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ABSTRACT

EyePod is a compact survey and inspection day/night imaging sensor suite for small unmanned aircraft systems (UAS). EyePod generates georeferenced image products in real-time from visible near infrared (VNIR) and long wave infrared (LWIR) imaging sensors and was developed under the ONR funded FEATHAR (Fusion, Exploitation, Algorithms, and Targeting for High-Altitude Reconnaissance) program. FEATHAR is being directed and executed by the Naval Research Laboratory (NRL) in conjunction with the Space Dynamics Laboratory (SDL) and FEATHAR's goal is to develop and test new tactical sensor systems specifically designed for small manned and unmanned platforms (payload weight < 50 lbs). The EyePod suite consists of two VNIR/LWIR (day/night) gimbaled sensors that, combined, provide broad area survey and focused inspection capabilities. Each EyePod sensor pairs an HD visible EO sensor with a LWIR bolometric imager providing precision geo-referenced and fully digital EO/IR NITFS output imagery. The LWIR sensor is mounted to a patent-pending jitter-reduction stage to correct for the high-frequency motion typically found on small aircraft and unmanned systems. Details will be presented on both the wide-area and inspection EyePod sensor systems, their modes of operation, and results from recent flight demonstrations.

Keywords: EyePod, NITF, Geo-aware, Georegistered, Georeferenced, UAV, UAS, EO/IR, LWIR, Uncooled; Infrared imaging

1. INTRODUCTION

The EyePod electro-optic/infrared (EO/IR) sensor systems were developed jointly by the Naval Research Laboratory (NRL) and Space Dynamics Laboratory (SDL) under the DUSTER[1,2] (Deployable Unmanned Aerial Vehicle (UAV) System for Targeting, Exploitation, and Reconnaissance) and FEATHAR[3,4] (Fusion, Exploitation, Algorithms, and Targeting for High-Altitude Reconnaissance) programs. Both of these programs were targeted to develop and demonstrate intelligent, cooperative geo-aware sensors. Geo-aware search sensors were developed under these programs to provide a capability to autonomously nominate potential targets and forward their coordinates to geo-aware inspection sensors. The inspection sensors automatically collect georeferenced high resolution digital imagery of each nomination. One of the specific program goals for both DUSTER and FEATHAR was to develop intelligent (onboard processing) day/night imaging sensors that meet the SWAP (size, weight and power) requirements for a Class III UAS: <10inch ball gimbal, <1ft^3 volume and <50lb weight. The EyePod sensor system described here is the EO/IR payload developed to meet these diverse requirements.

EyePod is a dual camera ball gimbal system consisting of a precision jitter–stabilized long-wave infrared (LWIR) sensor coupled with a bore–sighted high–resolution visible-to-near infrared (VNIR) sensor. The EyePod optical design provides for precision pointing and step–stare capabilities, enabling EyePod to conduct both wide-area survey and high resolution inspection missions. In addition, EyePod contains an embedded sensor control and retasking capability that enables the sensor to prioritize lat/lon based proposed targets and reports the resulting images in standard NITFS format frames. Below, the EyePod sensor system and development is described in detail, followed by a discussion of recent flight test results and future plans.

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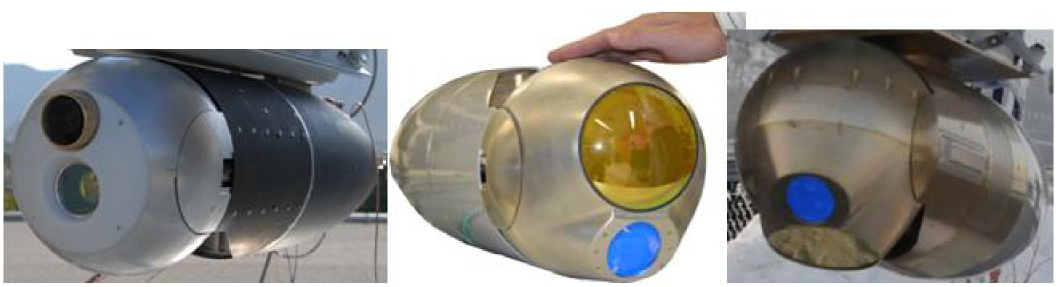
2. EYEPOD SENSOR SYSTEMS

The EyePod sensor systems are designed for deployment aboard a UAS, although recent flight test activities have been focused on manned aircraft testing as shown in Figure 1. To date, three EyePod sensors have been constructed and tested (as shown in Figure 2): Phase I consisted of a wide field of view (WFOV) (survey) sensor system, Phase II consisted of a dual focal length LWIR camera paired with a NFOV VNIR sensor, while Phase III consists of a narrow field of view (NFOV) (inspection) sensor system. For all three EyePod phases, the VNIR camera used was a standard high definition (HD) format sensor while the LWIR camera utilized a microbolometer array sensor coupled to a custom jitter-stabilization stage. These two cameras were then integrated into 9" diameter custom ball-gimbal systems while the associated control, data storage, datalink, and navigation systems were integrated into the trailing pod fairing.

