UNIVERSITY OF ARIZONA
COLLEGE OF OPTICAL SCIENCES
OPTI 521- INTRODUCTORY TO OPTO-MECHANICAL ENGINEERING

TUTORIAL ON HIGH PRECISION CRYOGENIC OPTOMECHANISMS

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1. Introduction

Cryogenic mechanical drives are complex high precision devices that are designed to work on extreme conditions; both low temperature and high vacuum, but they are build under normal conditions, therefore the design has to incorporate these variables to make a functional device in warm and cryogenic working environments, this make the design of such devices a difficult challenge.

They are normally used on Infrared (IR) instruments that require the utilization of cryogenic opto-mechanism to prevent thermal background on the images. Figure 1 show an example of an IR camera and spectrograph called ISAAC mounted on the Nasmyth focus on one of the 8.2 m telescopes at Paranal Observatory in Chile.

This tutorial will go over several topics of cryogenics mechanisms and it will use ISAAC as a common example to show a real application on each case.

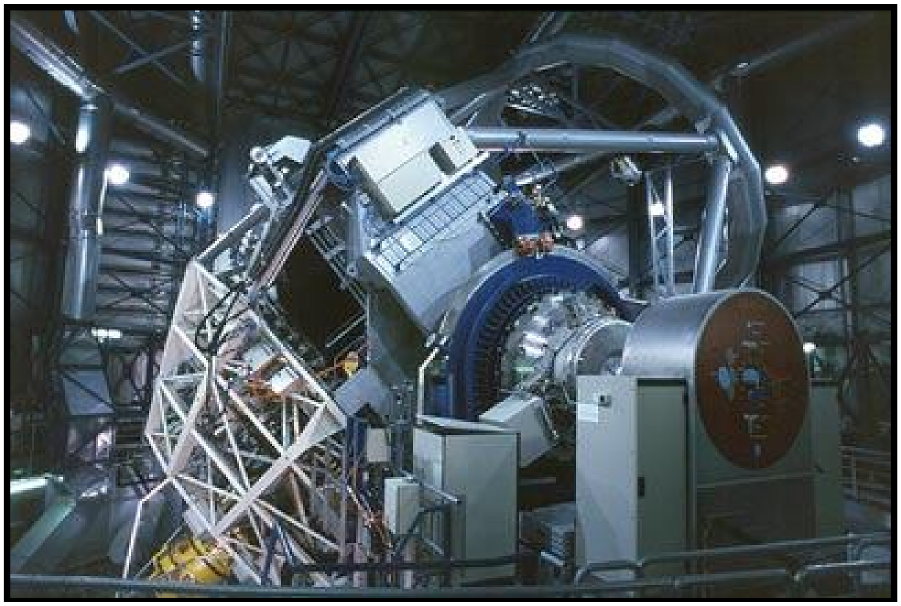

Figure 1: The IR instrument ISAAC mounted on telescope 1 at Paranal Observatory.

2. Cryogenic Instruments

IR instruments normally offer a set of modes or configurations to enable different capabilities like imaging and spectroscopy plus filter selection. To achieve this functionality the instruments are basically composed of four elements:

- *Vacuum vessel:* External structural component of the instrument. Acts as mechanical interface with the telescope and hold the cryogenic system. It is a container normally made of stainless steel or aluminum that holds the cold components inside the instrument and also keeps the interior of the instrument under high vacuum condition, normally on the order 10^{-6} mbar.

- *Radiation shield:* Layers of insulation material that reduce the radiation thermal load from the cryostat external vessel to the internal cold parts of the instrument.
- *Cold Structure:* Internal structure of the instrument where all the cryogenic opto – mechanical functions are contained. Normally is kept at ~70 K to prevent thermal background on the Near IR.
- *Detector:* IR arrays collect the light after passing thru the optics on the cold structure and form an image.

The vacuum vessel, radiation shield and cold structure are sometimes called cryostat. Figure 2 shows a view of ISAAC showing these components and table 1 presents some basic characteristics of the instrument.

