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Optical and structural designs for GEO orbit remote-sensing satellite and its camera system

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Abstract. Since 1957, when the Soviet Union launched the first artificial satellite, Sputnik I, attempts have been made to bring convenience to people by interacting with terrestrial facilities through orbital space. Geostationary Earth-orbiting remote sensing satellites provide the ability to continuously scan and explore a specific area, allowing researchers to obtain more accurate information about the Earth, which benefits mankind in many ways. This paper analyzes the payload satellite camera carried by remote sensing satellites, explains the working principle of the camera, and outlines the relevant parameters and their concepts. Taking China's Gaofen-4 as an example, it analyzes the design and limitations of the common satellite camera used in this template from the perspectives of thermodynamic, mechanical, and optical environments. Meanwhile, the article gives an outlook on the future development trend of Geostationary Earth orbit remote sensing satellites.

Keywords: Geostationary earth orbit, satellite camera, remote-sensing satellite, space environment.

1. Introduction

Satellites in geostationary (GEO) orbit are vital in modern society. The remote-sensing satellites on the GEO orbit can provide images containing information because their orbiting period is the same as the rotational period of Earth. This information can constantly provide messages for observing and surveilling a specific area. These aids include agricultural development, water pollution, meteorological status, atmospheric emission, and city development. The cameras installed on GEO remote sensing satellites are designed to have a high resolution and ground sampling distance (GSD). Ground sampling distance is the distance on the ground between two connected pixel centers.

Satellites in outer space face severe environments. The satellite experience the worst hot condition when it receives solar radiation for the maximum amount of time. The satellite experienced the worst cold conditions when Earth shaded it for the maximum amount of time. Between the worst hot condition and the worst cold condition. The environment can have a ΔT=200 K. The complexity of the radiation and optical environment is noticeable, too. In space, without the refraction of the atmosphere, the harsh light ray incidents challenge the ability of cameras. The space-borne cameras need the advanced ability to overcome complicated obstructive light environments.

Due to the overall complexity of the working environment of GEO remote sensing satellites, the material selection requires rigorous considerations. The inner structure has to be constructed with materials with low thermal expansion rates to keep the precision instruments in the satellite by not adding extra stress to them. The stiffness of the material is required to prevent inelastic deformation when experiencing overload. According to the standard, a GEO remote sensing satellite should meet optical designs that differ from commercial single-lens cameras must be developed. The high-resolution space-borne camera needs specialization to prevent unfiltered cosmic radiations and light rays. These unwanted disturbances cause degraded image quality.

In this research, the special designs and engineering involvements of GEO orbit remote sensing satellite is summarized to provide a perspective of the specialization of space-borne camera. A specific analysis of optical and structural design is presented. A summary of common designs of modern space-borne satellites is being proposed.

2. Working mechanism of satellite camera arrays

Satellite cameras work by essentially adjusting and optimizing a regular home camera to make the information captured by the camera completer and more accurate. There are many scenarios where people have access to commercial products such as SLR (single lens reflex) cameras, micro SLR cameras, and other cameras. Cameras work by focusing light through a lens and reflecting it several times so that the light strikes a light-sensitive imaging element, which converts the optical information into electronic information and stores it in a storage unit.

In order to understand cameras, it is important to understand the light-gathering properties of convex lenses. In all-optical imaging situations, light is focused through a convex lens, and the focused image is reflected and collected for imaging purposes. Remote sensing satellites use sophisticated electronic imaging units and storage units. After the imaging is completed, the electronic data must be guaranteed data integrity and should not be altered during radio transmission, which requires a closed and stable imaging unit environment to isolate it from complex external electromagnetic interference. In addition to this, the characteristics of Geostationary Earth Orbit (GEO) satellites allow for continuous imaging of a specific area, and their relatively geostationary nature makes it possible to obtain extremely detailed information. GEO is located 35,780 km normal to the Earth's equator. The rotation period of satellites in this orbit is synchronized with the Earth's rotation period.

3. Optical strategy

In outer space, satellites face several important challenges. Unlike on Earth, there is no opportunity for maintenance in the face of these challenges. Not only do satellites need to ensure that they can operate normally in outer space without damage, but they also need to operate maximally well over long periods to achieve the purpose for which they were launched, such as agricultural inspection, pollution monitoring, urban management, or espionage activities. The absence of an atmosphere in space makes it impossible to assist in the refraction and softening of stray light and the sun's harmful rays, which in turn places more and more stringent requirements on the satellite's lenses. Only a lens that meets the specifications can guarantee image quality in the complex optical environment of space. Otherwise, poor imaging will not provide the same quality of information that researchers expect when launching satellites.