Figure 1. EyePod installed on the SDL Skymaster



Phase I Phase II Phase III

Figure 2. EyePod Phase I, II and III LWIR/VNIR 9" ball gimbal sensors

The custom designed EyePod target management system is based in input of lat/lon-based target locations that can come from any source. Target source modes currently in place and tested include pre-planned targets; targets arising from user input through the live sensor control interface; or targets arising automatically from other cross-cueing sensors such as the WFOV phase I EyePod, GMTI tracks, or other sources. The EyePod control system is also capable of other coverage modes, including an area survey ("vacuum cleaner") mode and a high-rate/low resolution staring mode. These and other modes are described in detail below.

Resulting NITFS formatted EyePod images and products are transmitted to the ground station via Ethernet-enabled data links in real-time. Standardizing in NITFS enables the downlinked products to be readily stored in a geo-coordinated database and then screened in NRL/SDL developed screening systems as will be described below..

2.1 EyePod Spiral Development

The EyePod spiral development effort currently includes three phases. The Phase I EyePod is a WFOV survey sensor that merges the common LWIR and VNIR camera systems with commercial off the shelf (COTS) LWIR and VNIR optics. For Phase II EyePod is a combined WFOV and NVOF sensor containing a LWIR sensor with custom dual focal length optics and a NFOV VNIR sensor. Lessons learned from the first two phases were then implemented into the Phase III system design with custom NFOV LWIR and VNIR optics paired with the same camera architecture used in the prior phase; Phase III also includes a significantly improved ball-gimbal drive and control system. LWIR microbolometer jitter stabilization techniques, onboard integrated electronics, and embedded controls have been developed and tested throughout all phases of the EyePod development. The SWAP characteristics for these three systems are listed in Table 1; while Table 2 lists the key specifications for the three phases of the EyePod system.

Table 1. EyePod SWAP specifications

	EyePod Wide FOV (Phase I)	**EyePod Dual FOV (Phase II)**	**EyePod Narrow FOV (Phase III)**
Size (Diameter x Length)	9" x 24" (≈1ft^3)		
Weight	30 lb (EyePod harmonic drvie, C-migits, GPS mounting plate)	35 lb (EyePod harmonic drive, C-migits, GPS mounting plate)	40 lb (EyePod direct drive, IGS-200)
Operating Power	75W		200W RMS

Table 2. EyePod key specifications

	EyePod Wide FOV (Phase I)		**EyePod Dual FOV (Phase II)**			**EyePod Narrow FOV (Phase III)**	
Sensor Technology	Microbolometer	CMOS	Microbolometer Narrow	Wide	CMOS	Microbolometer	CMOS
	LWIR	VNIR	LWIR		VNIR	LWIR	VNIR
Spectral Band [µm]	7-14	0.510-0.84	7.6-10	10.7-12	0.510-0.84	7-14	0.510-0.84
Resolution	320x240 upsampled to 640x480	1920x1080	320x240 upsampled to 640x480		1920x1080	320x240 upsampled to 640x480	1920x1080
Pixel Size [µm]	28	5	28		5	28	5
Sensitivity	65mK (F1)	read noise <20e-	65mK (F1)			65mK (F1)	read noise <20e-
Optics	COTS Optics (interchangeable)		Compact Dual FOV Catadioptric		Ritchey-Cretien	Ritchey-Cretien	Ritchey-Cretien
Focal Length	50mm	50mm	256mm	42.5mm	146.0mm	139.2mm	146.0mm
Fnum	1	2.8-22	2.6	1.0	3.5	1.24	3.48
FOV	7.7°x10.2°	6.2°x11°	2.0°x1.5°	9°x12°	2.1°x3.8°	2.8°x3.7°	2.1°x3.8°
GSD @ 5000ft (nadir)	0.9m	15.2cm	16.7cm	1.0m	5.2cm	0.3m	5.2cm
Pointing							
Motor/Gimbal Drive	Brush DC/harmonic drive gear with belt (El) and linkage (Az)		Brush DC/harmonic drive gear with belt (El) and linkage (Az)			Brushless DC/direct drive	
Roll	±90°						
Pitch	+90°/-45°						
Geolocation	<20m CEP (embedded GPS/INS)					<10m CEP (embedded GPS/INS)	
Re-Pointing Rate	3-4Hz						

2.1.1 Phase I

The Phase I EyePod, shown in Figure 3, was designed as an inertially-stabilized step-stare gimbal system. It fits within a 9-inch ball and can be mounted under the wing of UAS or a variety of manned aircraft. The task for Phase I EyePod was to develop a WFOV VNIR/LWIR system based on COTS optics. This goal was set to enable the development focus to be on the jitter stabilization stage for the LWIR camera and on the initial development of the target management system. The optical system was designed for easy replacement of the COTS optics, by incorporating standard threaded lens mounts. As with all later systems, the Phase I EyePod fairing was designed to contain the electronics stack as well as the GPS/INS system.

The Phase I EyePod system consists of three major subassemblies: 1) a 9-inch ball housing the VNIR and LWIR cameras and the LWIR jitter stabilization stage, 2) a two-axis gimbal with azimuth and elevation drives, and 3) a pod fairing that houses the associated electronics. The mechanical design of the Phase I EyePod is shown in Figure 3. The Phase I EyePod uses a brush DC motor and harmonic drive gear with belt (El) and linkage (Az) power transmission to maintain low weight and power. An internally mounted Systron Donner Inertial MMQ-G GPS/INS was used for the inertial pointing system. An external mounted Systron Donner Inertial C-MIGITS GPS/INS was also tested as part of the Phase I development.

