The Hexapod Telescope – A Never-ending Story

Rolf Chini

Astronomisches Institut der Ruhr-Universität Bochum
Universitätsstraße 150, 44780 Bochum, Germany
chini@astro.ruhr-uni-bochum.de

Abstract

The 1.5 m Hexapod Telescope is the prototype of a worldwide unique design concept for future telecopes. Its technical innovations comprise i) a mounting where the classical axes are replaced by six high-precision struts of variable lengths, ii) an actively controlled primary which consists of a thin Zerodur meniscus that is permanently fixed to a CFRP grid structure, iii) a secondary whose support legs are also designed as a Hexapod to compensate for gravitational deformation due to different elevations and, iv) a laser gyro system to provide the pointing. The telescope is currently tested in the Botanical Garden of the Ruhr-University Bochum and it is planned to transfer the instrument to Cerro Armazones, Chile after the world exhibition EXPO 2000.

1 Introduction

The concept of a german large telescope (DGT) was initiated in the mid of the '80s by a consortium of nine german unviversity institutes. The objective of this working group was to build a 10 m class telescope with the aim to increase the observing time for german astronomers and to complement the ESO VLT project in the northern hemisphere (Appenzeller 1986, Fricke 1987). The final design converged to a 12 m single dish telescope with a segmented mirror in combination with a yoke mounting where the elevation axis was arranged below the primary (Schmidt-Kaler & Schnur 1986). Simultaneously, ideas were developed to support the primary actively and to reduce the mounting weight by adapting structures used in modern radiotelescopes. The search for light-weight solutions of the mounting culminated in a concept called SVELTE (**S**ix **V**ariably **E**xtended **L**egs **Te**lescope) which was presented by Brandt et al. (1987). The physical principle of such a six-leg mounting allows movements in all six degrees of freedom and was not new at that time. It had been originally proposed by Felgett (1969) for astronomical purposes, however, his suggestion for the technical realization of the length variation by pure hydraulic means did not meet astronomical accuracy requirements. Nevertheless, the idea itself, i. e. the movement of a body by means of length-variable legs, is successfully used in many technical applications like e. g. "Steward" platforms in flight simulators.

Despite various attempts to raise funds for the DGT project it was not possible to obtain money from any astronomy-supporting party. In contrast, a feasibility study for the DGT could only be started in December 1986 due to the support by the *Ministry of Economics, Trade and Technology* with the aim to investigate the influence of the DGT project on the industry in Northrhine-Westfalia (NRW). This unusual but successfull approach had been initiated and was henceforth lead by the Astronomical Institute of Bochum University (AIRUB).

The results of this feasibility study were summarized in a final report by Th. Schmidt-Kaler to the ministry in June 1988 with two alternative options for the mounting: i) an Alt-Az mounting with the elevation axis below the primary, ii) a Hexapod mounting with six legs below the primary. Simultaneously, a proposal was included to build a small prototype of the DGT. Eventually, in 1989 a fund of eight million DM by the *Ministry of Economics, Trade and Technology*, NRW, allowed the realization of the Hexapod prototype – now called the Friedrich-Wilhelm-Bessel-Teleskop – with the aim to prove the concept of the 12 m DGT. It cannot be emphasized enough that these eight million DM were not taken from the budget of the german astronomical community – and thus have not limited the progress of any other projects – but came from the reservoir of technology in NRW and were primarily supposed to push the technological development of the local industry. In close collaboration with VERTEX (formerly Krupp Industrietechnik) a 1.5 m prototype of the DGT was developed and mechanically assembled in Duisburg while the optics were manufactured at Carl Zeiss, Jena. The project was scheduled for 2.5 years and could be finished in time; tests of the individual mechanical and optical components demonstrated that the specifications were met. However, due to budget cutdowns caused by the re-unification of East and West Germany but also due to irritations between the industry and the AIRUB neither the optics could be transferred to Duisburg and implemented in the Hexapod Teleskop (HPT) nor could the telescope prove its astronomical suitability in a real celestial observation. The mechanical structure remained in the workshop of VERTEX while the mirrors were stored in Jena without aluminization; in 1992 the DGT/HPT project had come to a halt.

