexTek blanks have a much lower thermal mass, allowing them to more closely track changes in the temperature of the night air, thus helping to preserve the excellent seeing available at many mountaintop sites. Secondary blanks are also light in weight, and are typically made from a low-expansion material. The secondary for the KAO-40, for instance, was made from Cervit.

As mentioned above, the KAO-40 (and other AutoScope) mounts are made of aluminum alloy to increase their resonant frequencies and greatly reduce their moments of inertia. Aluminum is also highly corrosion resistant, especially when protected with an electrostatically attracted, baked-on, powder-coat enamel. Light weight also eases handling during assembly, disassembly, and shipping. Two persons can, for instance, easily handle the major subassemblies of the KAO-40 telescope without any assistance from cranes, etc.

The KAO-40 mount is shown in Fig. 1. As can be seen, it is an equatorial horseshoe mount somewhat similar in layout to the 4-meter telescopes at KPNO and CTIO and a number of other large telescopes. The secondary mirror is mounted on a swivel that is supported by a precision shaft passing through two linear bearings, thus totally eliminating all side play. Mirror movement, either focus or tilt, is provided by three fine-pitch linear stepper motors. The square top of the open-frame optical support structure, which is more efficient than the more conventional round top (which tends to "bow" out when compressed by the spiders), was modeled after the 3.5-meter telescope at Apache Point Observatory. We are grateful to the designers of the 3.5-meter telescope, Walter Sigmond, Charles Hall, and Edward Mannery, for this helpful suggestion.

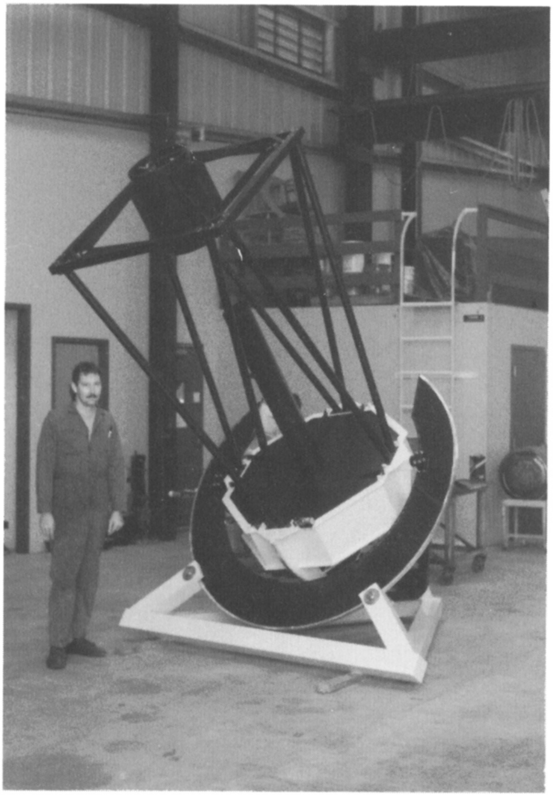

Figure 1 The KAO-40 mount uses aluminum alloy in its construction and a lightweight HexTek primary mirror.

The primary mirror cell, which is constructed of aluminum alloy, as is all of the telescope mount, provides support for the primary mirror via a central radial support and a rear 27-point flotation system. Two overlapping dust cover sets on the front of the mirror cell provide protection when the system is not observing. The dust covers are under automatic computer control. A fan (also under computer control) is used to draw filtered air through the rear of the fully enclosed mirror cell.

Very rapid response, very high torque, DC servo systems (Dynaserv DC servos made by Compumotor) are used to drive the telescope in both RA and Dec. These servo motors, mainly used by others for strong, high-speed industrial robots, are of such high precision, resolution, and torque, that only a single stage of friction drive reduction is needed. A small roller on each motor shaft directly drives, respectively, the large RA and Dec disks shown in Fig. 1. The acceleration and top speeds of the telescope have to be limited by software for safety's sake (and an audio chime sounds to warn humans during movement). There is nothing sedate about the movement of this telescope, it is extremely rapid.

The telescope's initial position is sensed by Sony "Magnaswitches" which provide about 1 micron of precision or, in an angular sense, a couple of arc seconds. Limit switches prevent accidental motion outside of the allowable observing window which is preset in the software.

All of the computers and electronic control equipment for the telescope, its instruments, and the observatory itself are contained within the single cabinet shown in Fig. 2. Rather than trying to run the telescope, all of its instruments, and the observatory itself with a single, expensive, multi-tasking computer, a hierarchial network of lower-cost computers is used to improve modularity and to ease the later addition of new automatic instruments. At the highest level is a single *Master Computer* (an industrial rack-mounted -386 PC). This Master Computer communicates to the outside world via modem or computer network, and to second-tier computers (also industrial, rack-mounted PCs) via Ethernet and well-defined ASCII messages to RAM disks. Thus a new instrument can be added at any time via a simple Ethernet connection. The computer used to control this new instrument can be of essentially any type (and can use any operating system and programing language). All that is required is the Ethernet connection. The third level of computers in the hierarchy consists of specialized control computers on cards within the PCs. These are used, for instance, to execute telescope motion commands, change filters, etc.