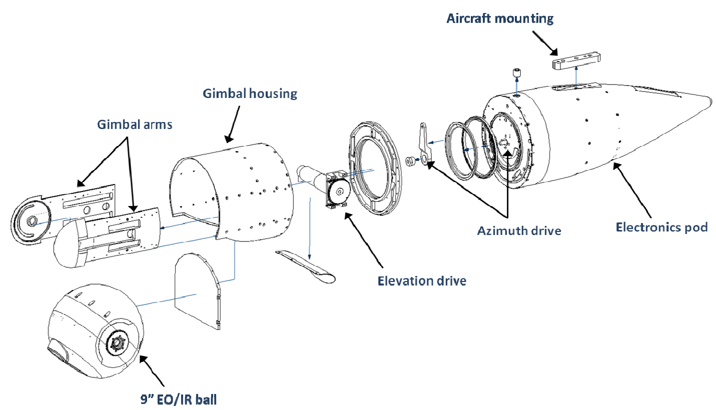


Figure 3. EyePod Phase I and II mechanical design

The VNIR detector array used in the EyePod sensor is a Teledyne Imaging Systems (TIS) UAV-Cam V2M camera having a 1936 (H) x 1086 (V) focal plane array (FPA) with 5µm pixels. The UAV-Cam is a CMOS camera in a compact package with low noise and low power. The LWIR detector array is a BAE MIM-500H focal plane array packaged with a camera link output board by Harsh Environmental Applied Technologies. The MIM-500H contains a 320x240 uncooled VOx microbolometer array that is upsampled to a 640x480 prior to being provided across the cameralink interface. The microbolometer array was chosen to enable operation without requiring the additional SWAP that come with typical LWIR cooler assemblies. The concern with use of microbolometer arrays in high-vibration environments (such as small UAVs) is their need for long integration times. To counter this issue, the LWIR FPA is mounted to a custom jitter stabilization stage.

Phase I provided a test bed for the image (jitter) stabilization, inertial pointing, onboard processing, and embedded sensor management. Phase I testing of the pointing gimbal system showed a stiction (stick-slip friction) problem in the harmonic drive gearhead that reduced pointing accuracy, resulting in imperfect ground coverage and a reduced pointing rate.

2.1.2 Phase II

The Phase II EyePod has a similar design as the Phase I system with an improved harmonic drive gear, custom optics, updated electronic stack, and thermal management. The custom optics are compact LWIR dual-FOV optics[5] and NFOV VNIR optics. Figure 4 shows the EyePod Phase II optical and mechanical 9-inch ball design. The compact dual-FOV catadioptric optical system operates in the LWIR with a 6× field ratio capability. The design involves the selection of the field by changing optical filters that transmit differing spectral wavebands. Each spectral waveband is associated with separate optical paths with differing focal lengths, resulting in different fields of view. In addition to dual FOV capability, the design provides optical athermal performance, allowing temperature independent performance over a wide operating temperature range (-25 to +40°C). In Figure 4, the 2° field-of-view is shown (red rays) focused onto the microbolometer focal plane array (FPA). The all-refractive element telescope inside the envelope of the Cassegrain obstruction is aligned to the same FPA and generates a 12° FOV (blue rays).

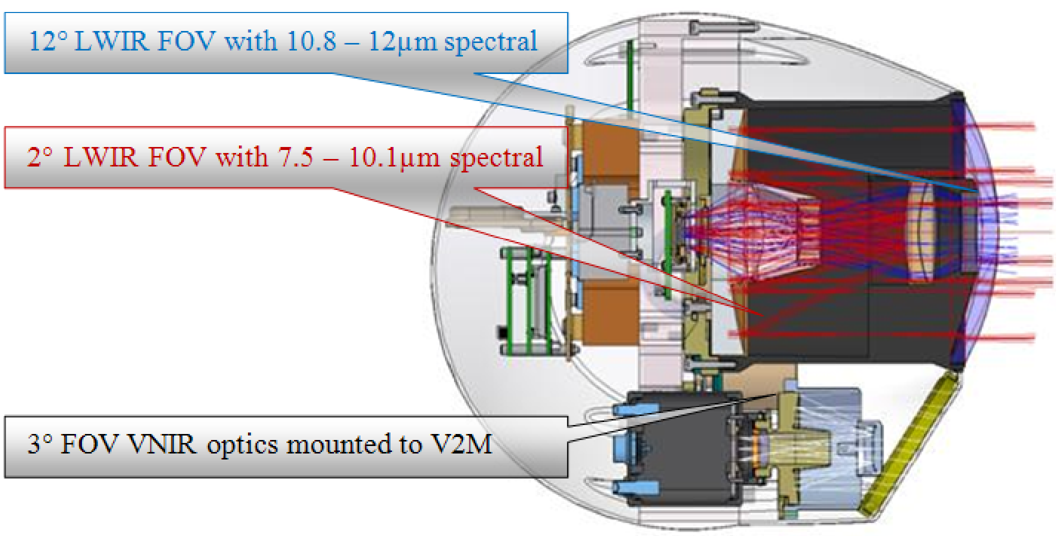


Figure 4. EyePod Phase II optical and mechanical 9-inch ball design

Initial testing of the Phase II EyePod again showed the harmonic drive gear stiction issue seen in Phase I. Testing also showed that the optical throughput was insufficient for the signal-to-noise ratio desired in moderate to low light conditions. The dual focal length design concept was successfully demonstrated, and an improved 2nd generation dual focal length LWIR optical design was completed; however, this design was not fabricated.