In the following years, there were several initiatives to bring the existing HPT into an astronomical operation two of which are acknowledged in the following. In 1993 the non-profit association MEGAPHOT e. V. was founded in Hamburg by 21 members with the aim to finance large instruments in a joint effort between the scientific community and the industry. During the first Megaphot Workshop the need for a dedicated optical quasar monitoring telescope was expressed. Certainly not by pure chance calculations were shown of how a 1.5 m telescope could be contribute to this project (Schramm & Borgeest 1993). Simultaneously, details of the recently completed HPT were presented by Stenvers (1993). The Megaphot group did not meet for a second time since then. During its meeting on November 15th 1994 the *Rat Deutscher Sternwarten* strongly supported the initiative by the AIRUB, the observatory of Hamburg and the Megaphot group to finish the HPT project. G. Morfill was designated to negociate with the *Ministry for Research and Technology* (BMFT) with the aim to realize the necessary funding in 1995. All these attempts were not successful. Before continuing with the never-ending political story of the DGT/HPT project some of its innovative details shall be reviewed in the next chapter.

Figure 1: The length variable struts of the Hexapod mounting and the ring structure that combines the upper Cardan axes. The lower system of Cardan axes and the linear drives are also visible.

2 The technical concept

The HPT is a synthesis of several innovative components which have not been established in classical telescopes so far and which are ideal for future airborne and satellite-borne applications. The telescope has a 1.5 m primary mirror with a focal ratio of $f/D = 2.5$; the complete optical design is a classical Ritchey-Chrétien system with $f/D = 8$. The important new features will be described in the following sections:

Mounting – Instead of a classical two-axes-mounting which is used so far in all telescopes, the HPT has six length-variable struts (Hexapod) in order to point the telescope toward the desired direction and to track the object. The adjustments of the legs are done via high-precision linear drives consisting of direct-motor driven roller screw assemblies to avoid mechanical backlash and stick-slip effects. The accuracy of such a drive unit was tested in the laboratory under realistic load conditions and yielded a residual noise of the order of 10 nm. This translates into a tracking accuracy of less than 0.05 arcsec for the entire telescope. The mounting of the struts and their connection among each other is realized by two sets of Cardan axes; this configuration only allows push and pull forces and avoids any bending moments. To maintain the unprecedented precision throughout the astronomical use even in a dusty environment the mechanics of the struts are encapsulated in pressurized Carbon Fibre Reinforced Plastic (CFRP) tubes which prevent the admittance of dust. The weight of a single leg is about 200 kg. The power consumption of the mounting system is extremely low: 1800 Watts are required for pointing and only 50 Watts for tracking.

The advantages of the Hexapod mounting are obvious: the position of the optical structure immediately above the six legs avoids compensating weights of classical telescopes and reduces the total weight considerably. Furthermore, rapid and complicated movements as required on board of balloons, aircrafts or satellites can easily be realized because the response of the drive units is in the range of several Hz. Field rotation can be compensated to an extent of $\pm 45°$ around the optical axis. Likewise, polarization measurements become possible by rotating the entire telescope.

Primary – In contrast to classical telescopes, where the required stiffness is achieved by fairly massive components, the HPT uses a light-weight, self-supporting hybrid structure consisting of a combination of Zerodur glass ceramics and CFRP. This concept of a hybrid-composite structure allows to make the optical surface rather thin and light whereas the required stiffness is provided by a Carbon Fibre Composite grid – which itself is also extremly light. In case of the HPT the mirror was manufactured at Carl Zeiss Jena as a 55 mm thin meniscus of 120 kg weight. In summary, all these details led to lightest optical telescope built so far: While the ESO NTT has a "specific weight" of 10 t per m^2 of optical surface, the HPT resembles more a light-weight radio telescope with $1.2\,t/m^2$.

Figure 2: The raw primary with its 36 permanently fixed support units at Carl Zeiss, Jena.