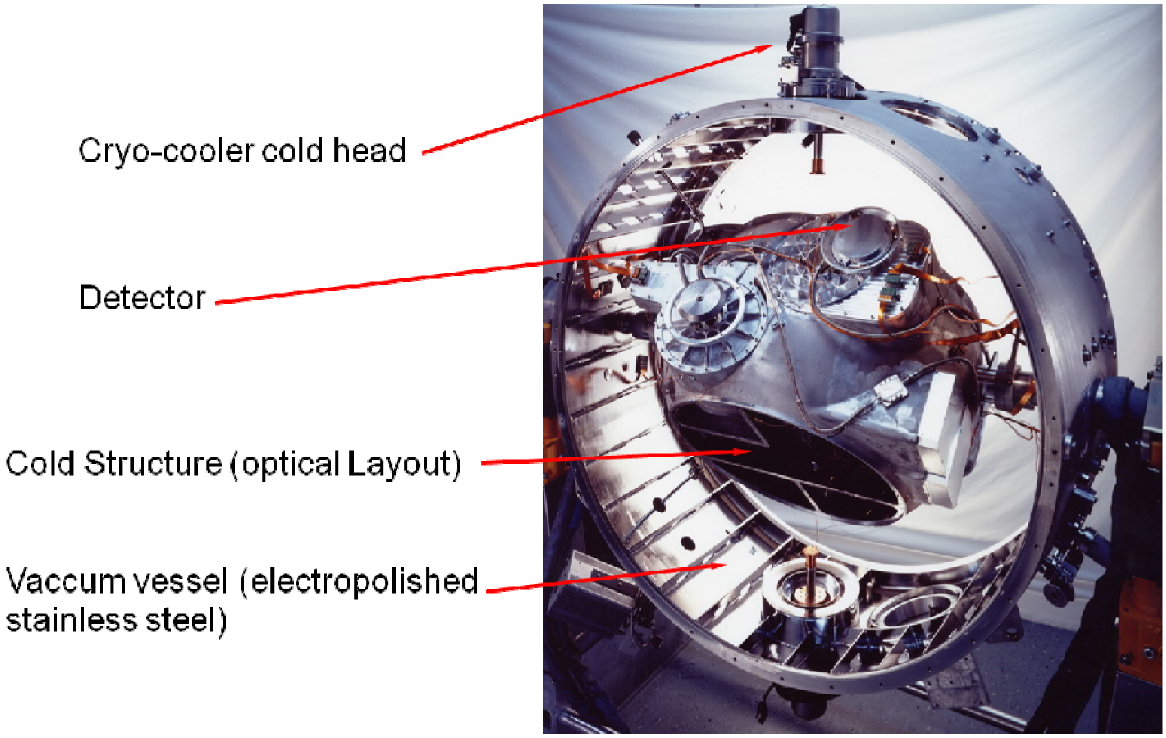

Figure 2: ISAAC and its internal components

Vacuum vessel volume	3m^3
Weight	2500 kg
Operational vacuum	1x10^{-6} mbar
Cold Structure operational temperature	70 K
Detectors temperature	30 K
Cooling system	Helium Closed Cycle Cooler.
Wavelenght	1-5 um
FoV	2,5 x 2,5 arcmin.

Table 1: ISAAC General characteristics

For this kind of instrument the challenge is to achieve a precise positioning as fast as possible to reduce the setup time of the instrument. An instrument like ISAAC has 11 cryogenic drives doing linear and circular movements. Figure 3 shows a schematic view of ISAAC optical layout and its opto mechanical drives indicated by red arrows.