2.1.3 Phase III

Phase III EyePod includes an updated physical/mechanical design, custom NFOV LWIR and VNIR optics, brushless DC motors with direct drive gimbal control, updated electronics stack, and improved overall fairing thermal management. In addition, a Honeywell International/Rockwell Collins Integrated Guidance Systems IGS-200 GPS/INS was embedded in the EyePod fairing and was under direct embedded control. Figure 5 shows the mechanical design for the Phase III EyePod.

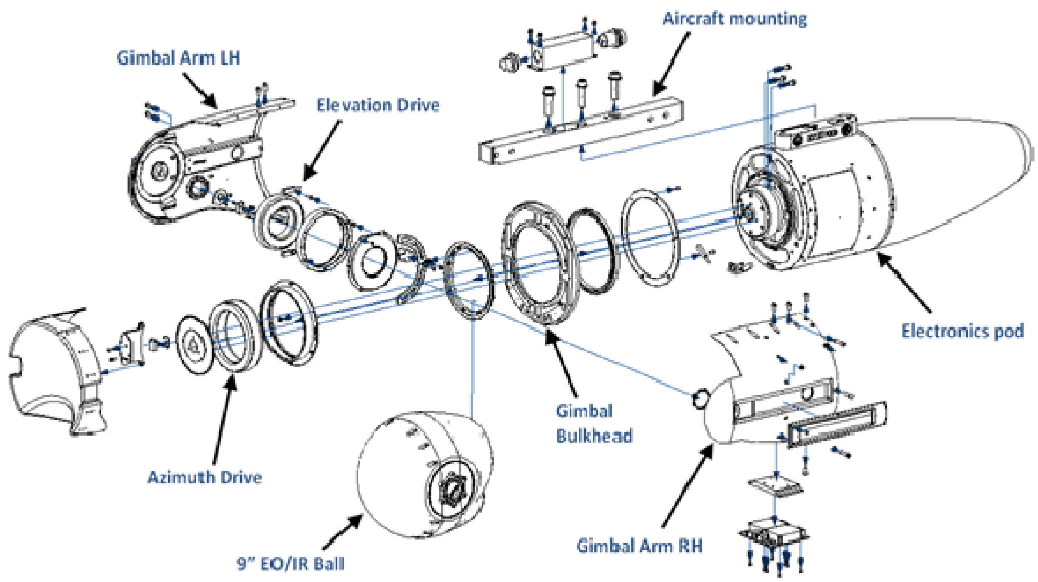


Figure 5. EyePod Phase III mechanical design

Driving requirements for the NFOV optics include a ground sample distance (GSD) of 30 cm LWIR and 5 cm VNIR ability to fit within a 9-inch ball, and low weight. Because no COTS optical solutions were identified, SDL designed and built the NFOV VNIR and NFOV LWIR optics. Experience from the first two phases indicated that the optics are required to have an F number near F/1, with optimum transmission. These criteria were incorporated into the Phase III LWIR optical design.

Figure 6 shows the raytraces for the Phase II/III NFOV VNIR and Phase III NFOV LWIR Ritchey-Cretien telescope designs, and Figure 7 shows the VNIR and LWIR NFOV optics mounted to the EyePod Phase III optical bench.