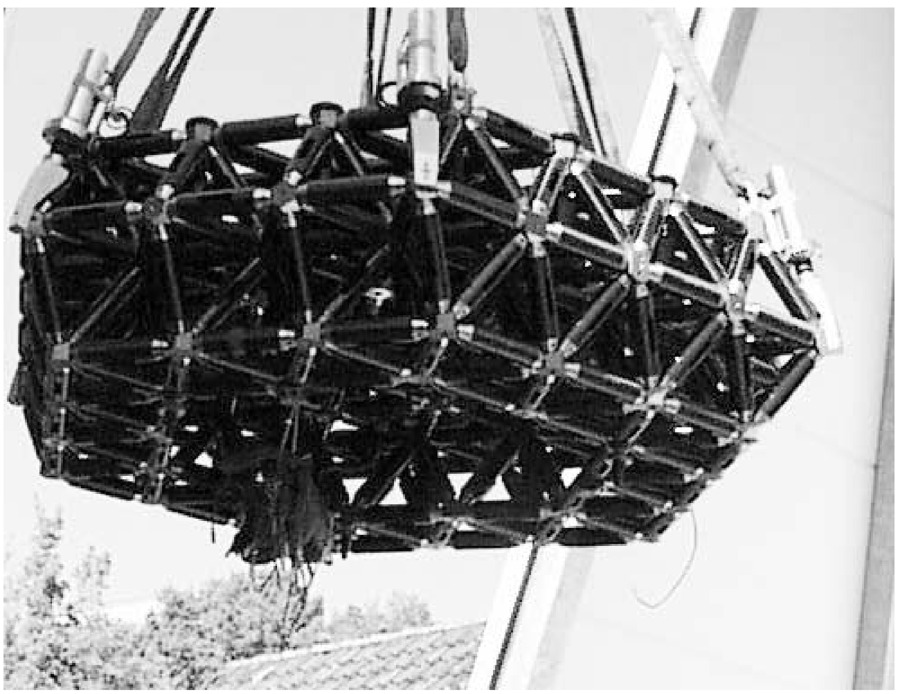

Figure 3: The CFRP grid with Invar steel knots.

Figure 4: The Hexapod for the secondary mirror.

Furthermore, due to the open grid-structure and the small masses involved the primary needs only minimum of time to reach thermal equlibrium with its surroundings which should manifest itself in faster reactions against temperature changes and in a more stable image quality.

Depending on the telescope position heavy primaries deform themselves under their own weight thus degrading the image quality considerably. The surface smoothness, i. e. the rms of the surface, should not exceed $\lambda/28$ which transforms to about 18 nm for optical observations. In order to maintain this accuracy under all circumstances Wilson et al. (1987) developed the principle of active optics. In the HPT design an optical analyzer, a so-called Shack-Hartmann sensor, will be implemented that permits to deduce errors of the optical system. The correcting signals are sent to 36 piezo-ceramic activators that support the primary. In contrast to other telescopes the HPT uses the first primary that can be pushed and pulled due to its firm connection with the 36 support units. In combination with the high elasticity of the primary this construction should result in an ideal optical surface of less than 13 nm rms and puts the HPT mirror among the most accurate primaries world-wide. Although not a prominent, aim the active elements can also be used to try adaptive optics corrections within a limited range to compensate for atmospheric disturbances.

Secondary – Classical telescopes exhibit deformations of their mechanical structure as a function of elevation. These gravitation dependent errors will be eliminated in the HPT concept by a second computer controlled Hexapod which serve as support legs for the secondary and allows to keep it always in the ideal position.

Laser-gyro pointing system – Obviously, the absence of axes does not allow the use of classical linear or rotary encoders for the determination of the telescope orientation. Therefore, it is intended to attach Ring-Laser Gyros (RLG) to the optical telescope assembly in order to decouple pointing errors caused by the mechanical components below the optics. The suitability of RLG for astronomical applications has been tested at the Bochum telescope on La Silla and a pointing accuracy of 1 – 2 arcsec was claimed (Schröder & Schnur 1990).

3 Project status

In order to start the astronomical performance of the HPT several components still have to be developed or purchased: The active optics require a wavefront sensor, the old PC of the drive system has to be replaced by a state-of-the-art computer and the tracking of the HPT needs an offset guider. In 1997, the Ministry of School, Education, Science and Research (MSWWF), NRW, could be convinced to provide the financial basis for the completion of the telescope by a fund of 240,000 DM.

