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In-orbit and Networked Optical Ground Stations Experimental Verification Advanced Testbed (INNOVA): The High-performance and Compact Ground-tracking System

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Abstract*—The high-performance and compact ground-tracking system has been developed for the terrestrial free-space optical communication network facility called in-orbit and networked optical ground stations experimental verification advanced testbed "INNOVA". It consists of the "dual" 2-axis gimbals, the fine pointing mechanism (FPM), the optical wide-range acquisition sensor (WAS), the optical coarse acquisition sensor (CAS), the optical tracking sensor (FPS), the wavefront correction sensor (WCS) and the deformable mirror for the adaptive-optics (AO) function, and the high-performance controller. The FPM, WAS, CAS, FPS, and AO function are unified as the optical module, and its beam-direction is directly controlled by the 2-axis gimbals. A CMOS image-sensor base of InGaAs is commonly applied to WAS, CAS, FPS, and WCS; the acquisition ranges for WAS and CAS are each tuned by the telescope magnification, and the accuracy of CAS and FPS is determined by the focus distance. In the optical module, the beam-direction is aligned to the optical-fiber by FPM based on the measurement signal of WAS, CAS, and FPS. The "dual" 2-axis gimbals have the mechanism of the coarse and fine axes for each azimuth and elevation axis. The corporation control between the gimbals and FPM is achieved using the synchronized WAS, CAS, FPS, and WCS signals. Then, 40Gbps digital coherent optical transponder / 10Gbps IMDD optical transponder can be chosen for the free-space optical communication on the system.

Keywords*—free-space optical communications; precision optical sensors; ground-tracking control system; adaptive-optics module; 40Gbps/10Gbps optical transponder

I. INTRODUCTION

Free-space optical communications have been developed for a growing requirement of high-speed and large-capacity data transport between the ground station and the mounted terminal on the spacecraft or aircraft vehicle, as an alternative to radio frequency communication and as a next-generation network system. All links, moreover, are anxious for both military and civilian infrastructure. The various experiments for the optical tracking system on near-Earth orbit were conducted by using the Japanese optical inter-orbit communication satellite "KIRARI" from 2005 to 2006 [1]. The system feasibility of the optical communications could be evaluated by the experiments using "KIRARI", and many worthwhile results were collected.

The terrestrial free-space optical communications network facility called "in-orbit and networked optical ground stations experimental verification advanced testbed (INNOVA) has been developed by the National Institute of Information and Communication Technology (NICT) for future airborne and satellite-based optical communication. It consists of several ground stations and environmental monitoring stations to explore the site diversity concept. The compact ground-tracking system is installed as one of the ground stations, and the usability and the tracking-performance of sophisticated optical communications equipment can be verified. This paper shows the overview of the developed compact ground-tracking system with the characteristics of some components.

Fig. 1. Overview of the compact ground station.

II. OVERVIEW OF THE GROUND-TRACKING SYSTEM

Fig. 1 shows the overview of the developed compact ground station. This ground station has the optical tracking system of 2-axis gimbals for the optical module, 40Gbps digital coherent optical transponder, 10Gbps IMDD optical transponder, and the system controller with the deploying roof for the gimbals. Its dimension is about 2m ×2m ×4m in Fig. 2, and the total weight is about 2.8ton. Two-box structure is adopted for the station, and the motion-gimbal and some controllers are completely separated. Because of its compact characteristics with the centered weight-balance mechanism, the whole system can be collectively moved using a tow tractor.

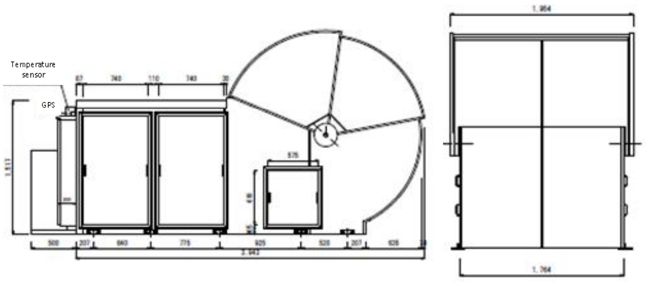

Fig. 2. The dimension of the developed ground station.

