Pointing Mechanism for Optical Communication

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ABSTRACT

Optical communication has been advancing at a rapid rate. Optical inter-satellite link systems (OISL) must be capable of high-accuracy pointing for reliable communication. The laser beam is normally controlled using a fine and a coarse pointing mechanism. This paper describes the coarse pointing mechanism for low earth orbit (LEO) applications under development at Kongsberg Defence & Aerospace.

INTRODUCTION

Compared to radio frequency (RF) communication, optical communication requires less power, has lower weight and has a higher bitrate capability. SILEX was the first commercial OISL experiment and the first SILEX terminal was launched on SPOT-4 in 1998. TELEDESIC is the first proposed Gbps OISL network and will be operational in 2005. Reliable communication requires a high accuracy pointing mechanism. The optical pointing mechanism may be split into a fine pointing and a coarse pointing mechanism. The fine pointing mechanism normally consists of a small mirror with a diameter of a few cm and has a bandwidth of 1 kHz or more. The LEO coarse pointing mechanism described in this paper consists of a two-axes gimballed mirror. Both gimbals, called the azimuth gimbal and the pitch gimbal, are directly driven by a brushless DC motor and a voice coil, respectively. An Inductosyn transducer provides the necessary feedback information in azimuth, and an optical encoder provides the necessary feedback information in pitch. The pointing mechanism is controlled using a digital signal processor (DSP).

1 COARSE POINTING SYSTEM DESCRIPTION

The systems presented in this paper include a two axis mirror gimbal and a DSP based servo-controller controlling the two gimbals. The systems were designed to meet the following performance requirements.

Mechanical Rotation Range

- azimuth: ± 170 °
- pitch: ± 14 °

Angular Acceleration:	≥ 2.5 °/s^2
Angular Velocity:	≥ 5 °/s
Pointing Accuracy:	≤ 100 μrad
Total Mass:	≤ 7 kg
Natural Frequencies:	≥ 200 Hz
Lifetime:	> 10 years

The mirror is 100 mm by 141 mm. The mirror is supported by a two-axis gimbal, the inner gimbal providing pitch motion and the outer gimbal rotating about the azimuth axis. A detail of the mirror gimbal is shown in fig. 1.

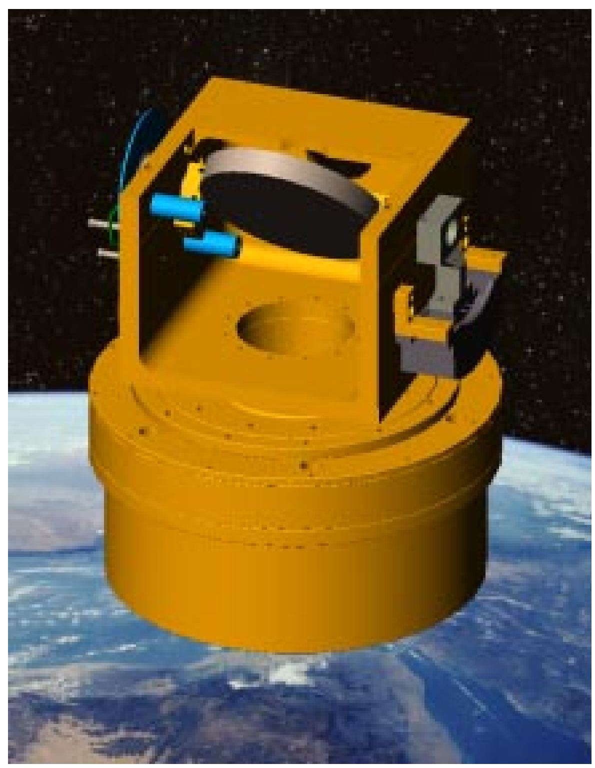

Figure 1. Coarse pointing mechanism.

