Configurable Slit Unit for Canary telescope

On the Canary Island of La Palma, the world's largest reflecting telescope is being built, the 'Grand Telescopio de Canarias' (GTC) with a diameter of 10.4 metres. Janssen Precision Engineering is involved in the development of instrumentation for the GTC. For the past four years, work has been done on the development of a specific and extremely compact drive and measuring system for cryogenic and vacuum applications. This has finally led to the realisation of a demonstration model of the Configurable Slit Unit for the GTC infrared instrument.

This is an updated version of the article that was previously published (in Dutch) in Mikroniek 2006, no. 2.

• *Norbert Meijs and Maurice Teuwen* •

The new generation of extremely large reflecting telescopes is a recent phenomenon. The concept of constructing an optical telescope's primary mirror from a number of mirror segments provided the breakthrough. The GTC on La Palma is a part of this new generation; see Figure 1. As a result of the pioneering optical sensitivity and resolution that this telescope will be able to realise, scientists can better study the underlying processes of the formation of stars, systems and the Universe. The most important research objective of the GTC will be obtaining and studying spectra in the NIR (Near-Infrared, 0.9-2.5 μm) wavelength region. For this purpose, the telescope will be equipped with an NIR multi-object spectrograph. To minimise background noise, vacuum (10^{-6} mbar) and cryogenic (77 K) conditions are prevalent inside this instrument.

Figure 1. Grand Telescopio de Canarias under construction.

Configurable Slit Unit

One of the most complex parts of the spectrograph is the Configurable Slit Unit (CSU). This is a configurable mask, which is positioned at the spectrograph's entrance focal plane (340 x 340 mm). The mask consists of 110 bars that can be positioned arbitrarily within the instrument's image field (see Figure 2). The space that remains between two bars placed opposite each other is called a slit. The slits are used as a mask during spectrographic recording. Because a number of slits can be distributed across the image field, it is known as a multi-object spectrograph. In this way, a number of stars can be viewed simultaneously. The configuration of the slits will be changed several times a night.

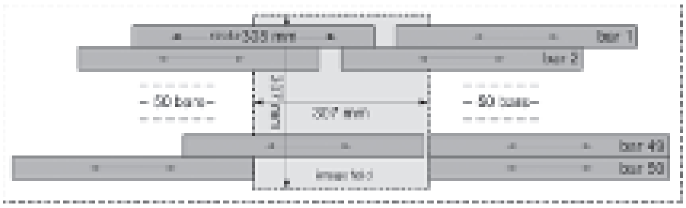

Figure 2. Draft layout of the CSU (in a previous 100-bar version).

The following specifications roughly apply to the mask.

Number of bars:	110 (2 x 55)
Stroke per bar:	340 mm
Bar position accuracy:	< 10 µm
Bar speed:	> 1 mm / s
Pitch bar - bar:	340 mm / 55 ≈ 6 mm
Environmental conditions:	10^{-6} mbar, 77 K (-196 °C)

Janssen Precision Engineering (JPE), situated near Maastricht Airport, the Netherlands, became involved in the development of the CSU at the end of 2003. Challenged by the extreme specifications, it developed a concept for the accurate positioning of the bars under cryogenic and vacuum conditions on its own initiative. The concept was developed into a prototype, which formed the basis for further collaboration with the 'Instituto de Astrofísica de Canarias'.

'Inertial piezo drive' concept

The given preconditions with regard to the environmental conditions drastically limit the options for a suitable actuator principle. In addition, there is limited available envelope in which to build, imposed by the 6 mm pitch between two successive bars. Furthermore, there is the requirement that the actuator must dissipate absolutely no energy when at a standstill; each heat source within the cryostat could create an aberration in the extremely sensitive infrared detector. Finally, the cost price is obviously also an important factor considering a total of 110 individual actuators are necessary.

It was decided to use a piezo as the fundamental building block in realising the actuator. Piezos are extremely suitable in this application because of a combination of properties: vacuum compatibility, minimal outgassing; cryogenic-compatibility and extremely low dissipation.