The KAO-40 uses five custom AutoScope controllers, each of which is described briefly below. The controllers are mounted in the left side of the equipment rack shown in Fig 2.

The Telescope Controller controls 2 or 3 axes telescopes (either equatorial or alt-az), with the third axes being an instrument rotator. Optical encoders on the main telescope axes provide positional feedback information. Besides control of telescope motion, sensing limits, sounding alarms, etc., the Telescope Controller positions the secondary mirror and also controls a four-port instrument selector that switches, under automatic control, the optical beam to any one of four permanently mounted instruments. A WWV or GPS clock provides precise time.

The Observatory Controller uses weather and environmental sensors to determine if it is safe to open the observatory, when it needs to be closed, when unsafe conditions are encountered, etc. This information is used by the Observatory Controller to open or close dome shutters or roll-off roofs. A "watchdog" timer is frequently reset by the computer, and if it fails to do this the timer will time out, control will be taken away from the computer, and the dome shutter or roll-off roof will be forced closed by the Roof Controller (which contains its own battery power). A Power and Environmental Controller manages the power and temperature environments for the equipment, executes emergency stop commands, etc.

Figure 2 Computers and Controllers for the KAO-40 automatic telescope, instruments, and observatory.

The Photometer Controller manages the ultra-precision photometer, including very tight control of filter and PMT temperatures, humidity, the positions of two filter wheels, a diaphragm wheel, and a photometer / CCD camera flip mirror, etc.

The KAO-40 and other AutoScope systems can be controlled in real time, either locally or remotely, or can be run automatically. Automatic operation adheres to the Automatic Telescope Instruction Set (ATIS) standard that specifies the format and content of observational requests and results.

3. Future

We feel robotic observatories have a bright future, perhaps eventually dominating research astronomy. Robotic observatories nicely solve two old problems: (1) the usually considerable physical distance between astronomers (and students) and the best observatory locations; and (2) the difficulty in staying up at nights to observe and teaching or attending classes during the day. Furthermore, the smart, automatic scheduling used by robotic observatories is much more efficient than the "block time" scheduling used by almost all non-robotic observatories. Finally, robotic observatories are very cost-effective. Large amounts of very high quality data are obtained at low cost. Robotic observatories are mainly "run" by their remote users, with only occasional on-site technical support being needed. Observers and large staffs are expensive to transport to and support on remote mountain tops, and robotic observatories do away with all of this. We briefly mention, below, some of the areas we are currently working on and hope to bring to fruition in the near future.

We plan to extend what full automation is currently doing for photometry (and imaging) to spectroscopy. We were very pleased to receive a Small Business Innovation Research (SBIR) award from the National Science Foundation for the development of a fully automated spectrograph. With R. Kent Honeycutt (Indiana University) and with the kind advice of many leading spectroscopists, we have completed Phase I of the SBIR grant -- the design of the spectrograph. During Phase II we plan to build and operate the prototype spectrograph. The spectrograph is a fiber-fed Echelle that covers 3900 - 9000 Angstroms with a single, fixed grating setting and output format. The spectrograph is housed in an off-telescope enclosure whose environment is rigidly controlled.

We also plan to extend the capabilities of our current automatic scheduling system, and to implement automated diagnostics. We were very pleased to receive a Small Business Innovation Research (SBIR) award from the National Aeronautics and Space Administration for the development of these advanced capabilities which should not only greatly benefit the operation of robotic telescopes here on Earth, but could lead, in a natural evolutionary process, to robotic telescopes at the Lunar Outpost operated in a similar fashion (i.e. operated directly by the users themselves without any significant permanent staff).

Working with Mark Drummond and his associates at NASA Ames, and with current users of robotic observatories such as Gregory Henry, we are extending the capabilities of current automatic scheduling system to include capabilities for automatically filling in phase (light or radial velocity) curves, scheduling observations during eclipses, switching between observational instruments (such as a photometer and spectrograph) depending on photometric and seeing conditions, and many other advanced features. We are also working on international standards for networking robotic observatories together. The advantages of such networking are discussed elsewhere in this volume by David L. Crawford.

Working with Ann Patterson-Hine and her associates, also at NASA Ames, we are developing extensive capabilities for automated equipment monitoring and diagnostics. Each of our current controllers has all of its key monitoring points wired to a "test jack", and these test jacks are now being connected to a switching high-speed analog-to-digital converter that allows the monitoring and diagnostics computer direct access to over 100 test points in the controllers. Besides allowing self checks at start up (or whenever desired), keeping track of possible adverse trends (health monitoring), and allowing remote human-assisted or on-site automatic diagnostics, we are planning on having a capability for automatically switching to on-line "spares". By having essentially two of everything, any failure would only cause the system to be down for an instant while the fault was automatically diagnosed and the backup unit automatically switched in. The system would then keep right on operating, and humans would be notified to replace the unit at their convenience. We feel that such an approach would be useful for systems at very remote locations, such as the South Pole or Lunar Outpost, or for systems which were critical, large, or expensive, where essentially no system downtime could be tolerated.