Both gimbals are directly driven. A brushless DC motor and a rotary voice coil provide the movement in azimuth and pitch, repectively. The pitch gimbal uses a C-flex bearing. In the azimuth gimbal design, a preloaded bearing is applied. An Inductosyn position transducer and an optical encoder are used for feedback in azimuth and pitch, respectively. Digital control is applied in both azimuth and pitch. It was important to minimise the prototyping time, and dSPACE was chosen as our real time system. dSPACE applies the MATLAB RT workshop and allows rapid control prototyping within the MATLAB enviroment. Algorithms can quickly be generated and tested without writing a line of native DSP code. dSPACE applies a Texas TMS320C40 DSP. Fig. 2 shows the complete system.

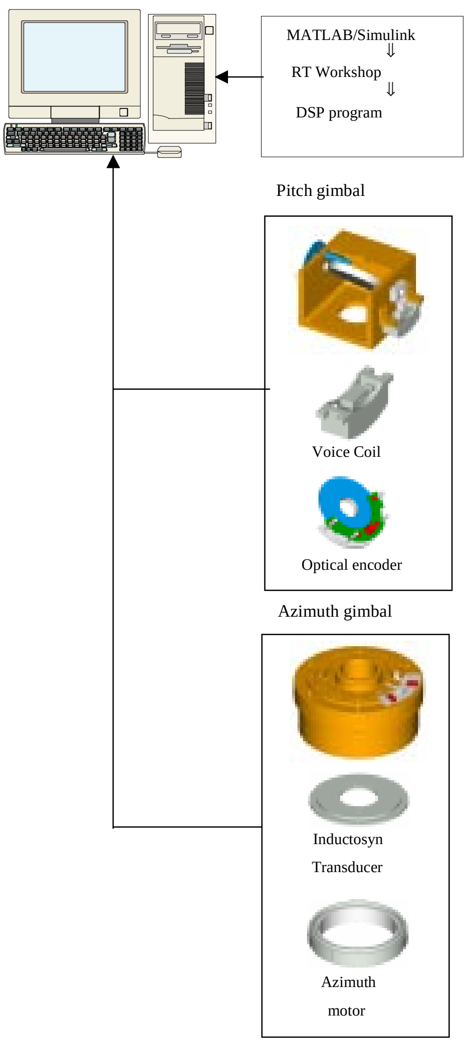

Figure 2. Complete coarse pointing system

2 GIMBAL DESIGN

The mechanical design is a conventional two-axis inner outer gimbal arrangement with intersecting axes of rotation. Great attention has been given to bearings. They provide sufficient structural stiffness, but they may also generate friction torques affecting the performance of the servo.

2.1 Material Choice

Before deciding the material type to be used in the prototype, several materials were evaluated. An overview over two alternative materials and their properties for use in the pointing mechanism is shown in table 1.

Material	Aluminium AISI 7075-T651	Titanium
Density g/cm^3	2,80	4,43
Thermal coeff. of expansion [10^{-6}/ ^{o}K]	22,9	8,8
Heat conductivity [W/m ^{o}K]	134	7,2
E-module [GPa]	71	110
Microyield tension [MPa]	124	482
Specific heat, C_p [J/Kg ^{o}K]	838	565
Advantages	- Low cost - High thermal conductivity Fast thermal equilibrium E-module approx. the same as alum.	- Light - Stable - Thermal coeff. of exp. almost like glass
Disadvantages	- High coefficient of expansion,	- Expensive - Low thermal conductivity

Table 1. Material properties

7075 T651 aluminium was chosen in the prototype. This is an aluminium alloy with good properties, but is difficult to machine. Manufacturing the mechanism in titanium was evaluated. However, because of the price and the fact that this only was a prototype model, it was decided to use aluminium. In order to get the required accuracy, the parts had to be produced with a fine surface finish of 1.6 µm.

2.2 Azimuth Gimbal

All parts in the azimuth assembly are designed using CAD tools. Minimising the complexity was an important design goal and the final construction consists of fourteen parts. The main parts can be seen in Fig. 2. The azimuth gimbal is directly driven using a brushless DC motor. The directly driven gimbal completely removes the gear backlash, but, due to the lack of gear, friction torque problem increases.

