AN OVERVIEW OF SENSORS IN SPACECRAFT ENGINEERING

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1 Introduction

Sensors play a vital role in space missions providing engineers with essential data concerning the general performance of a spacecraft. Further they may form part of a closed loop control scheme, as in the case of attitude control. This paper aims to give a broad overview of sensors used on-board spacecraft, in the fields of attitude determination and general engineering telemetry.

2 Attitude Determination Sensors

A satellite in space must point in a given direction as dictated by the mission requirements. Many satellites are Earth orientated while others are designed to face the sun, or perhaps a star of interest. The orientation of the satellite in space is referred to as its attitude and in order to achieve control and stabilisation of the spacecraft pointing, sensors must be used to determine the current attitude condition. This section investigates the range of sensors used on spacecraft for attitude determination.

The spacecraft attitude is determined relative to a reference frame in inertial space or a body of known position. Unit vectors are defined for the chosen axes system and attitude sensors are used to measure orientation of the spacecraft frame of reference with respect to these vectors. Commonly used vectors are defined by the following reference sources;

Earth, Sun, Stars, Geomagnetic field, Inertial Space.

This section will discuss sensors used to measure the orientation of the spacecraft relative to these references.

2.1 Earth Sensors

To near-Earth satellites the Earth covers a large proportion of the sphere of view and presents a large area for detection. The presence of the earth alone does not provide a satisfactory attitude reference hence the detection of the Earths horizon is widely used.

From space the Earth is complex in appearance. Firstly it is visible due to sunlight reflected back into space. The intensity of this reflected light is high from clouds and ice, but land masses and water give a poor reflection. Incident energy not reflected by the Earth is absorbed as heat and the resulting black body spectrum peaks at about 10um in the infrared.

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Earth horizon sensors generally operate by detecting changes in light intensity associated with Earth's edge. Knowledge of the horizon in-crossing and out-crossing times, together with the scan time, allow the computation of the desired Earth angle.

Sensors are designed for operation in both visible and infrared regions. Visable sensors are generally based on photovoltaic devices and may be of a relatively simple design. However this technique is prone to false horizon detection on bright features such as clouds, hence more elaborate systems are often used. Infrared devices avoid light reflection problems but the detectors often require cooling.

In order to detect a horizon crossing, the sensor must scan the celestial sphere. On spinning satellites this is easily achieved by mounting the sensor on the body of the spacecraft at a fixed angle with respect to the spin axis. Conversley, wheel mounted sensors are used to provide the scanning motion in the case of three axis stabilised spacecraft; these are often incorporated with a momentum wheel.

More advanced sensors use sets of scanning mirrors, which after the Earth is located, oscillate the detector fields of view across the horizon. Accuracies in the order of a few arc minutes can be obtained using this technique.

2.2 Sun Sensors

The Sun is the brightest light source in the satellites sky and appears as a small source of about 1/4 of a degree making it ideal for an attitude determination reference. Sensing the angle of the Sun is achieved by a wide range of ingenious techniques; some allowing measurement to modest accuracy with large range of coverage, others over narrow fields of view to high accuracy of better than 1 arc minute.

Some Sun sensors use analogue methods based on the sinusoidal variation of the output of a photocell with Sun angle, while others are based on the use of masks or apertures. In the case where the payload is designed to point towards the Sun, analogue sensors may be designed to work in two axes; these may use four photo-detectors arranged to detect quadrants of the Sun's image. Errors in pointing to the sun can be detected by differences in the signals from the four detectors.

Digital techniques are also used; these may encode the position of a narrow line of sun light projected through a narrow slit into a Gray code word related to the Sun's angle. The resolution of this method is limited by the finite size of the Sun in the sky. Digital sensors based on linear CCD arrays have also been used; these devices have a limited field of view of a few degrees but are capable of resolving angles of a few minutes of arc.

2.3 Magnetometers

Magnetometers are devices used for measuring magnetic fields. On-board spacecraft they can be used to measure the components of the Earth's magnetic field at the axes of the satellite. With the knowledge of the actual geomagnetic field, the magnetometer information can be used for attitude determination.

