Cryogenic actuators in ground-based astronomical instrumentation

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ABSTRACT

In the last few years, astronomical instruments with infrared detectors have become increasingly important. These detectors as well as the mechanical mechanisms inside the instruments are operated in high vacuum at cryogenic temperature.
Since ready-for-use cryogenic actuators are often not available from stock, the Max-Planck-Institut für Astronomie (MPIA) in Heidelberg has developed actuators for both linear and circular movement. Information about the use of materials, dry film lubricants, and components like motors, micro switches and resolvers for this temperature region is hard to find in literature. Thus, large-scale experiments and tests were made to gain experience and to qualify the actuators for their use at cryogenic temperatures.

Keywords: Instrumentation, cryogenics, actuator, mechanism

1. INTRODUCTION

Infrared astronomy is now on the upswing. Star-forming regions with their “cold” structures are increasingly being investigated by astronomers around the world. Consequently, more instruments are operated under cryogenic conditions below 80 K.
This paper describes the use of cryogenic actuators in modern astronomical instruments by means of some explicit examples. A variety of high-precision actuators is used to adjust and rotate detectors for image rotation compensation, to move masks, filters, mirrors, and other optical components. The positioning accuracy can reach 1-2 µm for linear actuators and only a few arcsec for rotational actuators.

2. MATERIALS AND LUBRICATION AT CRYOGENIC TEMPERATURES

The use of any material at cryogenic conditions around 70 K normally does not present problems. However, the material data are often only available for room temperature. These data (e.g. coefficient of thermal expansion - CTE) vary over temperature, but well-known values are required for a convincing mechanical design of an actuator (see Figure 1). CTE mismatches are a severe problem for all instruments at cryogenic temperatures. A steel bearing directly mounted into an aluminium housing will not work accurately at cryogenic temperatures. These problems can be avoided by a combination of two materials forming a matching CTE (bi-metallic compensator), the use of only one material, a material with a low CTE for the instrument, or the consideration of a special athermal design (e.g. spring elements).
Also, the lubrication guarantees a long lifetime and low friction of a cryogenic actuator. Only solid lubrications are useful for instruments working at cryogenic conditions. Table 1 shows a selection of solid lubricants for bearings provided by the company GRW in Würzburg [1]. These lubricants have different properties, and a careful selection for each application is necessary depending on load, required lifetime, drive torque and environmental conditions. For example, molybdenum disulphide (MoS_2) shows excellent small friction coefficients, but it is a hygroscopic material and changes its properties under standard atmospheric conditions. There are several methods to coat a surface with MoS_2. In vacuum, sputtered MoS_2 yields the lowest friction coefficient. At MPIA we use tungsten disulphide (WS_2) as dry lubrication for our ground-based instrumentation. Small bearings with low load are applied completely dry. Other coatings (e.g. lead) are also known. Lead can be utilized with high loads, although the friction coefficient compared to MoS_2 or WS_2 is higher. Please note the “SPACE TRIBOLOGY HANDBOOK” [2] for more information about solid lubrications.