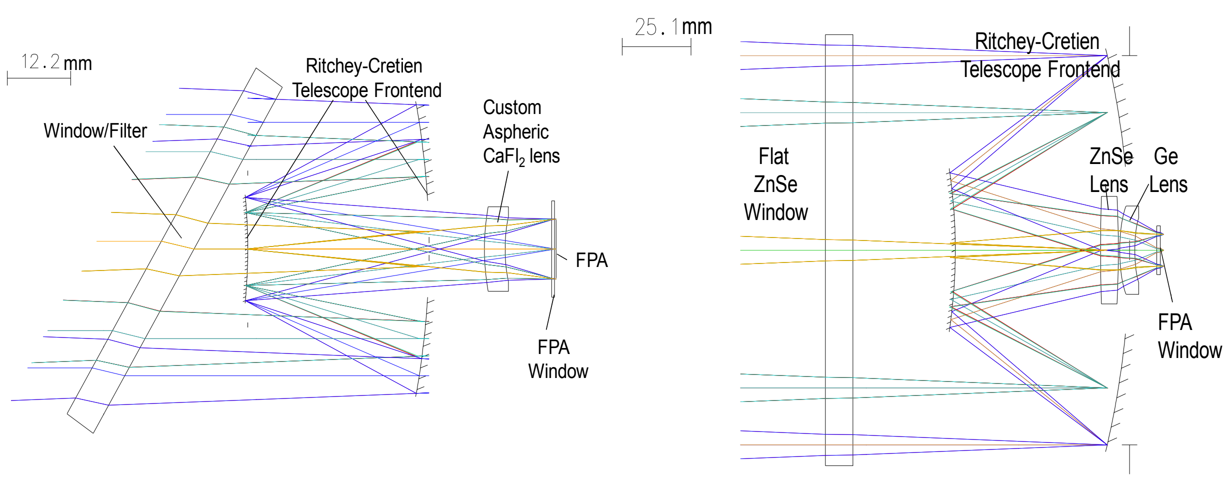


Figure 6. EyePod Phase II and III NFOV VNIR (left) and Phase III NFOV LWIR optical design (right) raytraces

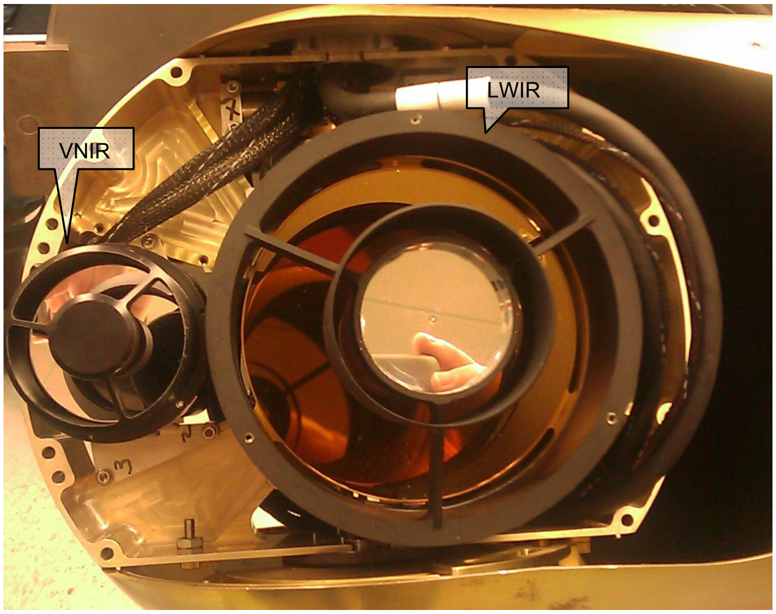


Figure 7. LWIR and VNIR NFOV optics mounted to EyePod Phase III optical bench

Fabrication of EyePod Phase III is complete and the system is currently being transitioned into the ONR Operational Adaptation exercises for flight testing against operational scenarios.

2.2 Control, Electronic, and Embedded Control Systems

LWIR microbolometer jitter stabilization techniques, onboard integrated electronics, and embedded controls have been developed and tested throughout all phases of the EyePod development. These systems are similar for each phase, with enhancements made as each phase was developed.

2.2.1 Control System Design

The EyePod control system consists of the hardware, software, and algorithms that maintain the boresight on target using feedback. This control system design contains two major parts: 1) the pointing control system (PCS) and 2) the image stabilization (IS) control system.

The PCS keeps the assigned lat/lon/alt target centered in the FOV during flight and attenuates gross aircraft disturbances by applying appropriate electric current to the gimbal direct-drive motors. These current commands are updated at a 200Hz rate based on feedback from the blending filter, which combines information from the GPS/INS, the optical encoders, and the angular rate sensors. Several navigation coordinate transformations are used in the real-time generation of setpoints for EyePod. A 3-axis rotational calibration offset (based on bundle adjustment) is embedded in the PCS, minimizing the effect of mechanical offsets in the EyePod system from manufacturing/assembly tolerances. A block diagram of the PCS is shown in Figure 8.

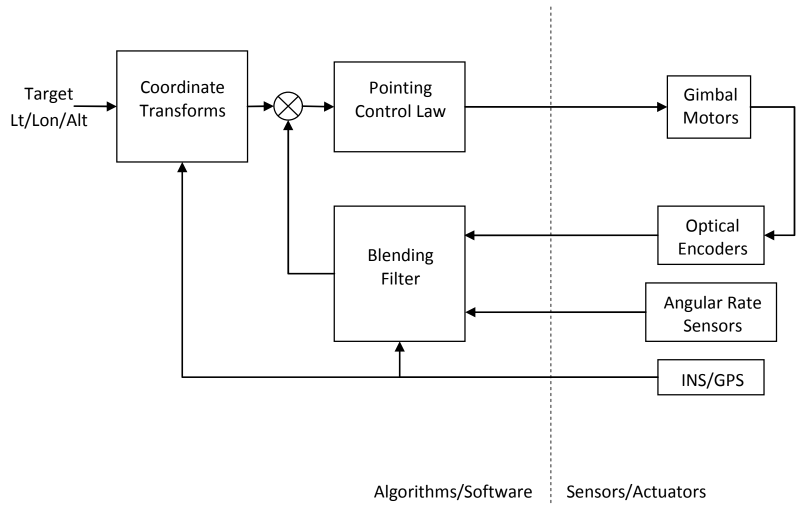


Figure 8. EyePod Pointing Control System (PCS)

Image smear due to boresight motion during integration is minimized by the patent-pending EyePod image stabilization (IS) control system. Boresight motion is attenuated to a sub-pixel level during the LWIR imager's integration time to keep incoming light energy from spreading to adjacent pixels. Image stabilization updates are generated at a much faster rate than the PCS loop rate (2.4 kHz), and are only enabled once the PCS has stabilized to an acceptable level. The custom 3-axis jitter reduction stage attenuates fine, high-frequency disturbances using feedback from the angular rate sensors in the ball portion of EyePod. Figure 9 shows a block diagram of the IS control system.