The geomagnetic field is essentially dipolar, tilted at 11 degrees with respect to the rotational axis. In order to predict departures from this simplified model, a multi-pole system can be used. Routine attitude determination on-board a satellite may be achieved by relating three axis magnetometer data to the local field components predicted by the model.

Attitude determination accuracies of better than a few degrees can be achieved in low Earth orbits. The use in higher orbits (> 6 000 km) is limited not only by the sensitivity of the magnetometer, but by difficulty in predicting the field which is distorted by the influence of solar winds.

Many spacecraft magnetometers are based on the flux gate principle. Instruments of this kind can measure fields down to a few tenths of a nano-tesla, compared to the Earth's maximum flux density of > 40 000 nT.

2.4 Star Sensors

Star sensors are generally the most accurate of the attitude determination devices, providing measurements down to a few minutes of arc; a performance which is only achieved by a complex, heavy, expensive and power hungry instrument.

Three general classes of star sensor exist; those sensors that use the rotation of the spacecraft to scan for stars, star sensors mounted on a gimbaled assembly capable of searching for stars and those which use a fixed head only operating over a limited field of view.

As with the case of Earth sensors, the effect of stray light sources such as the Sun present a significant measurement problem and an effective sun shade is a critical component of a star tracker system. Mounted within the shade are an optical system and image definition device which in turn focus and define the portion of the star field for the detector. CCD technology is commonly employed as a detector, alternatively the Vidicon tube etc may be used. The signal from the detector is then processed and the observed coordinates of any star are compared with a star catalogue.

The recent advances in microelectronics have enabled signal processing of star sensor data, together with detector pointing control to be carried out with comparative ease, all within a single sensor package.

In order to obtain a complete attitude measurement using stars, at least 3 stars need to be identified and the field of view of the star tracker must therefore be sufficient to permit 3 stars of adequate brightness to be included in the chosen star field.

2.5 Gyroscopes

The gyroscope (gyro) is a device which is widely familiar in the field of inertial guidance and although it cannot provide absolute attitude measurements, its ability to respond to changes in inertial orientation makes it a widely used device in space.

The action of the gyro is based on a rapidly spinning mass, the angular momentum vector of which remains fixed in inertial space in the absence of any applied torque. The spinning axle is supported by a gimbaled ring; the axis of rotation of this gimbal is called the output axis of the gyro. Any spacecraft motion about the axis perpendicular to the spin axis, the so called input axis, will cause the gimbal to precess about its output axis.

The simplest form of mechanical gyro used on-board spacecraft is the rate gyro, a device which measures angular rates. Some estimate of attitude displacement from an initial value may be obtained by integrating the output, either by use of the on-board computer, or directly using a so called rate integrating gyro.

The Gyro only gives angular information about its input axis and so three such devices are required to give complete angular information. The device also requires regular updates from other attitude determination sensors to provide initial angular information.

The performance and reliability of gyros is limited by mechanical friction causing drift and wear but devices which measure angular rates with minimal moving parts have been developed. One of these instruments, the fluid loop gyro comprises of an armature suspended in a fluid filled pipe, this acts in conjunction with a read out device to measure changes in position with respect to the pipe wall. Another device known as a laser ring gyro uses no moving parts and is based on the detection of rotation with light demonstrated by Sagnac in 1913. In this technique, a beam of light is split and passed in opposite directions around a loop, possibly of single mode fibre optic cable. Any spacecraft motion about the loop axis, causes a path difference to be set up for the two beams and a standing wave results, which can then be sensed at some point in the loop.

3 Satellite Telemetry Sensors

Voltage, current and temperature are widely measured on all spacecraft and this information can be correlated to provide a good indication of the 'health' of the satellite. Temperature measurement is vital to ensure that the satellite is operating in an acceptable thermal environment. On a satellite where there is either active or passive thermal control, temperature sensors may be implemented in a close-loop control system.

In the case of experimental sensors, the level of accuracy can be typically picoamps of current. Conversley, satellite 'house-keeping' sensors may only need to act as indicators, in which case accuracy of two decimal places is usually sufficient. Generally sensor outputs are converted to voltages in the range determined by the telemetry Analogue-to-Digital converter (ADC).