2.2.1 Bearing

Poor mechanical stiffness causes static deflections and will cause undesirable vibrations. Backlash in the bearing should also be avoided. These facts lead to the selection of a preloaded bearing. A heavily preloaded bearing has good stiffness, but also exhibits a large friction torque. A large friction torque leads to poor control accuracy, unless the available motor torque is much greater than the friction torque. The chosen motor handles large friction torques, but at the cost of large weight penalty. It become necessary to choose a bearing that compromises the preloaded force and the friction torque. The selected bearing has a run torque of 0.105 Nm and a break-out torque of 0.16 - 0.21 Nm. This leads to a motor size reduction.

2.2.2 Sensor

An absolute Inductosyn transducer was selected as the feedback sensor in azimuth. This sensor has an accuracy of about 5 μrad. The Inductosyn transducer applies inductive coupling between two moving parts to measure the angle. Because of the non-contacting elements there is zero wear and tear, normally no mechanical adjustment, and no lubrication is required. This sensor is ideal for space applications where components have to function the entire lifetime without maintenance. The Inductosyn transducer is also designed to resist the effects of light radiation, vacuum, high vibration and shock and a wide temperature range.

2.2.3 Motor

The chosen azimuth motor is a 3-phase brushless DC motor with peak torque of 3.5 Nm. The torque higher than the expected requirement was chosen based on experiments with lightly and heavily preloaded bearings. The motor has redundant windings. Ideally, the brushless DC motor shall generate a torque directly proportional to the current in the windings. The torque shall also be independent of the angular position of the rotor. In reality there will be small torque disturbances caused by geometric and magnetic imperfections. These effects are referred to as cogging and ripple and will influence the pointing accuracy.

2.3 Pitch Gimbal

The construction consists of 6 parts. The main part of the pitch gimbal can be seen in Fig. 2. The pitch gimbal is, as the azimuth gimbal, directly driven. However, the pitch angle is limited to ± 14 °, and instead of a brushless DC motor a rotary voice coil is chosen. The limited pitch angle also makes it possible to apply a C-flex bearing in pitch. The feedback sensor in pitch is located on the outside of the gimbal and an optical encoder was chosen.

2.3.1 Bearing

A C-flex bearing was chosen. The C-flex bearing is flexible and has extremely long life-time expectancy for limited ranges of rotation, even when used for constant cycling. They have crossed springs made of high-strength corrosion resistance steel, capsulated in a cylindrical housing. The spring element consists of an inner and a two-part outer spring, which interlock and are crossed at an angle of 90°. The bearing requires no lubrication, is maintenance free and has extremely low hysteresis. Starting and running torque variations, due to thermal and lubrication variations, do not exist. The C-Flex bearing has no friction, no wear and tear, no backlash, exhibit a constant linear torsion spring rate, and is self centring when deflecting forces are removed.

2.3.2 Sensor

An optical encoder was chosen as the feedback sensor in pitch. There are two types of optical encoders, the incremental and the absolute encoder. An incremental encoder generates a pulse for a given increment of the shaft rotation. The angular shaft rotation is determined by counting the output pulses of the encoder.

An absolute encoder has a number of output channels, such that every shaft position may be described by its own unique code. Optical encoders, with an accuracy of less than 1 μrad, are available. The mechanical mounting may influence the accuracy of the encoders.

2.3.3 Motor

The pitch movement is limited to a small angle and a voice coil is chosen. The voice coil actuator has high torque-to-mass ratio, no backlash, is cogging-free and has a low-hysteresis motion.

2.4 Analysis

The natural frequencies of the mechanism reveal the stiffness of the construction. FE analysis was performed on the mechanism. One important goal with this analysis is to see if the natural frequencies of the construction are above 200 Hz, and also to see the effect of changing the stiffness of the bearings in azimuth and pitch.

2.4.1 Static Analysis

CAD tools were used to find the natural frequencies of every mechanical part in the mechanism. In order to obtain the required stiffness of the total construction, it is important that each part has a sufficient stiffness. All parts have higher frequencies than the required natural frequency of 200 Hz.

