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The Oculus: A Nanosatellite for Space Situational Awareness

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ABSTRACT

As a part of the Air Force's University Nanosatellite Program, Michigan Technological University (Michigan Tech) has designed and built a nanosatellite for Space Situational Awareness (SSA) research. The Oculus has the capability to visually detect and monitor resident space objects (RSOs) using space-to-space imagers as well as the ability to perform known attitude maneuvers while flying over U.S. observatories in order to anchor models and algorithms used to determine spacecraft attitude from unresolved ground imagery. Over 150 students at Michigan Tech have designed and built the Oculus, a three-axis-controlled nanosatellite equipped with two visible imagers, releasable free-flying imaging targets, and a sophisticated computing and image processing system.

INTRODUCTION

In January of 2007, the worst space debris event in history occurred with China's deliberate anti-satellite (ASAT) test on the Fengyun-1C satellite [1]. This demonstration of military technology resulted in an additional 2,337 pieces of debris to be tracked by the North American Aerospace Defense Command (NORAD) and an estimated 150,000 pieces larger than 1cm [1] in orbital altitudes from 200-4000km. Even such small space junk particles can damage important space assets; in order to secure the safe operation of U.S. space assets, it is necessary to have accurate models tracking all orbiting objects. Knowledge of debris and vehicle trajectories is vital to continuously provide collision avoidance. Improving our nation's capabilities to catalogue and track orbiting objects falls under a current government initiative called Space Situational Awareness (SSA).

"Space Situational Awareness means knowing the location of every object orbiting the Earth, active or inactive, big or small; and knowing why it is there, what it is doing now, and what we think it will be doing in the future" [2]. SSA has become a matter of increasing importance as access to space has become easier. The U.S. has significant military and commercial assets in space that must be protected from impact with space debris or other objects.

Whether for GPS, global communications, or reconnaissance, satellite-based technologies have become vital to both the U.S. economy and national security. The predictability of the orbits of these assets puts them at an ever-increasing vulnerability to attack by hostile nations or terrorists, especially as access to space becomes available to additional countries and groups. For the future of the U.S. space force it is imperative to (1) protect U.S.-flagged spacecraft from hostile disruption as well as (2) have an accurate knowledge of our adversaries' space capabilities. There are two main avenues for the U.S. to reduce risk for space assets through SSA [2]:

1) Identify and monitor hazards

2) Increase the robustness of the U.S. space force

The United States' primary means of identifying and monitoring hazards in space is ground-based. With the onset of the space age, the U.S. realized its need for the ability to identify and track objects in space and thus created the Navy Space Surveillance System (NavSpaSur) [3]. This program involved the construction and operation of radar systems across the U.S. to create what became known as the "space fence." This system differed from normal radar systems because of its ability to detect previously unknown objects instead of beaming radar directly at known objects [3]. This allowed the U.S. to track and create a catalogue of space objects, using computers that calculated predictive orbital models. In 2004, the Navy relinquished control of NavSpaSur to the Air Force and the system is planned to be upgraded by Raytheon to S-band frequencies, allowing them to detect smaller objects [3]. Now known as the Air Force Space Surveillance System S-band Radar Program, the "space fence" is still being employed at sites from Georgia to California for space situational awareness through the acquisition and tracking of space objects [4]. This information is collected and sent to a central facility for processing; the end result is a catalogue with thousands of space objects [4]. The current space fence using very high frequencies is operating on old, obsolete technology, however, and the upgrade to S-band radar is a necessity for continued SSA. Radar technology is well suited for objects in low Earth orbits (LEO), but space objects in higher orbits are more easily detected with optical telescopes due to the fact that they are normally solar illuminated. The Defense Advanced Research Projects Agency (DARPA) is currently working on new optical telescopes with wide field-of-views to scan and search for objects in middle Earth orbits (MEO) and geosynchronous Earth orbits (GEO) [2].

While an array of optical telescopes would provide improved SSA abilities, the type of large-aperture imaging telescopes required to optically resolve LEO objects are very expensive and the few telescopes in the U.S. are insufficient in number and location to monitor all objects of interest. Alternatively, the Air Force Research Laboratory (AFRL) has been investigating the use of a network of smaller telescopes capable of precise photometric and spectral measurements of satellites to accurately track their orbits [5]. The technology for these telescopes, known as "RAVEN," [5], would allow for apertures around 30 centimeters in diameter, resulting in a less expensive system that would require minimal support personnel. These systems would, however, necessitate a method for determining the satellite's shape and function from the resulting photometric and spectral measurements taken because the aperture size is insufficient to obtain resolved images of spacecraft. In order to properly calibrate the algorithms being developed for the RAVEN telescope, an absolute knowledge of the shape, surface materials, and orientation of the satellite observed must be known. This level of detail is rarely available, but it is believed that once this technology is developed, a widespread network of simple sensors can be employed for SSA.