The accuracy targets for high-resolution cameras need to be achieved through a delicate manufacturing process and special camera internal structure design. By arranging and producing lenses made of special materials, unwanted interfering light can be effectively contained, which ensures that the image quality meets the requirements and a sufficient amount of information can be analyzed from the image. The space optical technology advancement brought new technologies to the camera systems. Military reconnaissance satellites owned by the U.S. military have at least 0.15 meters of ground sampling distance (GSD) in a 700-kilometer orbit, while China's synchronous Earth-orbiting, high-resolution remote sensing satellite GF-4, launched in 2015, has a GSD of 50 m. Ground sampling distance represents the distance to the ground represented by each pixel on a satellite image, and smaller geodetic resolution means that the more detail in the imaging. The smaller the geoid resolution, the more detailed the image and the more accurate the image [1].

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3.1. Lenses distribution

The arrangement of mirrors in an optical system is critical. Proper alignment can result in clearer images and minimize the effects of some of the systematic errors that are bound to exist during installation and processing. Today's mainstream high-resolution cameras mainly use a three-mirror imaging system.

The co-axial triple mirror optical imaging system was introduced in 1974 and collects and corrects the incident light through a curved mirror composed of three quadratic surfaces. A quadratic surface means that the tangent plane of the mirror exhibits a quadratic function in the tangent plane perpendicular to the mirror. This design provides enough variables to correct for aberration and also to reach the diffraction limit of the camera for a better-quality image.

However, the fact that its first mirror is a face mirror makes it necessary for a secondary mirror, which reflects light a second time, to be mounted before the primary mirror. This leads to an inevitable circular blocking area in the center of the image where no image is created. That's why most cameras require push-scan imaging for long panoramic shots to fill in the imaging of the missing area in the center. After the three quadratic mirrors reflect the corrected light, a folding mirror reflects the light to an off-axis image processing unit.

The off-axis triple mirror optical imaging system is a modification of the co-axial system, resulting in a reduction of the masked area or even an improved system design that allows the image to be completely uncovered. However, since the off-axis system does not use fully symmetrical quadratic mirrors, the processing difficulty is significantly increased. However, the advantages are more significant than the drawbacks, as the size can be reduced due to the possibility of folding and deflecting the optical axis. This, in turn, reduces the total satellite load and increases the overall satellite stability [1].

3.2. Stray light

Stray light is a serious interference that all camera systems wish to remove in systematic imaging. Stray light is a general term for all light that is not required for imaging. In addition to visible light, these include infrared rays from various heat sources and stars. They can introduce noise and interference into the imaging, greatly contributing to the failure of imaging [2].

Stray light can be categorized into several general classes, depending on the degree of focus. III-class, General-class, and Well-class. If the stray light is reflected multiple times into a single point and hits the imaging unit, a large spot exists in the image and greatly reduces the degree of information gained from the image. III-class is the stray light that is the most concentrated after the second reflection. III-class is the most aggregated stray light after the second reflection, which must be avoided because it is difficult to eliminate its effect through multiple reflections. General-class stray light is aggregated but not converged into a point, which more often leads to a region of the image to increase the noise. Well-class can be almost ignored because it is not aggregated; it belongs to the diffused stray light, and the majority of the light will be dispersed after multiple reflections, which is more likely to cause an unavoidable base noise for the full image instead of raising noise greatly [3]. Multiple reflections can drive stray light away from the image plane during the focusing process, creating a better image. A stray light test is required before the camera is loaded to ensure that its ability to handle stray light is as expected [4].

3.3. Manufacturing

The lenses undergo three main manufacturing processes: aspheric surface milling, robotic grinding/polishing, and ion beam polishing. By dividing the entire manufacturing process into three separate parts, the precision of the lenses is improved, and extremely fine lenses can be produced to meet the requirements. These lenses can be brought to a GSD of 50 meters or finer in synchronous Earth orbit, making it possible to acquire continuous information over a large area. In the first of the three processes, aspheric face milling is performed by first trimming the lens to the closest possible sphere and then driving the grinding wheel in a high-speed axial motion by ultrasonic waves, which in turn

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results in a lens close to the desired asphere. By calculating the respective milling amounts in each coordinate, a prototype of a lens with a large margin of error can be obtained [5].

Next, robotic grinding and polishing can further reduce the lens error from tens of micrometers for ultrasonic milling to a range of about a thousand nanometers after robotic milling and about 300 nanometers after robotic polishing. Robotic grinding and polishing require sophisticated equipment and instruments to remove inaccuracies and errors from the surface of the lens while maintaining the stability of the equipment to achieve further accuracy. Robotic polishing uses a robotic arm with 6 axes of motion, which is calculated to keep the arm moving parallel to the single point normal to the mirror surface to ensure processing accuracy. Robotic polishing results in a more accurate aspheric surface, which eases the next step in the ion beam polishing process.

Ion beam polishing uses a low-energy argon ion beam to impact the lens to remove deviations from the lens. Ion Beam Polishing can limit the polishing function to a very small amount to remove a single point of error, and the amount of removal is determined by the change in residence time at the same location. After multiple rounds of the final ion beam polishing process, the final face shape error can be minimized to about one hundred and fifty nanometers, which meets the accuracy requirements of space cameras.