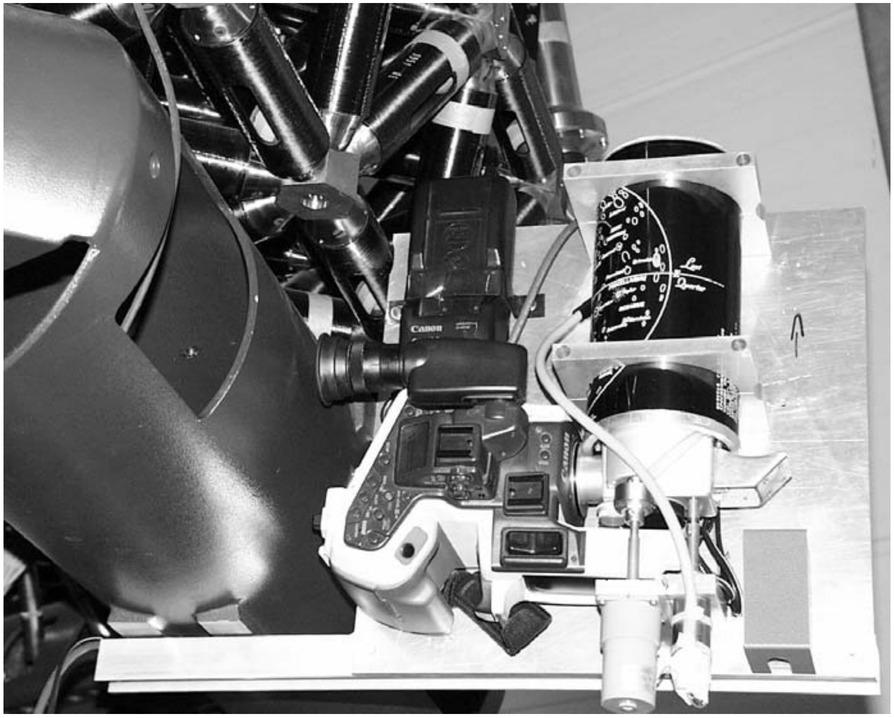

Figure 5: The Questar auxilliary telescope attached to the CFRP grid.

Simultaneously, the Ruhr-University of Bochum gave permission to develop a site at the Botanical Garden – one of the best astronomical locations within the university campus. A pyramid shaped dome was designed which appeared to be a compromise between astronomical functionality, architecture and costs. The pyramid has a basis length of 7.2 m and a height of 7.5 m. It consists of two equal halfs and is placed on top of two rails which run East-West. These halfs can be moved along the rails at a maximum seperation of about 7 m allowing for sufficient clearance of the telescope to track (elevation dependent) for several hours towards southern directions. The telescope electronics and the control room are hosted inside two nearby containers. The funding in the order of 310,000 DM for the entire site development including the dome construction and the two containers came from the Ruhr-University.

During 1999 the continuation of the HPT project yielded first visible progress: The pyramid dome was erected throughout spring and the telescope was assembled in May. In this context it has to be noted that the transport of the mechanical parts of the HPT from Duisburg and their assembly in Bochum was extremely fast. Even the mirrors which arrived in Bochum after their aluminization in Jena a few days earlier were implemented at the same time. Apart from minor adjustments the complete construction of this 1.5 m telescope could basically be performed in a single day.

A first order test unit has been developed by W. Schlosser and K. Weißbauer to monitor the pointing and tracking behaviour of the HPT without involving the telescope optics. For that purpose a Questar telescope (on kind loan from the MPIA, Heidelberg) has been adapted to the CFRP grid cell and was crudely aligned parallel to the main optical axis. The field of view of the Questar telescope can be remotely changed between 4° and 12′ in order to find a star in the low resolution mode and to control the tracking in the high resolution mode. By means of a video camera the images are recorded at a frequency of 6 Hz and transmitted to a monitor in the control room. The entire unit is functional since November 1999 and awaiting one of the numerous clear nights at the Bochum site. The project status will be updated on the homepage of the AIRUB (`http://www.astro.ruhr-uni-bochum.de`).

4 Future plans

On November 11$^{\text{th}}$ 1998 the HPT became registered as a so-called "*World-Wide Project*" of the EXPO 2000 as the only project of a university in NRW; it has also passed the final approvement by the EXPO GmbH which will be officially documented in a ceremony on December 15/16 1999 in Hannover. The telescope will remain in the Botanical Garden for the time of the world exhibition and visitors will receive guided tours after advance appointment. Apart from that the year 2000 is dedicated to the tests of the mechanical behaviour and to the development of the active optics control systems. Obviously, these activities require various kinds of expertise which exceed the capabilities of the AIRUB and which will be supplemented by VERTEX, IMECH and ESO. The necessary funding of 500,000 DM for the entire optimization phase comes from the MSWWF, NRW. The tasks have been splitted into 4 working packages which are not independent from each other and thus have to be pursued in parallel.