The communication range, moreover, of the system can be guaranteed for the 360degrees azimuth-rotation of the gimbals on the horizontal plane with the condition for the elevation-angle range of more than 20degrees in Fig. 3. Then, the deploying roof opens and shuts automatically, and it can be controlled by remote manipulation.

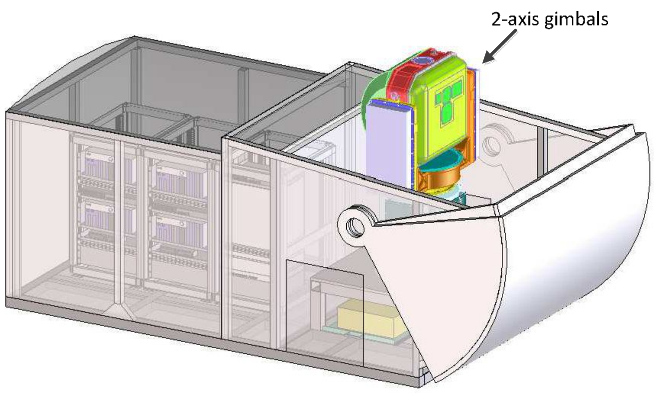

Fig.3 Configuration of the ground station apparatus.

III. THE OPTICAL SENSOR MODULE

A. Configuration of the Module

The optical module is mainly composed of the wide range acquisition sensor (WAS), the optical coarse acquisition sensor (CAS), the optical fine pointing sensor (FPS), the adaptive-optics function involved the wavefront correction sensor (WCS) and the deformable mirror, and the fine pointing mechanism (FPM). The transmission optical system is separated with the reception optical system, and the EO camera is combined with WAS for the target acquisition.

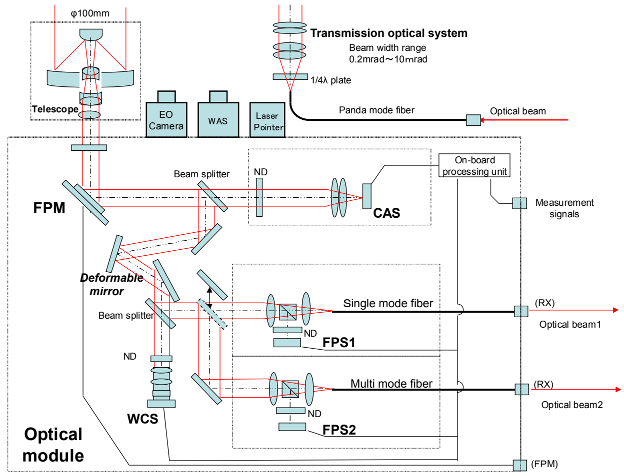

Fig. 4 Block diagram of the optical module.

A CMOS image-sensor based on InGaAs is commonly applied to WAS, CAS, FPS, and WCS. Fig.5 shows the overview and the dimension of its CMOS sensor, and Table 1 shows the specifications of it. The acquisition ranges for WAS and CAS are each tuned by the telescope magnification, and the accuracy of CAS and FPS is determined by the focus distance. Two FPSs are mounted on the optical module, each for the single-mode fiber and multi-mode fiber. Then, the tracking error angle can be obtained by the calculations of the center position of the optical intensity on the CCD sensor for WAS, CAS, and FPS. The gimbals error-angle is measured by WAS and EO camera, and the FPM error-angle measured by CAS and FPS. On the other hand, the distribution of the optical intensity on it, for each segment of 8x8 pixels, is measured and the obtained data is utilized as the WCS's output signal, i.e., it is a Shack-Hartmann sensor. Fig. 6 shows the overview of the optical module, and Fig. 7 shows the dimension of it. The total weight of the module is 15.4kg.

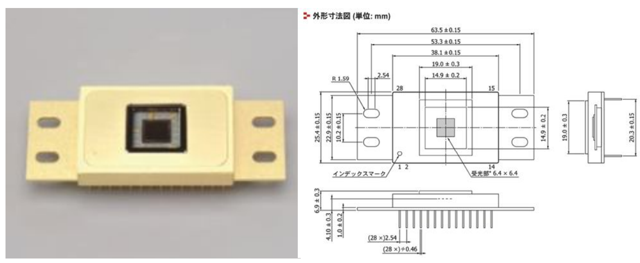

Fig. 5 Overview of the customized CMOS image-sensor.