To limit the number of piezo actuators, a concept was consciously sought with only one piezo for every moving bar. For this, the so-called 'inertial drive' concept was used. Figure 3 shows the actuator concept. The piezo is included in a mechanism that pushes against the bar with pretension force *F*. Together with two guiding wheels, this mechanism also forms the guide for the bar. By gradually increasing the voltage on the piezo, it will slowly extend. The accelerating power that occurs can be transferred by friction contact onto the bar, which will move in equal proportion. Should the piezo be abruptly discharged, the occurring acceleration will be so large that the accompanying acceleration power cannot be transferred from actuator to bar; through inertia, the bar remains virtually still while the actuator is dragged back over the full stroke. By repeating this cycle, a net-movement can be realised.

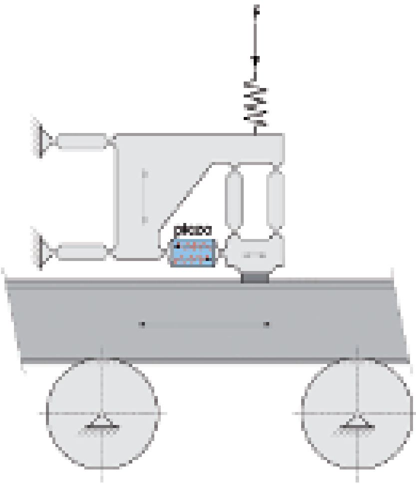

Figure 3. 'Inertial piezo drive' actuator concept.

From an electrical point of view, this cycle can be viewed in the following way. In the electrical respect, the piezo acts as a capacity. The speed of charging and discharging is proportional to the RC time of the equivalent network in which the piezo is included. Based on the electrical diagram in Figure 4, an amplifier has been realised for controlling the piezo. The design of the actuator is characterised by the following properties:

- simple, elementary; this is particularly important bearing in mind costs and lifespan;
- play-free design; this is particularly important for the transition from room temperature (assembly) to cryogenic temperature (operation), a large temperature transition that requires a design that can handle expansion differences;
- by definition, dissipation-free when standing still.

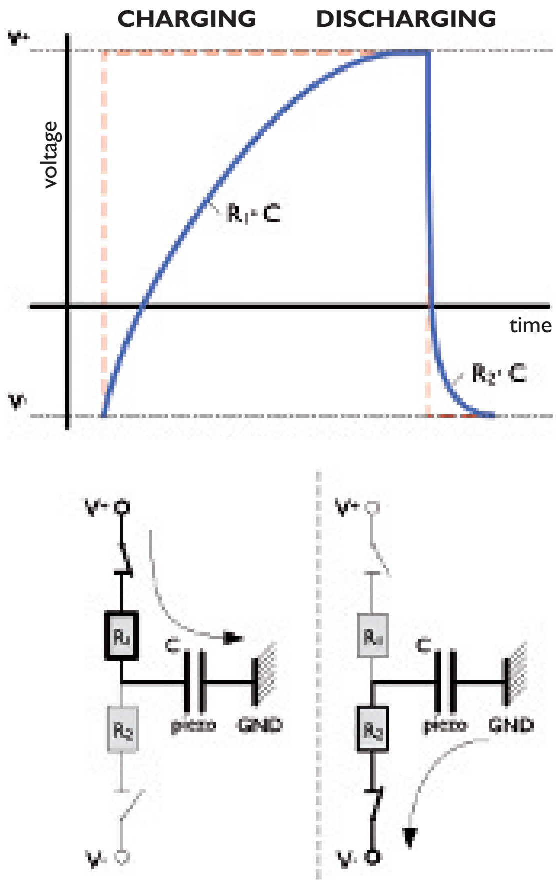

Figure 4. Electrical diagram of the piezo control.

Capacitive position measuring system

Position measuring per bar is necessary in order to realise an accurate positioning of the bars. The choice of this measuring system was, once again, limited by environmental preconditions, limited envelope to build within and cost price. A capacitive measuring principle was chosen. Decisive features for choosing this measuring principle are:

- the quantity (capacity) to be measured is not influenced by the environmental conditions (vacuum, cryogenic temperature);
- the actual sensor consists of no more than two conductors facing each other, so that:
  - the sensor can easily be made vacuum-compatible;
  - there is a relatively high degree of freedom in the sensor's design by finishing the required conductor plates as a vacuum vaporised conductor on a ceramic base plate.