4. Structural consideration

During loading, launch, and in-orbit operation, the camera is subjected to multi-directional accelerations and uneven forces. These stresses on the camera system can, in extreme cases, destroy the imaging capability of the camera and render it inoperable. In the selection of materials, the overall choice is to use high-strength and high-stiffness materials as support components to reduce the stress on precision devices. At the same time, the camera in the space environment will suffer extreme temperatures environment, and an extremely hot environment leads to device expansion force affecting the imaging quality. An extremely cold environment will affect the parameters of materials, making them more fragile and easier to be destroyed by external forces. Appropriate heat dissipation and insulation are therefore necessary in satellite structures.

4.1. Mechanical environment

Typical launch steps such as rocket launch, fuel stage detachment, and load detachment cause resonant coupling within the rocket, which is the phenomenon that two objects vibrate with alternating intensity when they come into contact. This effect can have a large impact on the payload and can lead to damage to the camera components if no suitable preventions have been made. The effect ultimately may cause the satellite to be ineffective, occupying orbital resources and posing a threat to other operational satellites.

During the initial phase, the uneven vibrations continue, especially during the launch and breakup phases. Later, in the second and third flight phases, the vibration frequency decreases as it enters a smoother phase. Instantaneous vibrations were significant when the payload was detached from the rocket [6].

4.2. Heat environment

The primary environment in which satellites operate is complex, as are the factors that need to be considered. Multiple factors are interrelated, thus creating an environment with very low tolerance for the operation of high-precision instruments [7]. The instruments themselves emit heat, and additional cooling systems are required to keep surface temperatures and temperature variations within safe limits to prevent irreversible damage to critical components of the satellite-mounted instruments, such as graphics processors and data transmitters. In space, due to the lack of an ozone layer, both the rays and radiant heat emitted by the sun are directly absorbed by satellites. This absorbed heat needs to be addressed promptly. Otherwise, the excessive energy input will directly damage the satellite. At the same time, a variety of cosmic rays will also have an impact on the satellite's electrical signal transmission [8].

For high-orbiting satellites, prolonged sun outages can also lead to a dramatic increase in instrument stress and disrupt data transmission. In synchronous Earth orbit, satellites receive an external heat flux of solar radiation in all directions of about 0-1400 W/m^2. The heat varies by more than two hundred kelvins between the time when the satellite is in sunlight and the time when it is in the Earth's shadow [8].

4.3. Heat control of lenses

Cameras recording on satellites require stable temperature conditions to ensure that temperature-driven changes in lens accuracy are negligible, and those temperature-driven image aberrations can be ignored. Expansion and even deformation of the lens or its main support structure under direct heat can affect the image. In the case of the GF-4, for example, the lens requires an operating temperature of 15 to 22 degrees Celsius and a temperature fluctuation of less than 1.5 degrees Celsius per hour during imaging.

With proper temperature control, the camera's primary lens temperature can be controlled between 18.253 degrees Celsius and 17.810 degrees Celsius, and the secondary lens temperature can be controlled between 19.185 degrees Celsius and 15.956 degrees Celsius in the lowest temperature environment of the satellite in synchronous Earth orbit. In the hottest temperature environment, the temperature of the primary lens can be controlled between 20.895 and 20.710 degrees Celsius, and the temperature of the secondary lens can be controlled between 20.204 and 20.028 degrees Celsius.

Temperature control is one of the core satellite cameras needed to ensure that the image quality requires material considerations. The shell emissivity needs to be minimized while ensuring that the material stiffness and toughness meet the stress environment conditions [9,10].

5. Conclusions

In the modern world, geostationary Earth-orbiting cameras play many irreplaceable roles, such as providing geographical information to help improve the well-being of people. They can also provide meteorological and geological information for scientific research and assist in ecological conservation. However, due to its special environment, its design mode is different from other cameras. Under the premise that researchers ensure the high precision of its lenses through special production methods, the camera's stray light resistance needs to be strong enough to minimize the presence of III-class stray light on the imaging module to ensure the integrity of the image. Generally speaking, the camera will filter out stray light by reflecting and focusing the incident light several times and, at the same time, reduce the imaging distortion. And the satellite needs to ensure its excellent performance in extreme thermodynamic environments to ensure that the camera is not damaged by the extreme thermal changes in GEO during imaging and idling. The camera also needs to have the ability to withstand high-frequency vibrations in multiple directions during launch. These designs allow the camera to function properly in orbit during its duty cycle.

Synchronized Earth orbit is a finite resource with a fixed total capacity. As human technology advances, the efficiency of orbit utilization escalates. Geostationary Earth-orbiting satellites are still used mainly for large-scale exploration work in fixed areas because of the limitations of their geoid resolution and their limited detection capability compared with low-orbiting remote sensing satellites. In this context, the main direction of development in the future should be to improve the camera's geoid resolution while integrating its functions, resulting in better utilization efficiency and ensuring the sustainability of the limited orbital resources that the Earth can provide.

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