TABLE 1 Specifications of the CMOS Sensor.

Descriptions	Specifications
Resolution	64 x 64 pixels
Pixel Pitch	50 μ m
Frame Rate	16kHz

Fig. 6 Overview of the optical module.

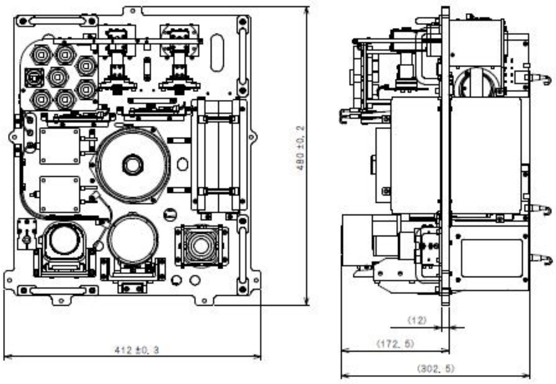

Fig. 7 Size of the optical module.

B. The Adaptive- Optics Functon

The AO function is composed of the WCS and the deformable mirror mounted on the optical module. The WCS is based on a Shack-Hartmann wavefront sensor, and the CMOS sensor in Fig. 5 is commonly applied for the WAS, the CAS, the FPS, and the WCS. The sensor's frame rate is 16kHz in Table 1. Because a genetic algorithm is implemented for the searching method of the wavefront condition in the AO function, the shape of the deformable mirror is adjusted to the derived solutions for the obtained data by WCS. The function of the AO can be synchronized with the motion control of the FPM and gimbal by the unified controller.

IV. "DUAL" 2-AXIS GIMBALS SYSTEM

To achieve the agile and precise control-performance, the dual 2-axis mechanism is adopted on the tracking-gimbal system for the motion target. The "dual" means the double structure of the orthogonal 2-axis (for example, azimuth and elevation axis) mechanism, and it comprises the inner 2-axis gimbals and the outer 2-axis gimbals. Then, the outer-gimbal is the role of the coarse pointing for the wide motion-range, and the inner-gimbal the fine pointing for the narrow motion-range. Fig. 8 shows the overview of the "dual" 2-axis gimbal, and Fig. 9 shows the drawing of it. The whole weight

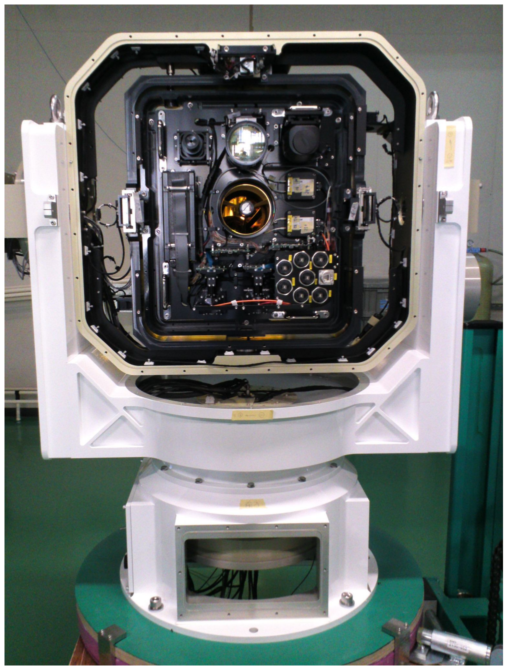

Fig. 8 Overview of the "dual" 2-axis gimbal.