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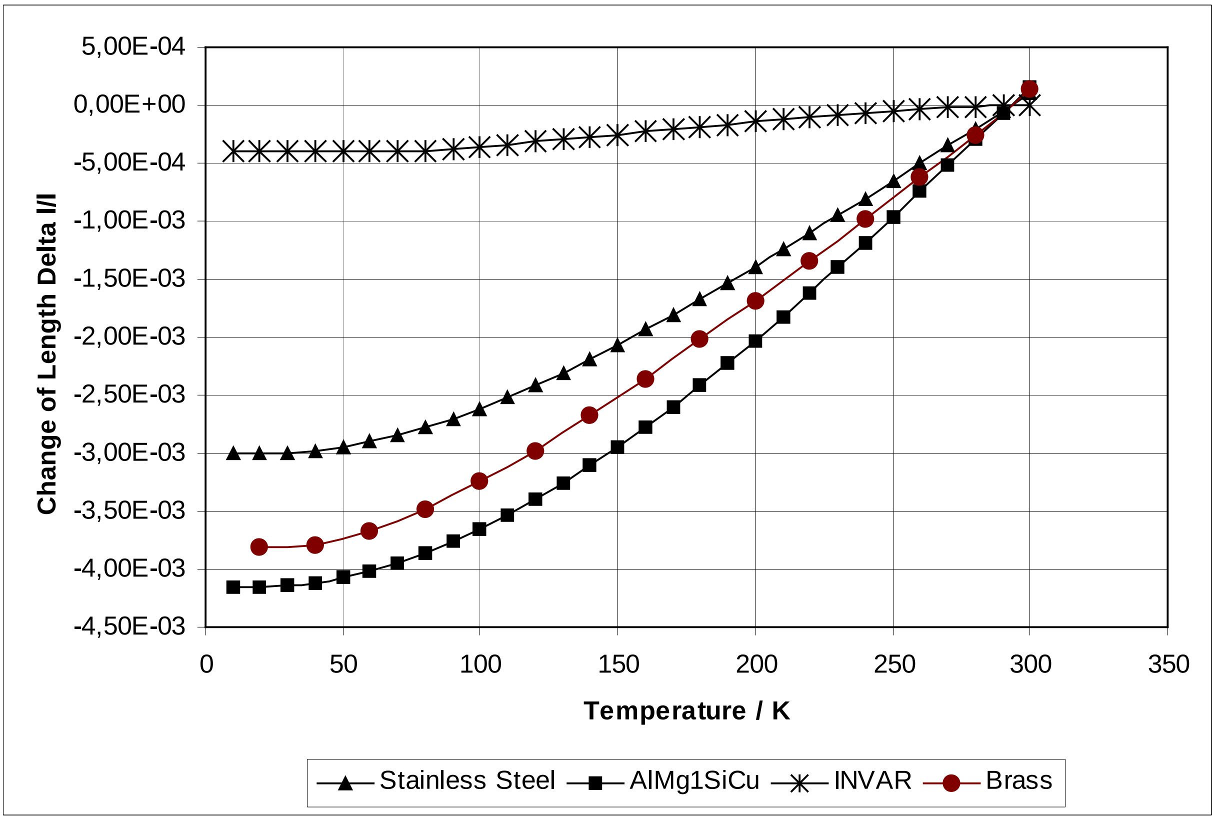


Figure 1. Change of length at different temperatures for selected materials

GRW designation	Coating at races and/or balls	Remarks
B-01	Gold	Only for small loads
B-05	MoS2 (Molybdenum disulphide)	Hygroscopic
B-07	TiC (Titanium carbide)	Only balls, avoids cold welding
B-18	WS2 (Tungsten disulphide)	Coating thickness max. 500 nm

Table 1: GRW ball bearing coatings for cryogenic applications

3. CRYOGENIC ACTUATORS

Operating a stepper motor in a controlled way requires some experience or a lot of testing because there are a number of parameters to be set, like minimum and maximum speed, acceleration, jerk etc. One should take care not to meet the resonance frequency of the motor.
Stepper motors that are supposed to also keep their exact position while they are switched off, should only be used in single step mode. Micro stepping can only be used for systems that are permanently switched on, but then heat dissipation and electromagnetic noise are usually a big problem.

3.1. Stepper motor with Harmonic Drive gear

Motors for cryogenic applications are available from different manufacturers. Often they are designed for space applications and the drawback is the very high cost. We have good experience of stepper motors made by Phytron. These motors are now in use in several ground-based instruments built at MPIA. It does not make sense to use other