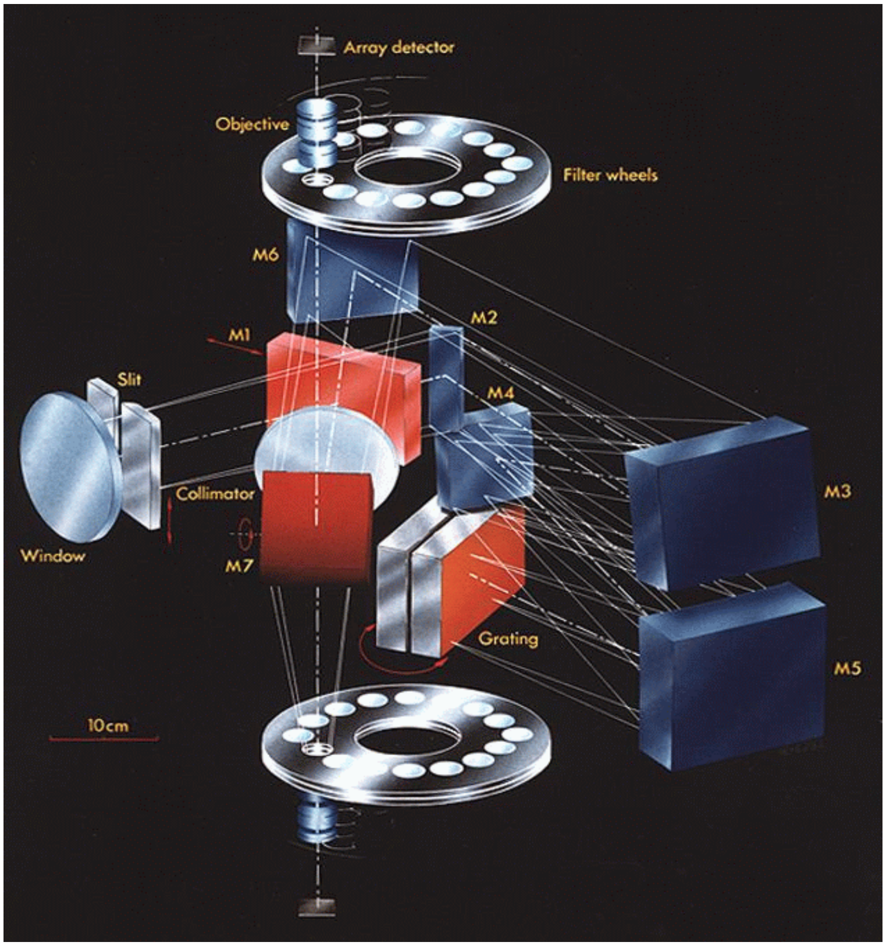

Figure 3: Optical layout of ISAAC

3. Cryogenics optomechanisms

Most high precision opto-mechanism like the ones used inside a IR instrument has the following five essential components in order to achieve their requirements; Motor, position feedback system, initialization system, mechanical gear and optics. Figure 4 shows a drawing of a typical drive of a circular cryogenic function where the motor can be indentified on the left which is connected to the worm shaft using a flexible coupling and the worm rotates drive the main drive where the optics are mounted. Note that normally a worm gear will move one tooth of the main drive per complete revolution of the worm and therefore of the stepper motor.

The angular resolution of the drive if given by the expression

$$R = \frac{2\pi}{S\,T}$$

Where R is the minimum angular resolution in radians, S is the steps per revolution of the motor and T is the number of teeth of the main gear. To provide and order of magnitude we can consider the actual numbers of a function on ISAAC where S = 1000 and T = 402. As a result we obtain R = 16µ rad or 3.2 arcsec.