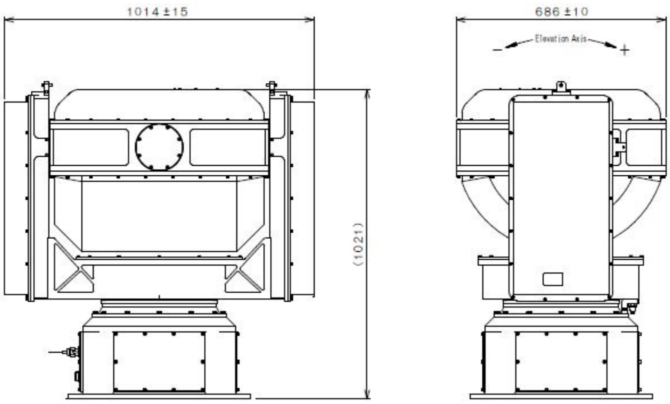

Fig. 9 Size of the 2-axis gimbals.

of the gimbals is about 255.2kg. The inertia around the azimuth axis is deferent for the elevation angle/the direction of the optical module and the typical vales is shown in Fig. 10.

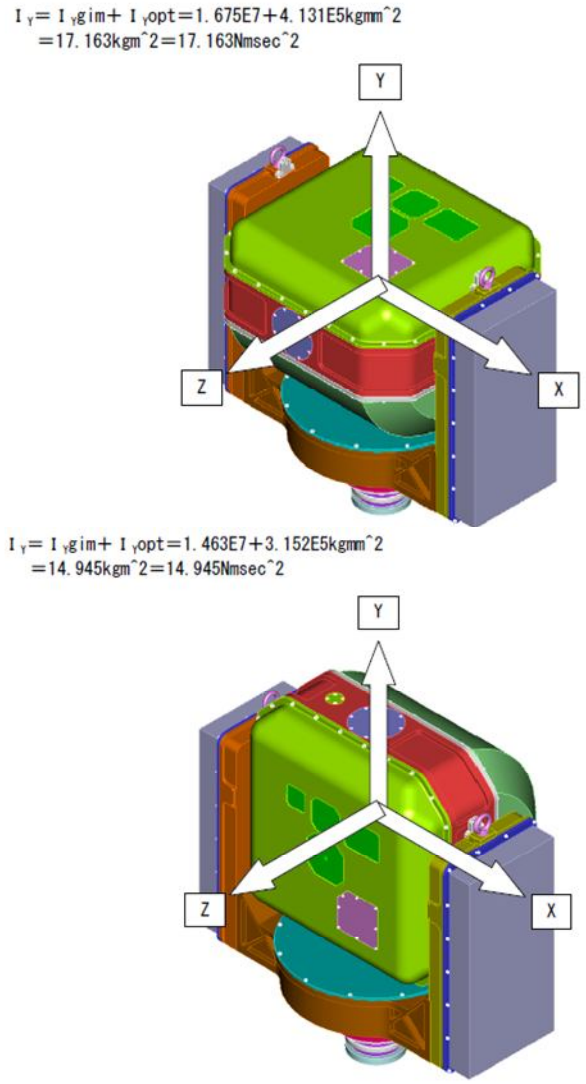

Fig. 10 Typical inertia condition around the azimuth axis.

V. UNIFIED CONTROLLER FOR THE SYSTEM

The system performance can be determined by the optimizations between the lower level controller, to achieve the tracking accuracy by using the 2-axis gimbals and FPM, and the upper level controller, to manage the control-mode of the gimbals, FPM, and the optical sensors. In the lower level controller, the 2-axis gimbals and the FPM are interactively controlled by measurement signals based on WAS, CAS, FPS, and WCS. To improve the control performance, especially for some disturbances, the synchronized tracking-control method between the gimbals and the FPM is introduced in the controller. In the upper level controller, on the other hand, some control modes for the gimbals and FPM are defined by the optical sensors.

A. Lower Level Control Scheme

Fig. 11 shows the lower level control scheme on the system. In Fig. 11, “Gimbal Controller” is the motion controller for the 2-axis gimbals, “FPM Controller” is for the FPM, and “Cooperative/Predictive Controller” is the cooperative controller for the Gimbals and FPM [2]. The tracking motion by the Gimbals and FPM is interfered between them because of the kinematic redundancy, and each motion induces the disturbance torques. “Cooperative/Predictive Controller” can be generated the control commands for the kinematic and dynamic couplings. The WAS, CAS, FPS, and WCS are included in “Optical Sensors”.