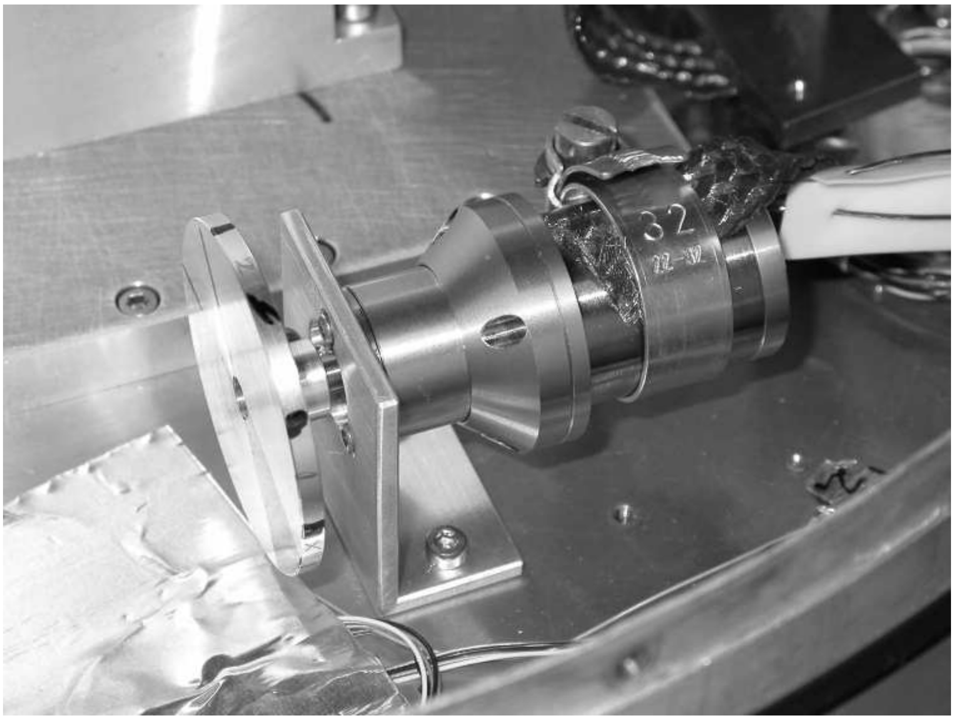


Figure 2. Rotational cryogenic actuator (stepper motor with Harmonic Drive gear) mounted in the test cryostat.

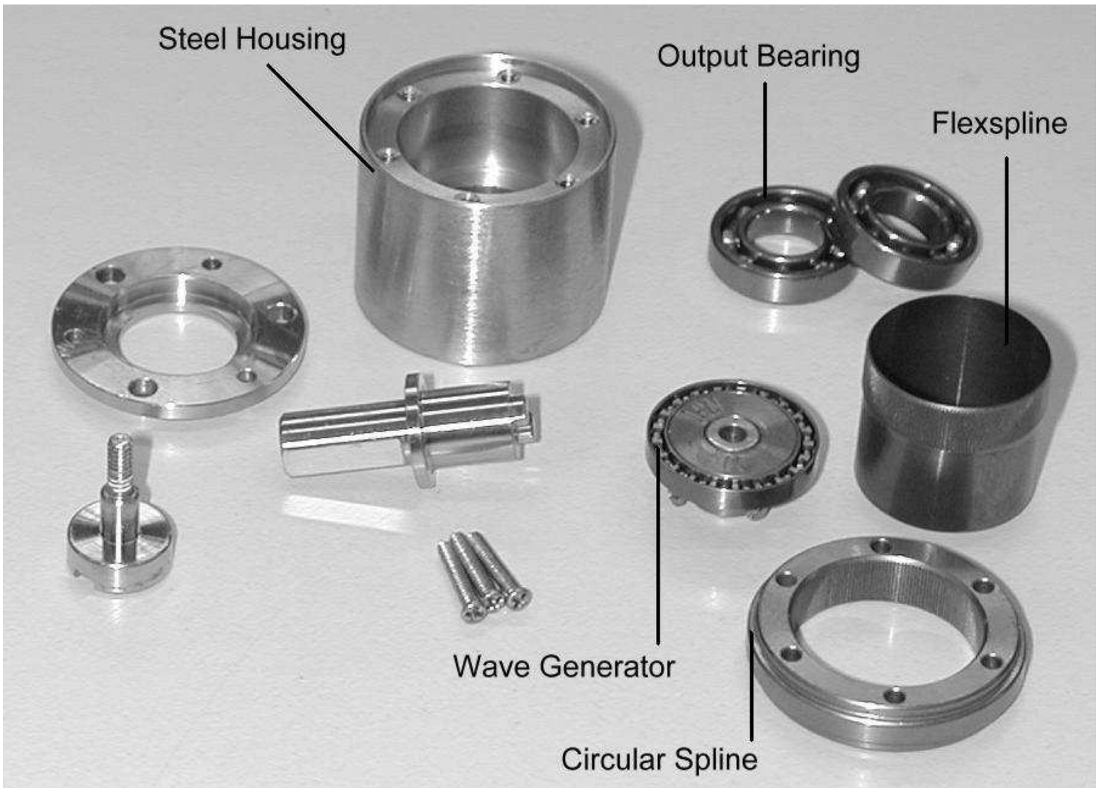


Figure 3. Disassembled Harmonic Drive gear coated with tungsten disulphide.