While ground-based telescopes can provide valuable SSA data, there are situations in which the best awareness will only be possible by viewing resident space objects (RSOs) from other space-based platforms. A fleet of satellites capable of imaging nearby space debris and other vehicles would provide the space-based system needed to compliment a network of ground-based observatories. To provide sufficient response and coverage, it is important that these satellites are inexpensive to allow for an adequate number of them to be distributed in orbit around Earth. Therefore, a smaller platform, such as a nanosatellite, that has space-to-space imaging capabilities is ideal for this application. A key feature of these satellites would be precision 3-axis attitude control, which would allow the satellite to track an RSO and provide multiple images of it. These satellites would be able to image passing satellites as well as have the capability to monitor objects to provide images for longer periods of time. A system of inexpensive and responsive satellites capable of imaging and monitoring resident space objects would greatly improve SSA by filling the gaps in coverage experienced by telescopes on the ground.

The University Nanosatellite Program

The University Nanosatellite Program is a competition hosted by the Air Force Research Laboratory's Space Vehicles Directorate (AFRL/RVSV). The program receives sponsorship and funding from the Air Force Office of Scientific Research (AFOSR) and the American Institute for Aeronautics and Astronautics (AIAA). The stated goals of the University Nanosatellite Program are to, "educate and train the future workforce through a national student satellite design and fabrication competition and to enable small satellite research and development (R&D), payload development, integration and flight test." [6] This is accomplished by hosting a 2-year competition during which teams from universities are given $110,000 with which to design and build their own nanosatellite. The winner of the competition is determined by a panel of judges from industries and government agencies working in the field of small satellites, and the winning team is provided a launch opportunity for their vehicle [6].

Each team is made up of students, mostly undergraduates, and is assisted by a faculty advisor. Students are responsible for all aspects of the program including project management, systems engineering, risk management, and obtaining additional sponsorship and funding. Students also perform the vast majority of the work on the vehicle – from initial concept sketches through system-wide integration and testing.

Throughout the two-year time period, the AFRL hosts numerous opportunities for students to receive feedback on their project as well as learn more about the intricacies of payload design and fabrication. Six reviews are held during the competition and are targeted towards making sure the students are properly carrying out their project and following the correct development procedures. The AFRL also sponsors two Student Hands-On Training (SHOT) workshops. During the SHOT workshops, students build a small payload which is launched via weather balloon. The University Nanosatellite Program also features Expert Area Teleconferences. These lectures are focused on essential areas of satellite design and are delivered by AFRL employees or faculty from the participating universities who specialize in a particular area of spacecraft development.

The Flight Competition Review (FCR) is the final review of the competition, and it is during this review that a panel of judges selects the winner of the competition based on the criteria of educational outreach, student involvement, technical relevance, flyability, probability of mission success, and program management [6]. The winner of the competition then enters a rapid integration and testing phase which involves integration with the Lightband separation device as well as environmental testing. The goal is to have the winning nanosatellite prepared for launch as soon as possible after the competition's end. Once the integration and testing is complete, the AFRL works with the Department of Defense's Space Experiments Review Board (SERB) to arrange potential launch opportunities [6].

A SATELLITE FOR SSA

Michigan Technological University's (Michigan Tech's) entrant in the sixth University Nanosatellite Program competition, the Oculus, has been designed and constructed in order to further small satellite research and development supporting SSA. The mission for this vehicle is two-fold, encompassing near-field space-to-space imaging as well as serving as an imaging target for ground-based telescopes. The Oculus' imaging mission is to acquire, image, track, and monitor resident space objects. As an imaging target, the Oculus will seek to aid in the calibration of ground-based telescopes by providing a vehicle of well-known physical characteristics that is able to significantly alter its shape while in orbit.

Space-To-Space Imaging

As an imaging satellite, the Oculus is outfitted with two cameras – referred to as a Narrow Field of View (NFOV) imager and a Wide Field of View (WFOV) imager. The WFOV imager is utilized for acquiring and imaging resident space objects (RSOs) near the vehicle while the NFOV imager has higher magnification and lower light sensitivity for tracking more distant and faint RSOs. The orientation of the imagers on the vehicle is shown in Figure 1.

The Oculus NFOV imager is the primary monitoring tool for space-to-space imaging. The NFOV imager operates in the visible band and is currently equipped with a 200-mm f/2.8 lens. The lens is a commercially available terrestrial photography lens that has been ruggedized for space. The ruggedization procedure consisted of fixing movable components, replacing the iris with a fixed aperture, locking the auto-focus to infinity, venting closed compartments between optic elements, and structurally reinforcing the device to withstand launch loads. The detector for the NFOV imager is an electron-multiplied charge coupled device camera (EMCCD) provided by Raytheon Missile Systems. The EMCCD detector was designed for ultra-low-light imaging applications and is based on the Princeton Instruments PhotonMAX 1024B having single-photon sensitivity with greater than 90% quantum efficiency and less than 1 electron RMS read noise. Detector attributes are shown in Table 1. A photograph of the ruggedized imager and lens is shown in Figure 2.