2.4.2 Dynamic Analysis

The dynamic FE analysis was performed using a mechanism program called FEDEM developed by FEDEM AS. The program is intended for design and optimisation of the performance of mechanical systems. The program can perform mechanism simulation to optimise the motion behaviour, run FE analysis of individual parts, run FE analysis of the complete mechanism and design the control system in order to obtain required damping and optimal system performance. FEDEM is a non-linear FEM program. The program also includes full stress analysis and eigenvalue solution for selected time steps. It is possible to analyse the overall performance of flexible body systems including control systems in a single run without time consuming data transfer operations.

FEDEM analysis shows that the construction is sufficiently stiff, as the lowest natural frequency of the complete mechanism was higher than 260 Hz. This indicates that it is possible to slim the structure and/or choose a less preloaded bearing. Less preloading results in lower friction torque and a slimmer construction saves weight. Modelling different stiffnesses of the bearing in azimuth indicates that it is possible to use a bearing with 40% lower preloading and still have natural frequencies above 250 Hz. The weight optimisation has not yet been performed, but weight reductions are expected. The FEM simulations will be compared to vibration analysis performed on the protype.

3 CONTROL

3.1 Azimuth

The chosen preloaded bearing in azimuth removes the backlash and stiffens the construction, but at the cost of an unwanted larger friction. It is difficult to obtain a high precision servo unless the available motor torque is much larger than the friction of the bearing. Even if this requirement is fulfilled the movement of the gimbal may be rough and, in order to reduce this problem, the friction is estimated using the Dahl friction model. The motor is driven from a pulse width modulated amplifier and the motor is current controlled. The dynamic equations of current controlled DC motor reveal that the armature resistance, the inductance and the back EMF constant do not influence the current being delivered to the motor. Since the torque is proportional to the armature current, the current actually produces torque control. The servo applies digital control and the sampling rate will be chosen according to the bandwidth of the servo. Fig. 3 shows a mathematical model of the azimuth servo, where K_T is the motor torque constant and the motor amplifier, LIM is the motor torque limit, J is the total moment of inertia, $H_2(s)$ is the controller of the velocity loop, $H_1(s)$ is the controller of the position loop. Lead , lag or PID controllers may all be applied in order to obtain an accurate position and velocity loop. Other control strategies will also be considered. The brushless DC motor applied in azimuth exhibits two unpleasent effects, namely cogging and ripple. Both effects are strongly reduced by measuring the back EMF, and using these measurements as a part of the control signal.

3.2 Pitch

The voice coil behaves like an ordinary DC motor. The pitch gimbal has no friction, no backlash and exhibits a constant linear torsion spring rate. The maximum motor torque is 0.3 Nm and an ordinary analogue power amplifier drives the voice coil. The controller is, as in azimuth, digital.

Hardware and software from dSPACE controls both the azimuth and pitch servo. dSPACE applies the MATLAB RT workshop and allows rapid control prototyping within the MATLAB enviroment.

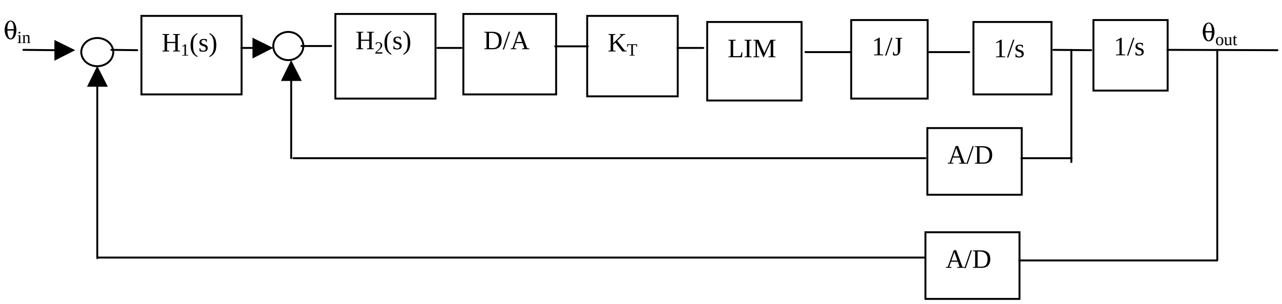

Figure 3. Azimuth control loop.