motor types like DC or AC motors in a cold environment since they require an encoder feedback to find out the actual position. However, encoders for cryogenic applications are not available commercially.
For a rotational actuator operating at 80 K, we use a combination of a PHYTRON stepper motor with a Harmonic Drive gear (Figure 2). Off-the-shelf Harmonic Drive gears cannot be used at low temperatures because they are filled with grease. We disassembled the complete gear and coated the wave generator, the flexspline and the circular spline with tungsten disulphide (Figure 3). The original gear housing is made from aluminium. The CTE mismatch between the output bearings and the aluminium housing causes problems at low temperatures. Therefore, we manufactured a new stainless steel housing.
The rotational actuator described was tested for a long period at 80 K without any failures and exceeded the lifetime needed for a filter wheel in an infrared wavefront sensor.

3.2. Cryogenic linear actuators

Conventional linear actuators usually consist of a motor which turns a spindle. This changes a rotational movement into a linear one of a nut that has to be guided precisely.
We build our linear actuators with spindles that have a fine-pitch thread. But in principle, recirculating ballscrews can also be used in a cryogenic environment. The advantage of such spindles is that the backlash effect can be neglected. We tested the slightly modified model ED410X/V404X from RMB successfully at 77 K. However the off-the-shelf version of this spindle is much too long for our needs. A customized one could be ordered at relatively high cost and with a delivery time of several months. For this reason we decided to use fine-pitch threaded spindles. They are supported by a set of two preloaded ball bearings in duplex configuration.

Table 2 shows a comparison between the two types of actuators described below.