The accepted method for measuring movement with the aid of a capacitive measuring system is the measuring of the capacity between two conducting surfaces. With this, the measured capacity is inversely proportional to the variable distance between the conducting surfaces. The accompanying range, however, is typically $\leq$ 1 mm and therefore not suitable for the measuring of movements up to 340 mm Therefore, an alternative application of this measuring principle has been developed. The two conducting surfaces are placed a set distance apart from each other. By moving a conductor between the two conducting surfaces, the measured capacity will increase. This principle is illustrated in Figure 5. The measured variation in capacity is now, on the one hand, dependent on the movement x and on the other it is limited by the ratio between distance D and distance D-d. Note that a transverse movement of the conductor between the plates ($\perp x$) has no influence on the measured capacity!

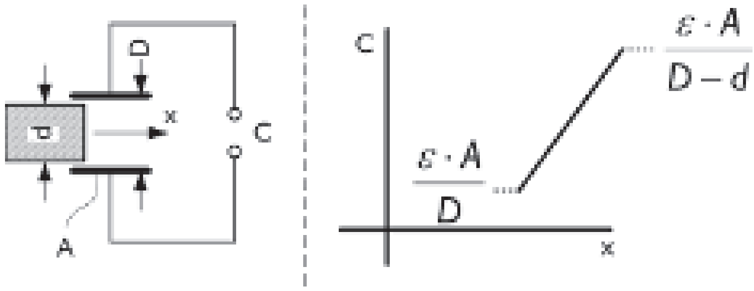

Figure 5. Capacitive movement measuring system.

The dynamic range of simple electronics for measuring a capacity is typically 10^3 to 10^4. Assuming a desired movement measurement resolution of typically 5 µm, we can conclude that the dimension of the sensor in the direction of the movement must be typically about 5 mm. The chosen measuring principle can easily be applied as an 'endless' movement measuring system. For this, the bars have slots at equal distances, so that the capacitive sensor alternately is or is not filled with the metal (conducting) bar if it is moved in a linear direction

To also be sure that this measuring sensitivity is not dependent on the position of the bar in relation to the sensor, four sensors are used that are placed at a different pitch in relation to the slits in the bar. In this way parasitic capacities are also avoided and, above all, the sensitivity of the sensor is generally increased. This layout can be seen in Figure 6.

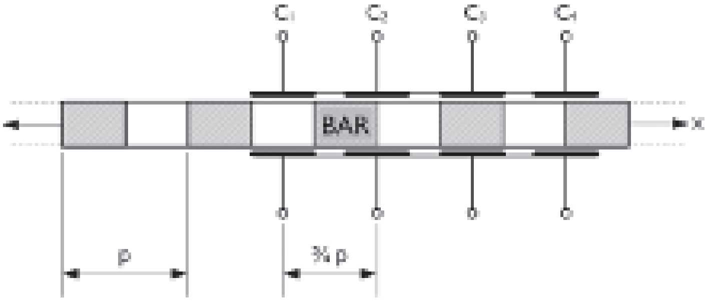

Figure 6. Endless capacitive measuring system.

Prototype

Based on the chosen principles for the drive and the position measurement, a prototype has been built. First, the functionality of both principles was evaluated under standard atmospheric conditions. To evaluate the behaviour of the piezo and the friction in particular, a test was then carried out at cryogenic temperature.

During this process, the prototype was placed in an insulated and sealed set-up. By ventilating the set-up with dry nitrogen, any damp was dispelled. After a while liquid nitrogen (77 K) was injected (from outside the set-up) at the base of the set-up. The base of the prototype now had adopted the temperature of the liquid nitrogen through conduction. Figure 7 shows the prototype after the tests had been completed. Upon opening the set-up, the moisture from the ambient air formed ice crystals on the set-up. The successful demonstration of functionality under cryogenic conditions was an extremely important milestone in the development of the CSU.