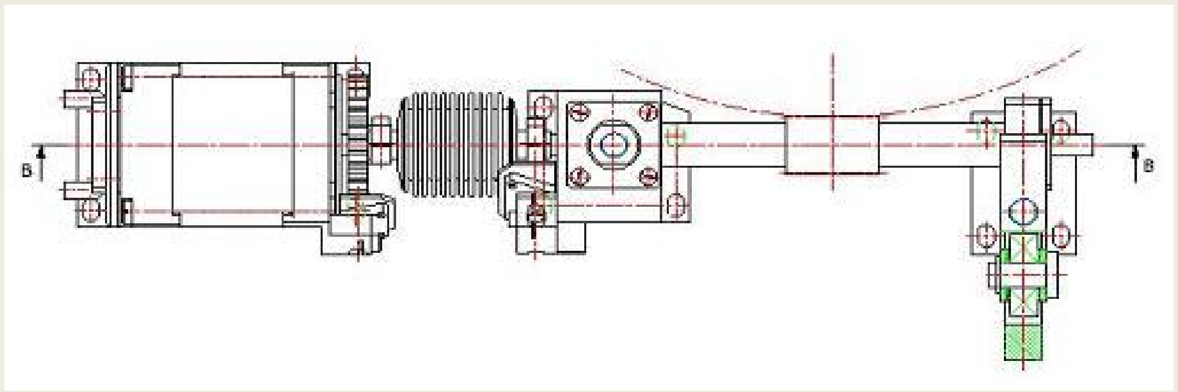

Figure 4: Typical circular cryogenic drive

The alignment of the worm with respect to the main gear is critical to achieve a low friction motion. The worm should not have any tilt with respect to the plane of the main gear. On the other hand there is a tradeoff between backlash and friction when the preload of the worm is set against the main gear. More preload reduces backlash but increases friction. This is one of the most critical parts of the alignment since the gear is adjusted warm but under cold condition the preload will increase. It may require more than one thermal cycle to adjust this properly.

3.1. Motors

Cryogenic and vacuum conditions make the selection of a motor a difficult problem. There are mainly two alternatives: Stepper motors or DC servo motors. Steppers motors have a

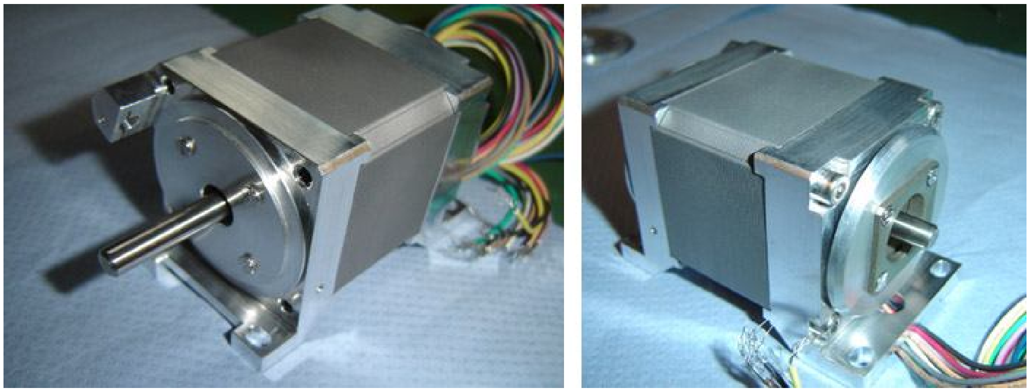

Figure 5: Berger Lahr 545/100 steppers motors prepared for cryogenic operation

certain number of phases, normally from two to five, and they move in steps as different combinations of phases are energized in a coordinated manner by the controller. This produces a semi continuous motion of the motor shaft. There is only a unique synchronous speed that will allow continues motion. This kind of motors can provide positioning feedback using the step signal from the controller but not directly from the real position of the motor.

Alternatively, we have the DC servo motors which basically rotate at a speed which is a function of the voltage applied by the controller. In this case, the position is unknown and an optical encoder or other positioning device is required to determine the position of the drive. This aspect is particularly difficult under cryogenic condition because optical encoders and inductive sensors do not work well in this kind of environment.

As a result, the stepper motors are wide spread on cryogenic applications. There are manufacturers that built motors specialized for vacuum and cryogenic conditions like Phytron but they are extremely expensive. Alternatively some instruments developers buy high quality stepper motors (i.e. Berger Lahr) and prepare them for cryogenic operation replacing casted parts by polished metallic surfaces to prevent outgasing and the bearings are replaced for special dry cryogenic bearings. The cost reduction can be of the order of 10 times.

Figure 6: Regular stepper motor preparation for cryogenic operation: Casted parts are replaced by polished metallic surfaces to prevent outgasing and the bearings are replaced for special dry cryogenic bearings. Cryogenic components are on the right.

3.2. Torque versus temperature on steppers motors

Another important factor to consider is the fact that the torque of a stepper motor is function of the speed and the temperature of operation. Figure 7 presents a plot of torque of the motor versus speed of operation at two different temperatures. Clearly the faster the operation of the motor the less torque it will deliver. Also, cold operation reduces the torque of the motor. Here we find another critical tradeoff on the configuration of the opto-mechanical system, since the slower we operate the system we have more confidence in the step counting positioning, however the drive will take more time execute a certain configuration. This is the reason why is critical to do a proper calibration of the preload in order to reduce the friction without introduce backlash. In the case of this instrument normal operation speed is 4000 steps/sec.