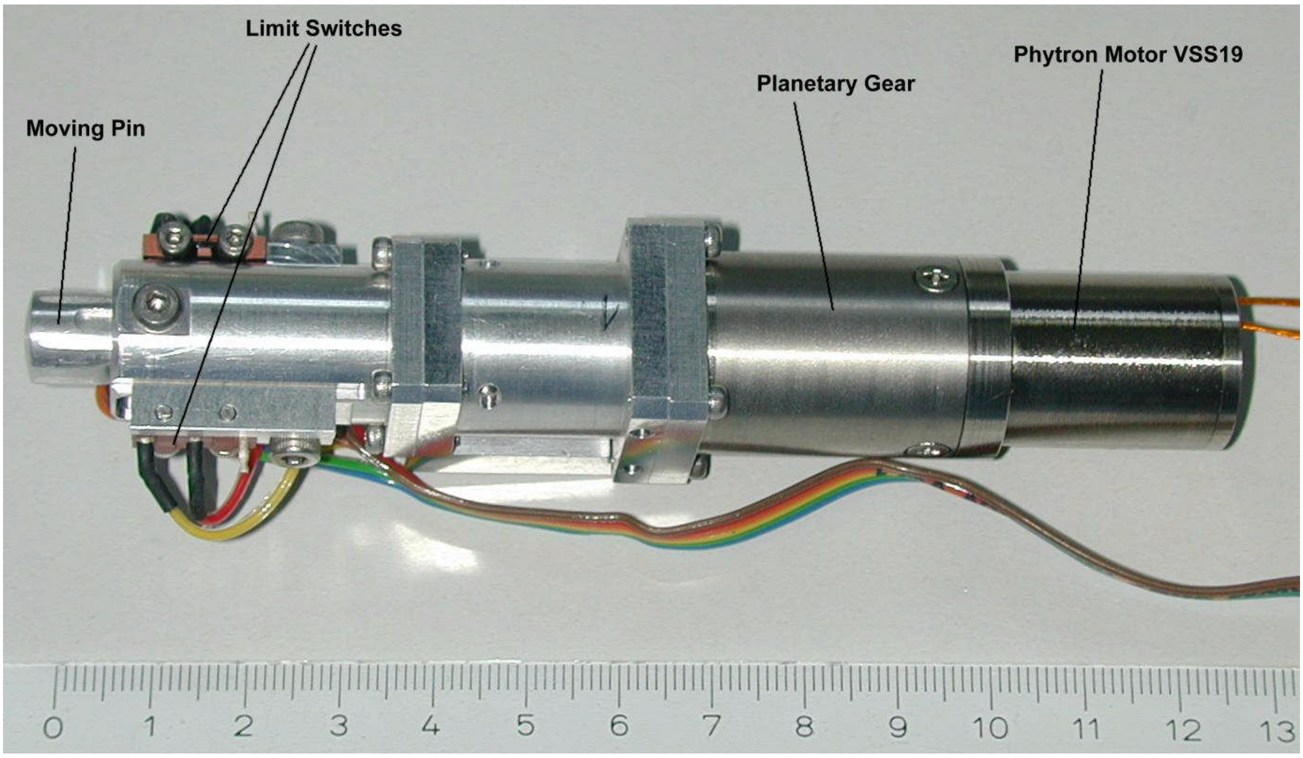


Figure 4. Cryogenic linear actuator with stepper motor, planetary gear and limit switches. The units on the ruler are cm.

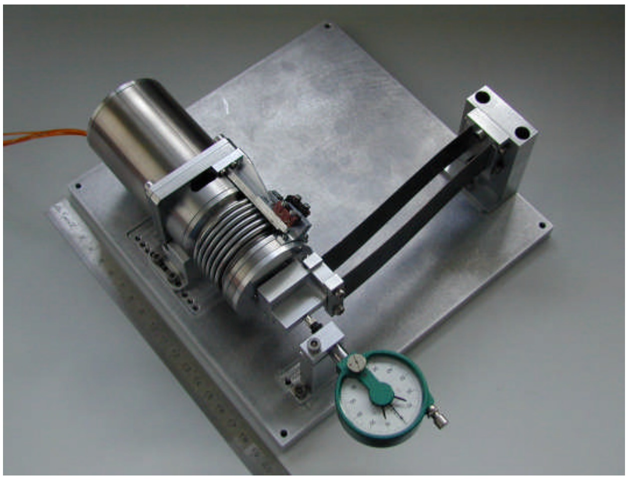
3.2.1. Cryogenic linear actuator with planetary gear

Some cryogenic mechanisms require a precise linear positioning with a relatively big stroke in very limited space. For such applications a new linear actuator has been developed using the smallest Phytron cryogenic stepper motor available with a planetary gear (reduction ratio of 1:49), very small limit switches from SAIA and a fine-pitch threaded spindle (pitch 0.5 mm). Using a gear is necessary because of the very low torque of the motor of 3.4 mNm. All parts (except motor and gear) are made from aluminium. The full stroke is 12 mm, which is fully sufficient for most applications. It could be easily extended. The overall length with the moving pin at its minimum stroke is about 120 mm, the diameter is 23 mm (without limit switches). The theoretical resolution of this system (that means one motor step) is 0.05 µm, which of course is nowhere near reality. This is because of manufacturing tolerances of motor, spindle and nut. Measurements (Figure 6) show that the repeatability is better than 1 µm.

3.2.2. Cryogenic linear actuator without planetary gear

This type of actuator uses a bigger stepper motor (Phytron VSS 52) without a planetary gear. Instead of a sliding pin like in 3.3.1., a commercial stainless steel bellow is deformed by a fine-pitch threaded spindle. Figure 5 shows a simple device with this actuator mounted for testing the positioning accuracy and reproducibility by use of a gauge (resolution 1 µm) at room temperature. Since the actuator has a small spherical surface in the center of its moving plate, it is necessary to use a flat part between the actuator and the spherical surface of the gauge pin. This part is held by a parallel spring system.