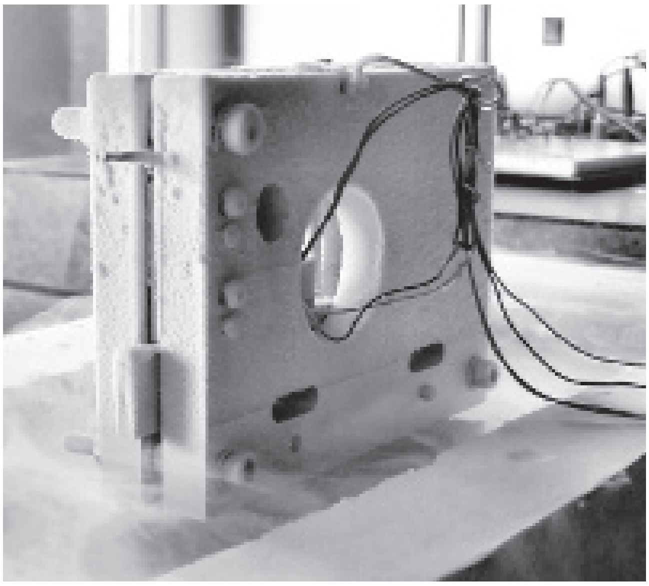

Figure 7. Prototype after the cryogenic test.

As a result of these tests, JPE and the Instituto de Astrofísica de Canarias have set up a joint Demonstration Programme as an intermediate step in the final development of the CSU. The goal of the demonstration programme is the further development of the chosen concepts into a fully-fledged demonstration model which covers all the technological developments and risks.

Demonstration Programme: 6-bar prototype

As far as hardware is concerned, the outcome of the demonstration programme is a full-scale prototype based on six bars. One of the greatest challenges in the mechanical design was the design and dimensioning of the bars. Many preconditions have to be met at the same time. Of primary importance are optical requirements (surface, geometry) but from a constructional point of view, thermal (material) demands, compatibility with actuator and guide (geometry), vacuum compatibility (material, surface), compatibility with the measuring principle (geometry and material), stiffnes (E/ρ) against deformation as a result of gravity, producibility and cost price also apply. Furthermore, the thickness of the bar is, in fact, determined by the imposed pitch of 6 mm between two successive bars.

Figure 8 shows the final design of the bars. On the left side of the figure, a cross-sectional profile of the bars can be seen; in the final application, light (in this view) will enter from the right side of the instrument. In order to block the light as well as possible, the bars overlap in a labyrinthine construction. On the right of the figure, it can be clearly seen that the bar has slots required for the measuring system.

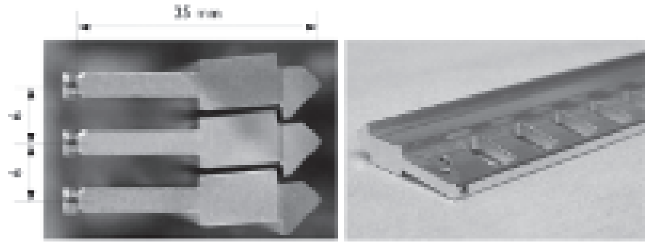

Figure 8. Design of the bars.

Ceramic sensor

The sensor is made of ceramic material. Metallic surfaces, applied by CVD, form the active sensor probes. The measurement signal is read out by a specifically designed measuring system that uses the ‘active guarding’ technique. This means that the capacitive measuring signal is actively fed back to the shielding of the vacuum-compatible, coaxial measuring cable. In this way, the capacity between core and shielding is eliminated from the measurement and the sensitivity to environmental disturbances is also limited. The four capacities are sequentially read out using a multiplexer. Then an AD converter digitalises the measuring signals. Figure 9 shows the sensor.

The actuator mechanism is realised as a monolithic design in aluminium; see Figure 10. The two guides inside the mechanism are realised by means of elastic hinges. The piezo is mechanically pre-tensioned within the mechanism using a wire spring. A second wire spring realises the pre-tension of the actuator in the direction of the bar. For the positioning of the bar, feedback from the measuring system is necessary. Control of the piezo and measuring of the position are carried out by a 32-bit micro-controller. The signals from the four capacities, read out by the AD-converter, must be combined into a linear measuring signal. For this purpose, an interpolation algorithm has been designed that determines positions within the periodic slot pattern in the bar. This algorithm is based on a look-up table, obtained through calibration of the bar. The micro-controller is further equipped with an interface for a higher control level. Homing and positioning commands can be introduced at this level, which is equipped with a graphic user interface. See Figure 11 for the measuring system.