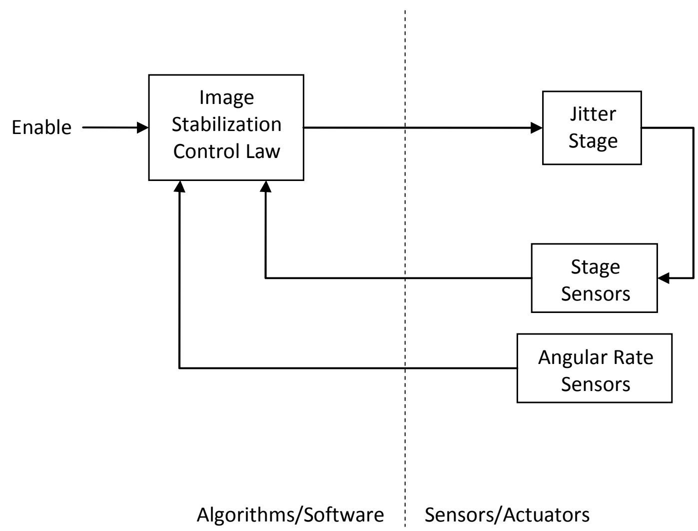


Figure 9. EyePod Image Stabilization Control System (IS)

During the Phase I test flight, this jitter system maintained better than 1/5 pixel accuracy during each 30-msec integration time. Figure 10 shows flight images that demonstrate this stabilization mechanism for sequential frames taken with the Phase I EyePod. The left image was taken with the jitter stabilization mechanism turned off, and the right image was taken with the mechanism turned on. Engineering data analysis showed better than 1/5 pixel stabilization which can be seen by the marked improvement in image quality.

Figure 10. EyePod jitter stabilization mechanism turned off (left) and turned on (right).

The PCS and IS control systems accomplish a pointing solution that is always lat/lon/alt based with the FPA pointing solution continually tracking ground intercept points. A lat/lon/alt-based system enables easy transfer of targets between EyePod and other sensors and also enables a simpler user interface for on-the-fly retasking. An external user simply needs to supply a new target lat/lon/alt or click on a point, or select an area in the real-time map display to command EyePod to collect against a new target. Target lat/lon/alt can also be entered in advance and stored in the onboard database.

2.2.2 Electronic Design

Figure 11 shows a top level EyePod electronics diagram. The system electronics are a combination of COTS electronics and custom electronics separated into three main categories: processor stack, gimbal control, and jitter stabilization. The integrated electronics consist of two custom PowerPC 405 CPU boards (image and control processors), along with field programmable gate array (FPGA), frame grabber, SSD and control electronics. Figure 12 shows the PC-104 sized processor stack including SSD data storage.

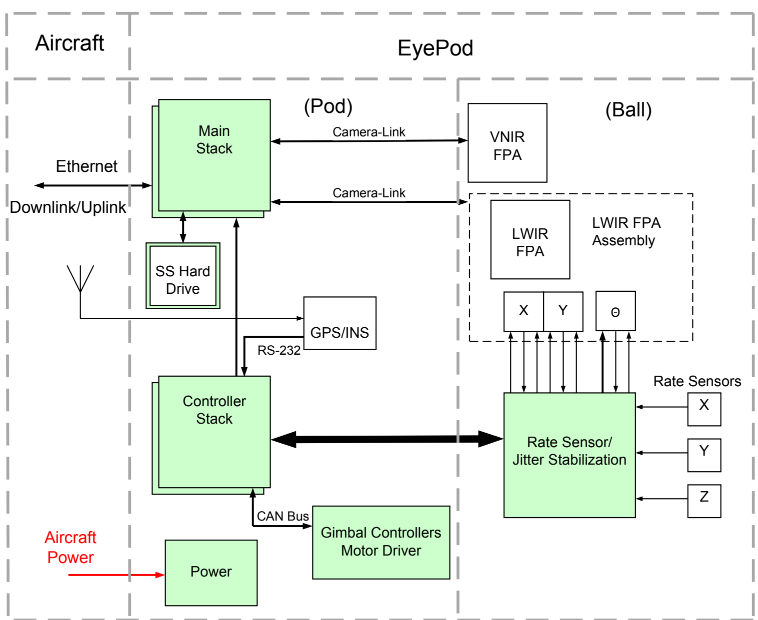


Figure 11. Top level EyePod electronics diagram

Figure 12. Processing stack including main stack, control stack, and SSD (4.55” x 3.775”x2”)

2.2.3 Embedded Sensor Management

One of the primary capabilities of the EyePod system is its high degree of embedded sensor and system management. The sensor autonomously ingests target cues (lat/lon/alt) from external sources and then decides how and when to best collect imagery consistent with the priorities, flight plans, and needs of the sensor system. This capability enables the system to manage the collection of imagery without continuous monitoring by a ground or airborne operator.