The spindle of the actuator is made from stainless steel, the corresponding nut is made from titanium. Titanium has a slightly lower CTE than stainless steel, so for cryogenic temperatures, the thread of the nut is always bigger in diameter than the thread of the spindle. The steal bellow can be stretched or compressed, which means that there can be either a tie force or a force of pressure on the spindle. When the movement of the actuator passes the point of force direction change, the backlash of the fine-pitch thread degrades the positioning accuracy if only small external loads are applied.
Therefore the stroke is limited to 6 mm. Using a steel bellow rather than a sliding pin like in 3.2.1. means that the spindle force is a function of stroke. So the maximum external load on the actuator can be higher for small strokes than for big strokes. The load limit applied on the center of the actuator pushing plate for strokes between 0 and 2 mm relative to the neutral bellow position was measured to be about 80 N. A stroke of 5-6 mm limits the load to about 30 N.
Figure 6 shows that the repeatability is about 1 µm, the minimum travel is about 2.5 µm. The nominal positions are 50 µm and 100 µm, the system was not calibrated before measuring. The maximum speed is about 10 mm/sec. In this case, the maximum precision cannot be reached. If loads of more than 30 N are applied, the velocity should not exceed 1 mm/sec.



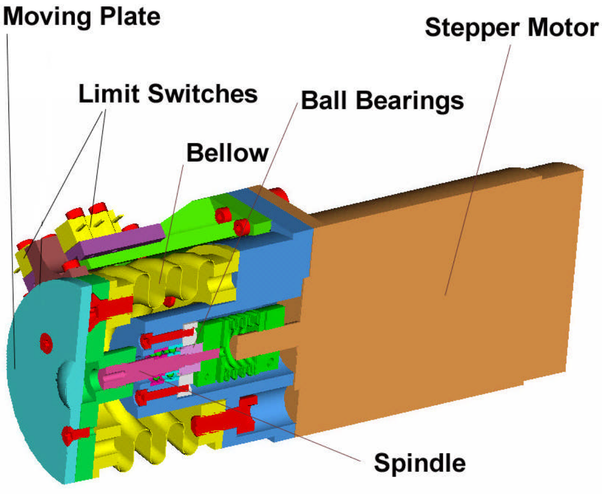


Figure 5. Test device including linear actuator without planetary gear mounted and cut through this actuator.

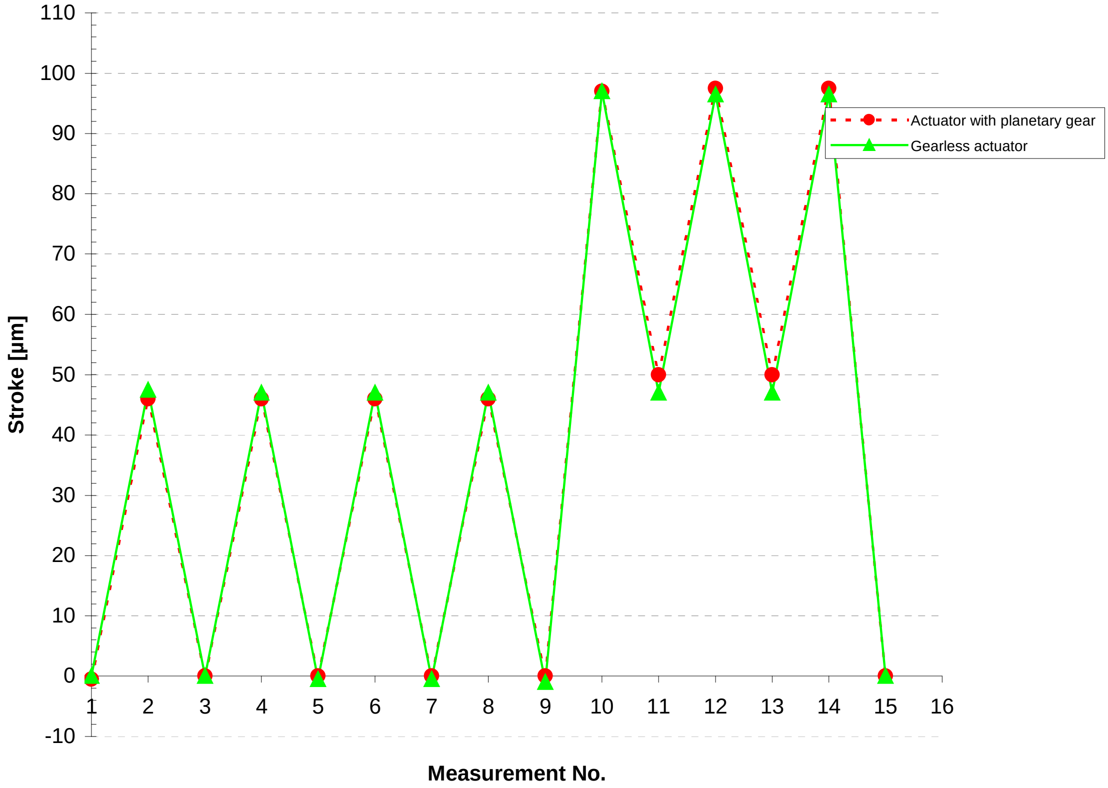


Figure 6. Positioning accuracy of both linear actuators (3.2.1. and 3.2.2.).