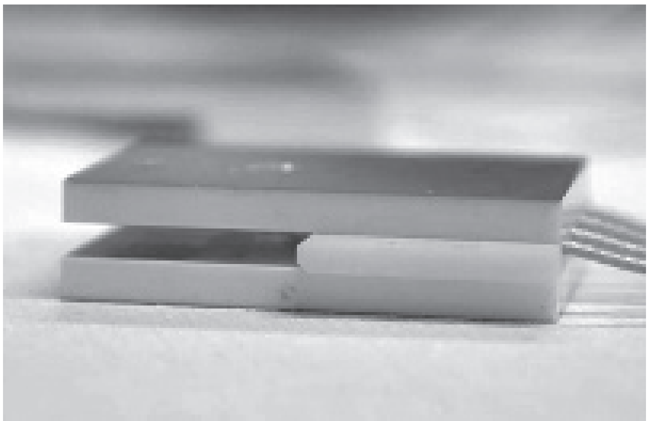

Figure 9. The capacitive sensor.

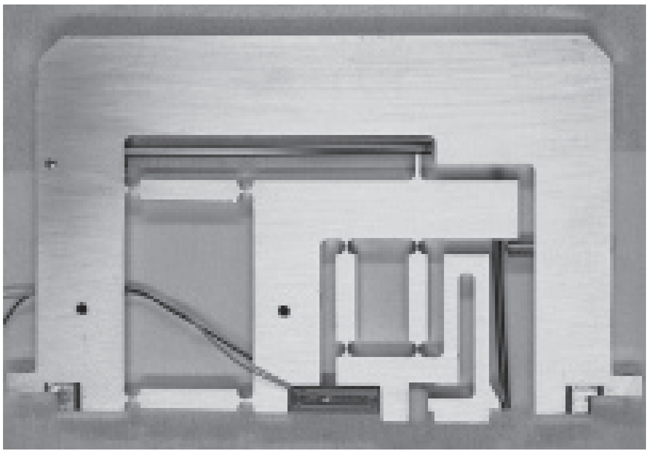

Figure 10. The actuator mechanism.

Future

The successful delivery of the 6-bar CSU prototype by Janssen Precision Engineering to the Instituto de Astrofísica de Canarias does not mark the actual end of the development. In the meantime, the public tender procedure for the development of the definitive instrument has been completed and the contract awarded to JPE. The development of the definitive instrument with 110 bars (see Figure 12) will be realised based on the tested concepts. Delivery is planned for the beginning of 2009. In the project, JPE is ultimately respon-

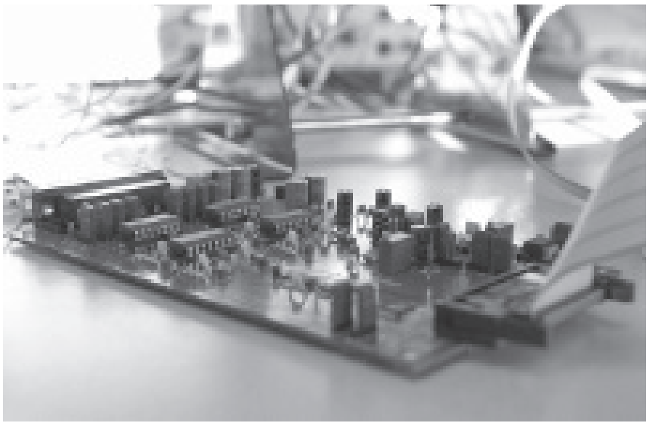

Figure 11. The measuring system for reading-out and digitalising the measuring signal.

Figure 12. Design of a Configurable Slit Unit.

sible for the total realisation of the instrument. The project will be carried out in co-operation with the sub-contractor NTE (Barcelona, Spain). NTE is responsible for the working out and realisation of the necessary electronics.

The acquired experience in the development of instruments for use in cryogenic applications is, for Janssen Precision Engineering, supplementary to the existing expertise in the development of vacuum applications and precision mechatronic systems.

Authors' note

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