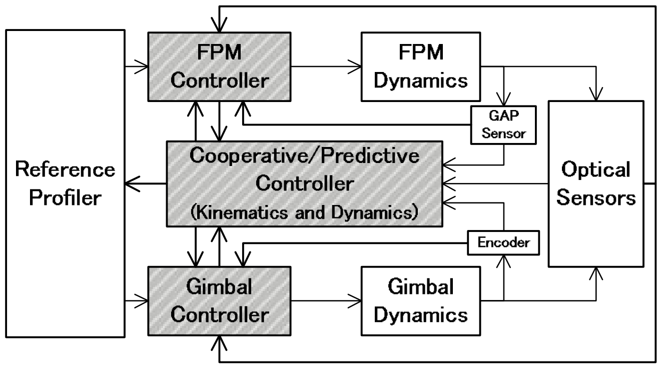

Fig. 11 Lower level control scheme.

B. Upper Level Control Scheme

Figs. 12 and 13 are each shown the upper level control scheme for the 2-axis gimbals and FPM. In this control system,

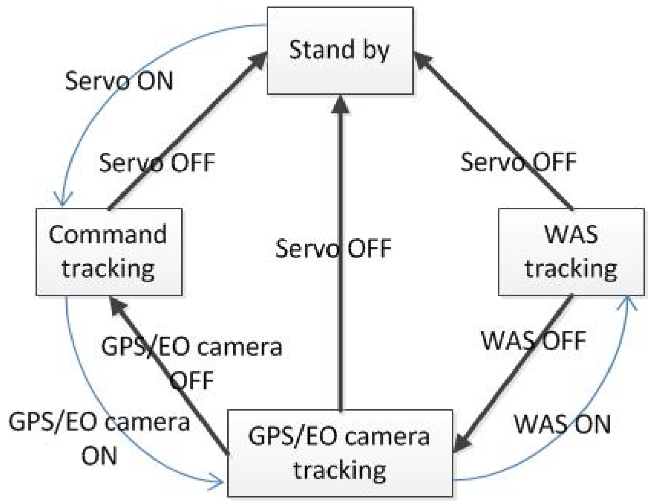

Fig. 12 Upper level control scheme for the gimbals.

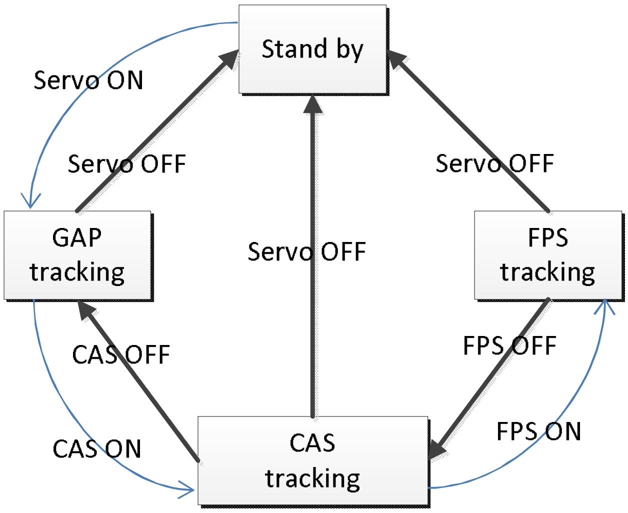

Fig. 13 Upper level control scheme for FPM

the unified scheme is adopted, and the simple management based on the optical sensor conditions can be applied for the control modes. For the gimbals, in Fig. 11, the control mode is chosen by EO camera data and the measured signals of WAS. And for FPM, in Fig. 12, it is chosen by the measurement signals of CAS and FPS. In the developed tracking-system, the simplified upper level controller makes the remote control using the local network possible because of the easy manipulation for appropriate information.

VI. Conclusion

For the advanced testbed "INNOVA", the compact ground-tracking system has been developed. The system consists of the optical sensors, WAS, CAS, FPS, and WCS, two-stage actuators, 2-axis gimbals and FPM, and the high-performance controller. This system can be achieved the free-space optical communication with equipped 40Gbps digital coherent optical transponder / 10Gbps IMDD optical transponder because the high-performance optical sensors and actuators are introduced in the compact structure with their controller.

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