	Actuator with planetary gear (3.2.1.)	**Actuator without planetary gear (3.2.2.)**
Absolute precision	High absolute precision if backlash effect is eliminated: < 1µm	Lower absolute precision: about 3-4 µm
Relative precision	About 1 µm	About 1 µm
Weight	180 g	1340 g
Size	120 x 23 x 23 mm	135 x 52 x 52 mm
Maximum actuator force	About 40 N, depending on speed	About 80 N, depending on stroke and speed
Maximum speed	1 mm/s, depending on load	1-10 mm/s, depending on load and stroke
Resonance frequency	About 100 steps/sec	About 50-100 steps/sec
Travel range	12 mm	6 mm, depending on load and speed

Table 2. Comparison of some important properties of the two linear cryogenic actuators described in this paper

4. APPLICATION EXAMPLES

4.1. Three-axis detector adjustment

The exact position of a detector sitting on a fan-out board within a limited tolerance is normally unknown. Therefore, exhaustive and thorough work is necessary to adjust the detector inside the cryostat. Sometimes several cooling-down cycles are needed to reach the final position. Figure 7 shows a three-axis (tip/tilt and focus) adjustment unit for a CCD.
The three actuators consist of a stepper motor and a leadscrew/nut unit transforming the rotation of the motor into a linear movement. Leadscrew (stainless steel) and nut (titanium) are coated with WS_2. The three actuators are mounted on the fixed base plate. The moving plate is spring-loaded against the actuators. If all actuators are moved equally, a focus adjustment is achieved. Limit switches prevent the adjustment unit from blocking in one position.

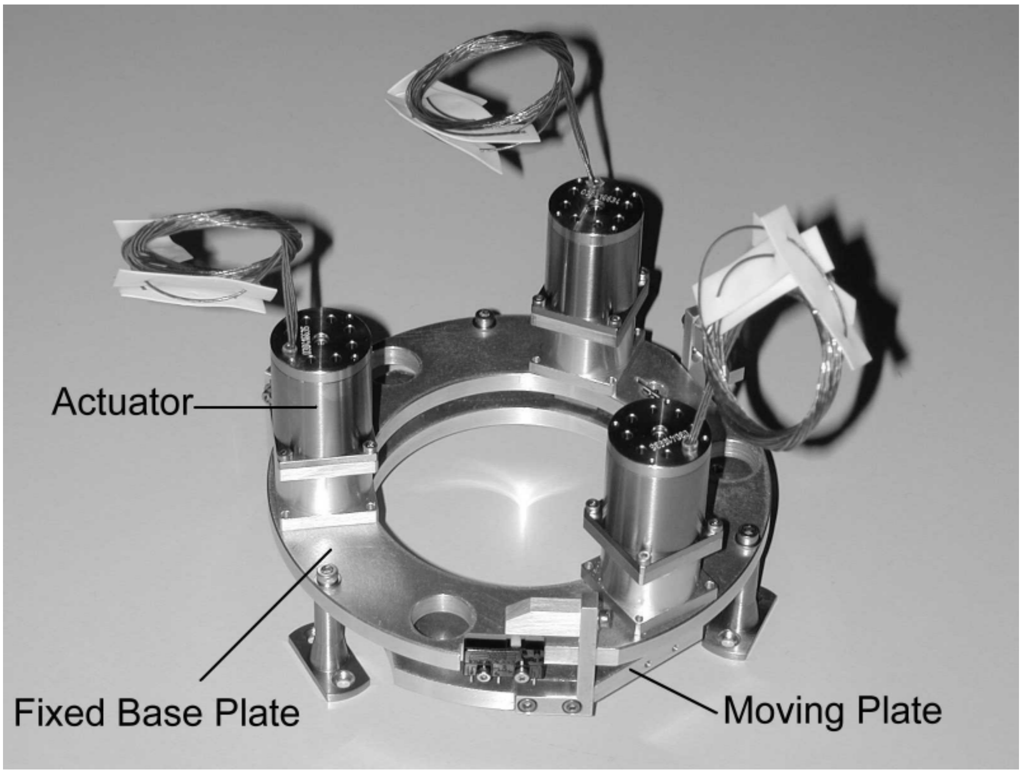


Figure 7. Three-axis detector adjustment unit.