A problem that cryogenic stepper motors operators must be aware is the loss of phases either on the controller or the motor reducing the torque from the nominal value a causing step loss despite having a good calibrated drive and therefore introducing an error on the step counting positioning.

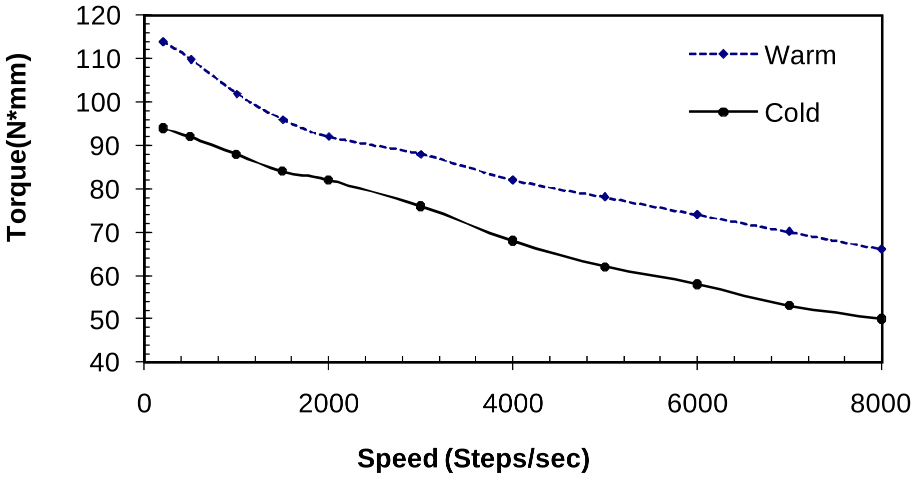

Figure 7: Torque vs speed and temperature of a stepper motor.

4. Positioning and initialization.

As it was mentioned before, compute the drive position based on the count of steps sent by the controller to the motor has a weakness. It will not work if the motor does not have torque enough to execute the commanded steps and therefore it doesn't move and the controller will still count one step more each time. This error is cumulative and large drifts can be observed after a long time operating the function.

But before the controller can start to count steps, it is necessary to define a zero in a precise and reproducible way with respect to a physical feature of the drive. This process is called initialization. To do this, magneto resistive sensors are used causing a voltage oscillation when a metallic actuator passes in front of the sensor. However the use of single sensor on the main drive would give an absolute position but the oscillation would be too coarse to identify adequately the zero point. Alternatively, a sensor can be installed in the worm causing an oscillation per worm revolution or tooth of the drive. However this will not provide an absolute initialization or zero point.

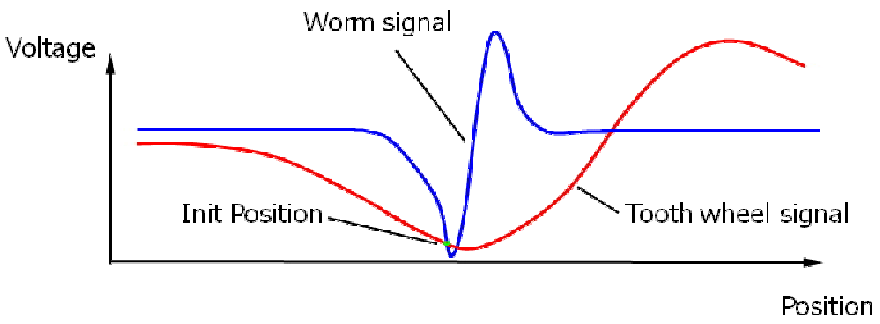

Figure 8: Drive initialization using 2 magneto resistive sensors.

The solution is to use both, a sensor on the main drive and another sensor on the worm, therefore the initialization will occur when both signal intersect reaching the same voltage as shown in figure 8. This procedure provides an accurate and unique initialization point. This implementation is shown in figure 9.