Figure 13 shows a top level diagram of the EyePod sensor management functions. The sensor can be controlled in two modes: 1) Ethernet connection via laptop and/or data link, and 2) autonomous mode using a stored mission plan. In non-autonomous mode (Mode 1), inputs and outputs are handled by network server processes. Inputs may be user-prompted and/or cooperative sensor target coordinates, or live direct control via mouse-tracking over the FEATHAR developed “Blackjack” screener maps database. Positional, status, and low resolution images are broadcast.

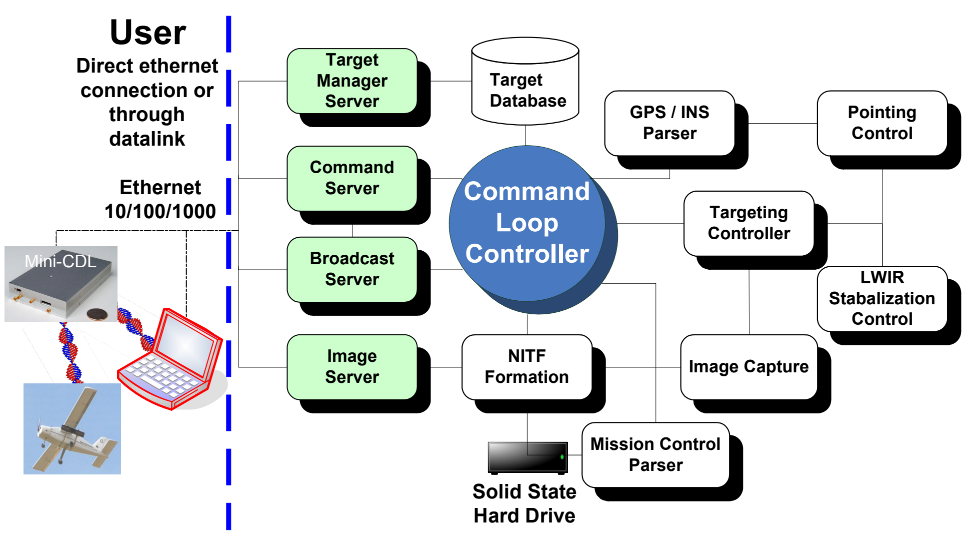


Figure 13. Embedded sensor management top level diagram

A successful demonstration of this second mode of operation was performed during test flights when an operator on the ground sent real-time targets from the Blackjack screener maps over a data link. EyePod returned live, NITF-tagged imagery of the selected target. The resulting imagery was overlaid in real-time on the Blackjack screener map.

EyePod uses a command loop controller to manage all sensor systems and functions. These functions include imagery collection, maintenance of an onboard SQL image and target database, and the air-ground data link. For imagery collection, the controller builds the prioritized target cue and area list and then tasks the sensor to collect the needed imagery. Collection is performed when allowed by the flight parameters and the target location based on an assigned priority value. Priority values are calculated using several parameters:

- User or sensor assigned priority of 0-9 for each target
- Best acquired slant angle of image
- Number of times the target has already been imaged
- The time of day when the target was last imaged (age of prior images)
- Heading of plane during past images (aircraft orientation)
- Altitude of plane during past images

All collected imagery is stored onboard and is accessible via a database. The database also stores all past and future target cues and areas. For the air to ground data link, an active throughput manager coordinates the priority of images to be downlinked to avoid large latencies. The command loop controller coordinates command and control communication with operators to include promotion of new target cues.

EyePod supports both on-demand and autonomous (pre-planned) mission capabilities. It operates under step-stare pointing driven by geocoordinate inputs. These inputs may be preplanned target lat/lon/alt coordinates from the database, user-prompted and/or cooperative sensor target lat/lon/alt coordinates sent to the database, or live direct control inputs via mouse-tracking over a maps database (e.g., single point lat/lon, area boundary lat/lon, road (shape file) lat/lon). If the target location is passed as lat/lon without altitude, then EyePod uses a Digital Terrain Elevation Data (DTED) database to assign an altitude to the target. The sensor is also capable of other coverage modes, including an area sweep ("vacuum cleaner") mode. Figure 14 shows an EyePod Phase III VNIR area boundary collection using an area selected on the Blackjack screener Earthview. This image shows the power of EyePod to collect detailed georeferenced digital imagery of large areas (280 m x 250 m region) with enough resolution to track people by a user of a ground based screener software.

Figure 14. EyePod Phase III VNIR 2x4 area boundary collection over Old Main building on the campus of Utah State University, Logan, Utah (280 m x 250 m region)

3. EYEPOD FLIGHT TEST RESULTS

The EyePod sensor systems spiral development cycle began with the development and test of the Phase I survey (WFOV) sensor and was followed by the current Phase III inspection (NFOV) sensor. Figure 15 shows representative Phase I and Phase III VNIR and LWIR images of the Old Main building on the Utah State University campus. The Phase I data were collected on September 28, 2007, while the Phase III data were collected on January 20, 2010.