4.2. Detector rotation and adjustment unit for LINC-NIRVANA

The IR science detector of LINC/NIRVANA (see [5] for details) is cooled to a temperature of about 70 K. It has to rotate during image integration due to the movement of the sky. This is done by a Phytron VSS 52 and a modified Harmonic Drive gear (as described in section 3.1.) with a reduction ratio of 1:206. Figure 8 shows a cut through the 3D-CAD model and a lab test device. The range of rotation is 30°. The maximum time for a reset to the initial position is 3 sec. To avoid smearing of the interferometric fringes, a positioning precision of 15 arcsec or better is required at any time during integration. Tests show that a unidirectional precision of 6 arcsec can be reached, which means that backlash effects have to be eliminated by always starting the movement coming from the same direction of rotation. Further details about this detector unit are described by Bizenberger et al. [4]

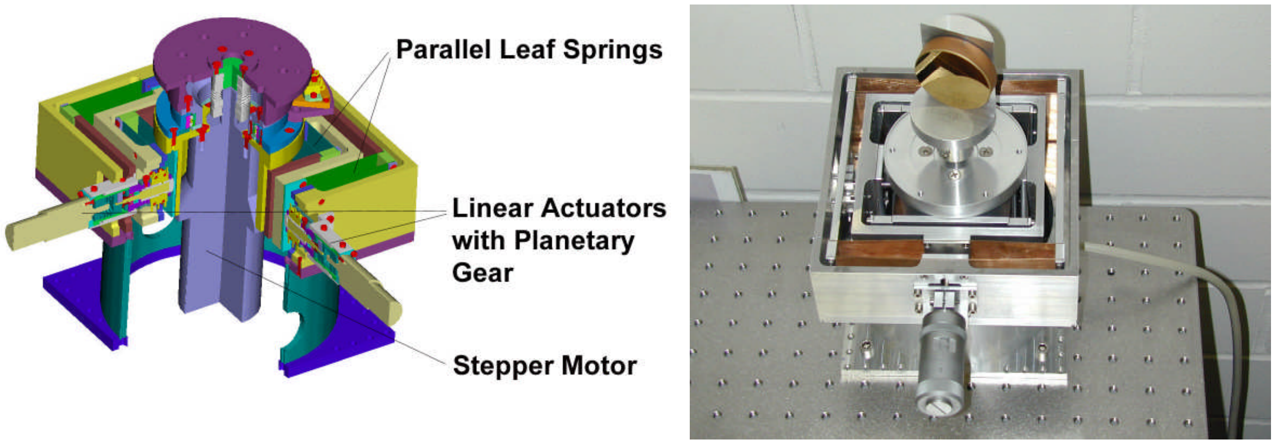


Figure 8. CAD model and lab prototype of the LINC-NIRVANA detector rotation unit. The lab model has a mirror mounted that reflects a laser beam for measuring the position accuracy.

5. CONCLUSIONS

We have described the design of several cryogenic actuators, for both linear and rotational movements. A real prototype is necessary to verify all important properties of a cryogenic actuator.

Tests in cryostats and in liquid nitrogen baths have demonstrated that these actuators work at a temperature of 77 K. Their positioning precision has been measured, mainly at room temperature. Measurements at 80 K will follow in a test cryostat. The measured precision is fully sufficient for using the actuators in a number of cold mechanisms in future ground-based instruments, like LINC-NIRVANA [4].

The Max-Planck-Institut für Astronomie in Heidelberg is also involved in the development of mechanisms and actuators for space projects (JWST [6,7]and HERSCHEL). The demands for these space mechanisms are much higher but we can profit from the experience made in these projects for our ground-based instrumentation.

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