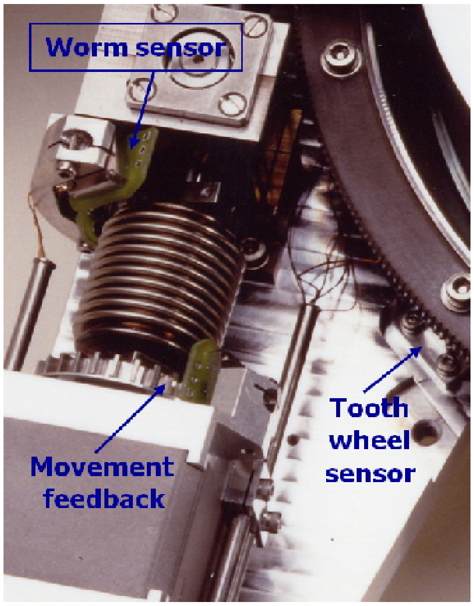

Figure 9: Initialization implementation on a real drive using stepper motors.

5. Drive example

A complete cryogenic drive is shown in figure 10. This drive moves a flat folding mirror that allows changing the instrument mode from imaging to spectroscopy. In this figure most of the features of the drive can be seen as the motor, main gear or worm wheel, drive bearing, counterweight and the Aluminum mirror.

6. Conclusion

A cryogenic drive is a complex opto-mechanical system that requires extensive fine tuning in order to obtain a precise and reproducible operation. Adjusting the drive properly before cool down is critical to achieve an adequate tradeoff between the friction and the backlash to prevent step loss. Also operators must be aware of phase damage or loss on motors or controllers to compensate the associated torque reduction with a reduction on the operational speed to prevent step loss. Finally, adequate coordination of initialization signals is critical to achieve a precise and reproducible zero point.

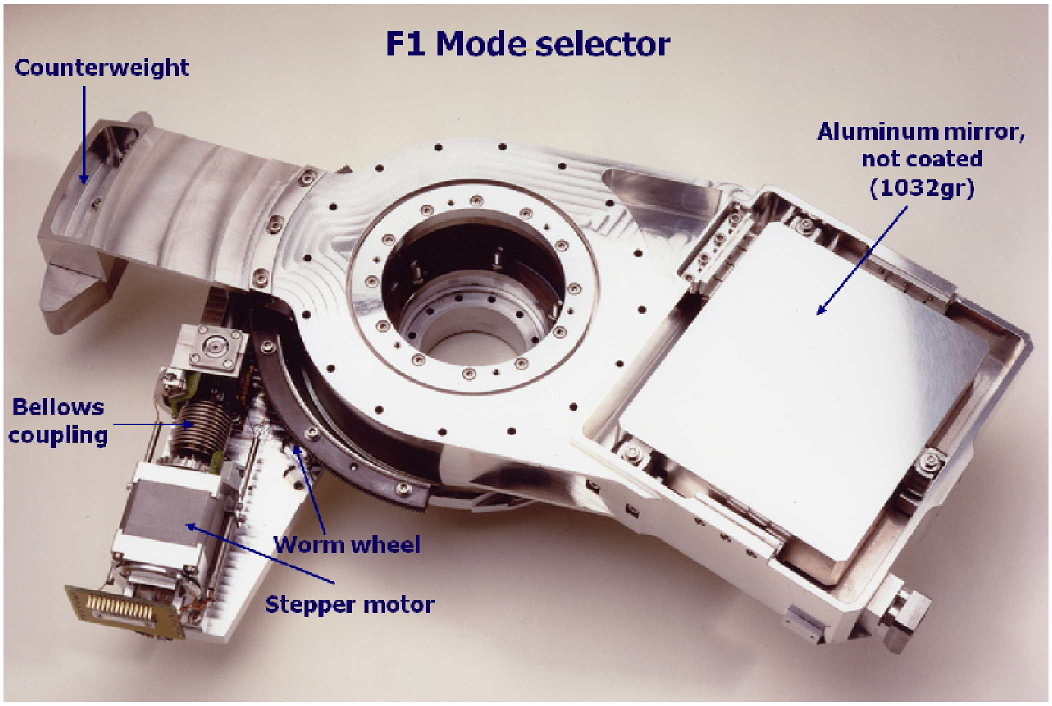

Figure 9: Cryogenic drive example