Tracking
An agreement between VERTEX (Duisburg), IMECH (Moers) and the AIRUB was established to join the efforts for optimizing the mechanical performance of the HPT. As mentioned before, the telescope has not been looking at a star so far and thus the astronomical suitability still has to be verified. IMECH as an expert in mechatronics will dedicate a PhD thesis to the optimization of the drive system in collaboration with VERTEX. A PhD student (A. von Düsterlohe) at the AIRUB will record the improvements during clear nights and provide the necessary feedback to the ingeneers. It is forseen that this iteration process can be completed within the year 2000.

Mechanical control of the secondary
The drive system for the support legs of the secondary has to be developed and implemented. This task will be also part of the PhD thesis which deals with the control of the hexapod for the primary.

Optical control of the primary
A second PhD thesis (K. Fieger) at the AIRUB is dedicated to the control of the active primary and will be supported by experts from the ESO VLT team. A wavefront sensor and an offset guider have to be designed and adapted to the CFRP grid structure.

Pointing
The laser gyros have been tested in the labortory and need to be installed in the telescope.

Astronomical operation
After the HPT has proved its suitability for astronomical observations it is planned to transfer it to Cerro Armazones (3064 m) in Chile. This mountain was tested by ESO during the site testing campaign for Paranal and showed similar meteorological conditions, i. e. in particular about 350 clear nights per year. The AIRUB already operates a 87 cm telescope at this site, where the basic infrastructure is available.

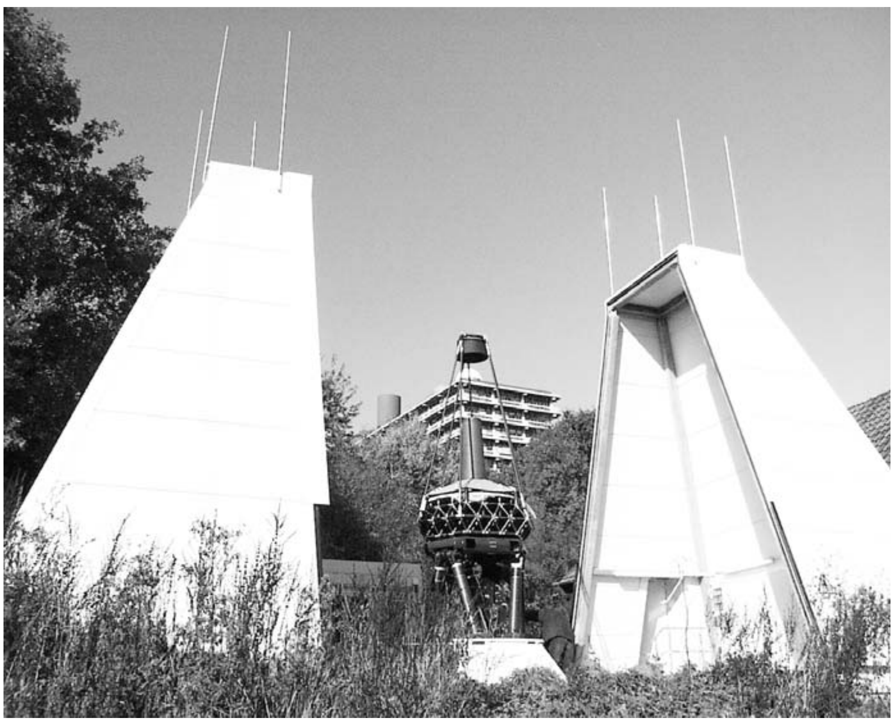

Figure 6: The HPT pyramid inside the Botanical Garden.

5 Conclusions

The dream of the german large telescope DGT is certainly over. Nevertheless, it seems worth to spend the described efforts and the money to bring this prototype project HPT to an end – in one way or the other. If the expectations concerning the performance of the telescope become true, the astronomical community will have a small, high quality telescope at one of the best sites in the world; this allows the realization of projects for which larger telescopes do not provide observing time. All colleagues are welcome to use the facility for their projects. Furthermore, a successfull HPT may serve as a future design for larger ground-based and airborne telescopes.

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