The Phase I VNIR images were collected with a 25mm focal length COTS lens and the LWIR images with a 50mm focal length COTS lens. The Phase I VNIR and LWIR images were collected during the same flight path but at different aspect angles whereas the Phase III were taken consecutively. Note the different slant ranges and scene temperatures for the two phases. Phase I images were taken at noon with temperatures near 20°C while the Phase III images were taken in the late afternoon with temperature near 1°C. People are readily discernible in both the Phase III VNIR and LWIR imagery.

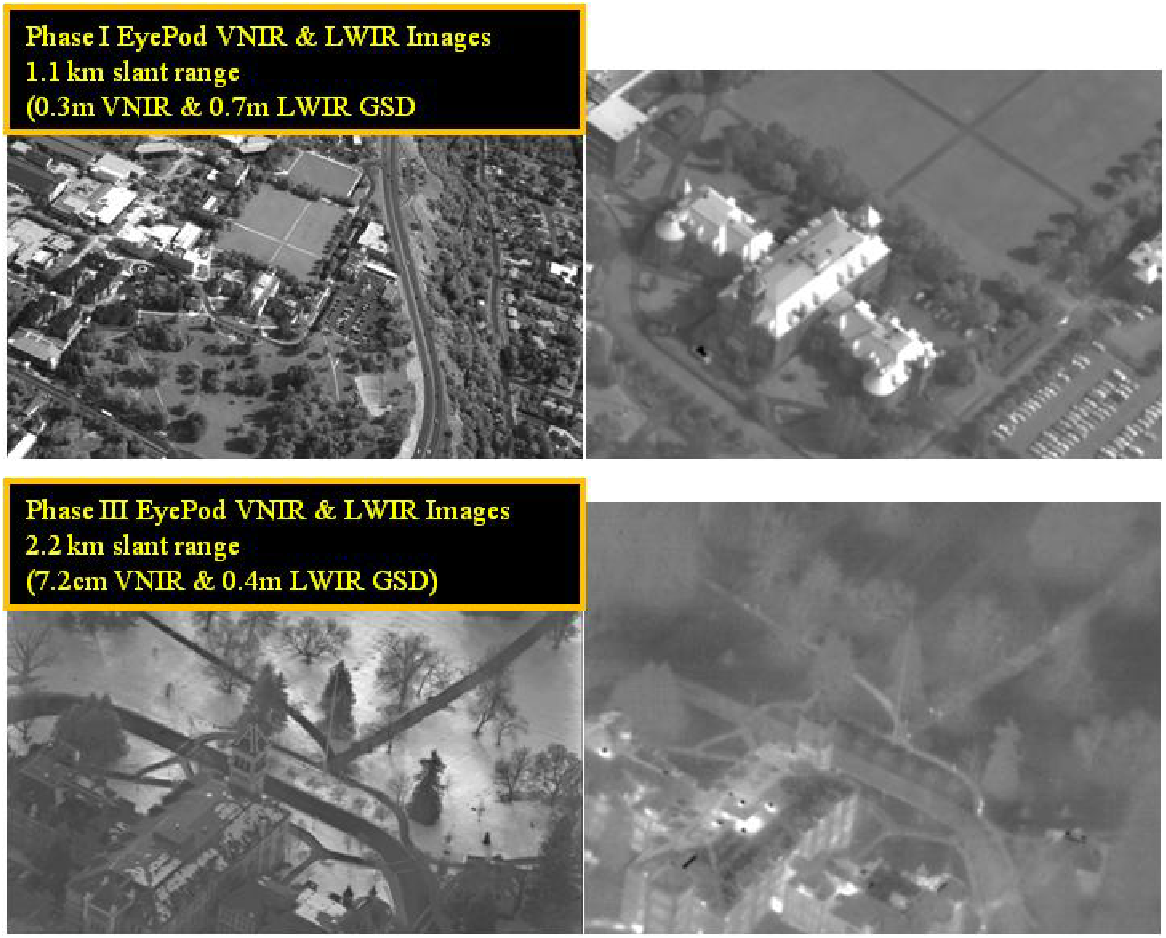


Figure 15. EyePod Phase I and Phase III VNIR and LIWR image of USU Old Main

4. FUTURE WORK

The EyePod spiral development has resulted in an intelligent geo-aware EO/IR sensor system for small (<50 lb payload) manned and unmanned platforms. EyePod Phase III is currently being used in conjunction with synthetic aperture radar SAR sensors such as NuSAR and with other sensors to further develop and achieve the FEATHAR program goals.

The following demonstrations of the EyePod EO/IR sensor system and FEATHAR program are currently planned:

- February 2010 – ONR Operational Adaptation. This was a coordinated, multi-sensor, red-force/blue-force event. The Phase III EyePod EO/IR sensor system wsa demonstrated in a mode where it was cued by other participant sensors as well as by airborne operators and through pre-planned target sets.
- May 2010 – Multi-INT Demonstration. This demonstration will include SIGINT-to-EyePod and HSI-to-EyePod cueing.
- June/July 2010 – ONR Operational Adaptation. This will be a follow-on to the February 2010 demonstration.

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