With the assistance of Butler Hine (NASA Ames) and Jack Burns (New Mexico State University), we are giving serious consideration to the problems of operating robotic observatories at such very remote sites as the South Pole and the Lunar Outpost. We plan to build a system with all of the advanced features mentioned above and eventually place it at the South Pole.

Finally, we are working on the design of an "advanced technology" 2.5-meter production robotic observatory. This would be the largest aperture telescope, instruments, and enclosure every produced commercially in quantity -- robotic or otherwise. We expect that it will be unusually compact and light weight -- even more so than our already lightweight systems -- perhaps employing carbon composite fibers in a few critical areas. We expect that the system will incorporate adaptive optics and, on nights of excellent seeing, will provide images of fractional arc second quality.

References:

Boyd, L. J., and Genet, R. M. 1984, in *Microcomputers In Astronomy II*, Ed. by K. A. and R. A. Genet, Fairborn Press, Fairborn.

Genet, R. M. 1986, in The Study of Variable Stars Using Small Telescopes, Ed. J. R. Percy, Cambridge University Press, Cambridge.

Genet, R. M. and Hayes, D. S. 1989, *Robotic Observatories*, AutoScope, Mesa.

Maran, 1969 in *Stellar Astronomy*, Ed. H. Y. Chiu, J. Remo, and R. Warasila, Gorden and Breach, New York.

McNall, J. F., Miedaner, T. L., and Code, A. D. 1968, *Astronomical Journal*, **73**, 756.

Meinel, A. and Meinel, M 1990, in *Robotic Observatories: Present and Future*, Eds. S. L. Baliunas and J. S. Richard, Fairborn Press, Mesa.

Trueblood, M, and Genet, R. M. 1985, *Microcomputers In Astronomy*, Willmann-Bell, Richmond.

Discussion

W. Tobin: *What will a 2.5-metre APT cost?*

Genet: We expect that the cost for a complete telescope, control system, observatory, and instruments would be about US$2.5m to US$3.5m .

I. S. Glass: *What happened to the amateur space telescope mooted by Rochester?*

Genet: I wrote to them about their project, but never received a reply, so I do not know the status of their system. I have never met any of them at meetings.

E. F. Milone: *Do you envisage the large Autoscope telescopes to be single-instrument telescopes? There may be advantages to single instrument telescopes; maybe relialibity and precision can be better maintained. If so, it makes sense for a consortium of like-minded users rather than institute/university consortia.*

Genet: I expect that typically there will be four instruments permanently installed, such as a high-resolution Echelle spectrograph for bright objects, a low-resolution spectrograph for faint objects, a CCD camera with filters for imaging and red photometry, and perhaps an aperture photometer. It may be necessary that IR telescopes be different from optical telescopes.

J. B. Hearnshaw: *For your proposed automated spectroscopic telescope, there are many different spectrograph parameters one could select (such as resolution, wavelength region etc.) Will you select a fixed set of parameters or have the ability to change these from observation to observation? Ideally the science you want to accomplish should dictate the instrumental design of any spectrograph. What scientific program do you envisage for an AST?*

Genet: To begin with we plan to have only a fixed configuration, without changes except minor adjustments. Spectral coverage will be from 3900Å to 9000Å or so, with 1 pixel covering 0.5Å or slightly less. We are aiming for a fairly simple but fully automatic spectrograph that would appeal to many, but not all, users.

M.S. Bessell: *To answer John Hearnshaw's question: with a large format 2048^2 CCD, a 31.6 g mm^{-1} echelle and prism cross dispersion one can get full wavelength coverage without any wavelength adjustment at a resolution suitable for almost all stellar spectroscopic work using a camera with a focal length of about 80 cm.*

Genet: It is correct that a fibre-fed Echelle spectrograph allows the entire spectrum to be displayed simultaneously. This helps to minimize adjustments. Our goal is to have no user adjustments that must be regularly made.

J. Tinbergen: *Whatever type of millimagnitude photometry your users are going to do, with a Nasmyth arrangement you will have to do something about polarization-induced photometric errors. Depolarizers unfortunately are small, so an intermediate focus is needed before the Nasmyth flat. Do look at the LEST designs for alternatives.*

Genet: This is an important consideration. We have not fully dealt with it yet and will be looking into it after the meeting. You are certainly correct that it must be considered!

J. Tinbergen: *There is a world of difference in observing five extinction stars per night or doing so every half hour. In the interests of disentangling extinction gradients from local or global time variations, could you tell us what your slewing speed is and how many seconds it takes to come to a dead stop, on the star, from full slewing? (take a 1-metre telescope, for example).*

Genet: For safety reasons we limit slew speeds to 1.0 degrees/second, although faster speeds would be possible. The system which weighs only a tenth as much as conventional telescopes, (a hundredth of the moment of inertia) can stop in one second or less from full speed. If centering on the star is required, this may take a few seconds more.

J. Tinbergen: *That's fantastic news for extinction fighting! You mention having an offset guider. Have you considered using those CCD frames for monitoring extinction variations during a long photometric exposure?*

Genet: This is a good idea. There is no reason why it could not be done as the data is there in the computer.