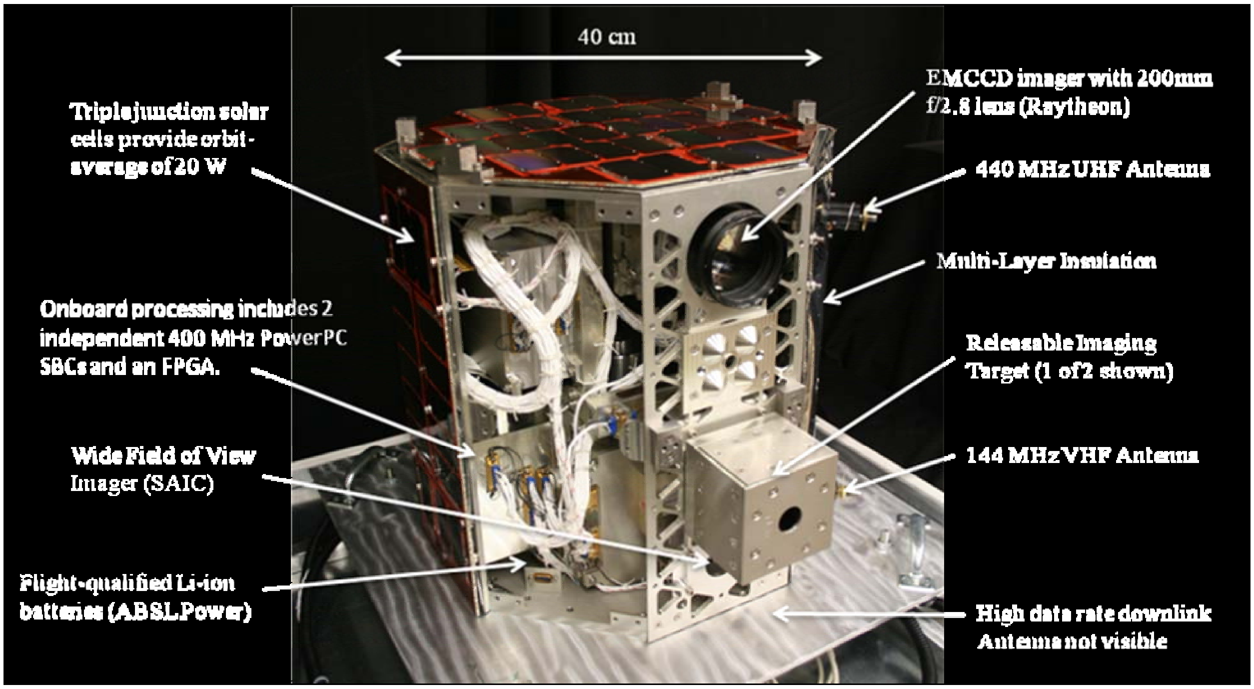

Figure 1: The Oculus

Table 1: NFOV Imager Detector Performance.

Sensor format	1024 x 1024 frame transfer, back-illuminated EMCCD
Pixel Size	13 x 13 micro-meters
Imaging Area	13.3 x 13.3 mm
Frame rate at Full Resolution	8.5 fps
Digitization	10, 5, and 1 MHz @16bits

Figure 2: The Oculus NFOV Imager Assembly.

The Oculus WFOV Imager is intended for close proximity operations and, specifically for the Oculus mission, is intended to monitor and confirm the release of the two free-flying imaging targets. The WFOV Imager is a Microspace camera manufactured by SAIC. This small, space-qualified multi-purpose detector requires only a small footprint and modest power, yet fills a valuable local space imaging role. Specifications of the SAIC instrument are shown in Table 2 and a photograph is seen in Figure 3.

Table 2: WFOV Imager Detector Performance

Sensor format	752 x 480 pixels CMOS
Full Well	20K e-, Linear
Pixel Size	6 μm x 6 μm
Analog to Digital Converter	10 bits
Output Data Format	LVDS Serial (Channel Link)
Frame Rate	0.2 to 60 Frames/ Second
Integration Time	Commandable: 88μsec to 5 sec

Figure 3: SAIC WFOV Microspace Camera

Telescope Calibration

The Oculus will also be outfitted to serve as a commandable imaging target to provide controlled viewing opportunities for ground telescope facilities seeking to determine the properties of an orbiting object. Using the Oculus, ground observatories will have the opportunity to test the functionality of instruments and algorithms. The reflective properties of the Oculus, such as spectral characteristics and bi-directional reflectance distribution function (BRDF), will be fully characterized pre-launch. The vehicle will be equipped with a variety of surface materials that are relevant to space imagery. In addition, the Oculus will be capable of changing its shape by deploying hinged panels as commanded from the ground.

To accomplish the ground-imager calibration portion of the mission, an additional module will be added to the current Oculus vehicle that will incorporate shapes and materials commonly used in space-based applications. This module will feature deployable side panels covered in materials such as gold foil, kapton, or anodized aluminum. The module concept can be seen in Figure 4 with various colored panels representing aluminum honeycomb covered with materials of interest.

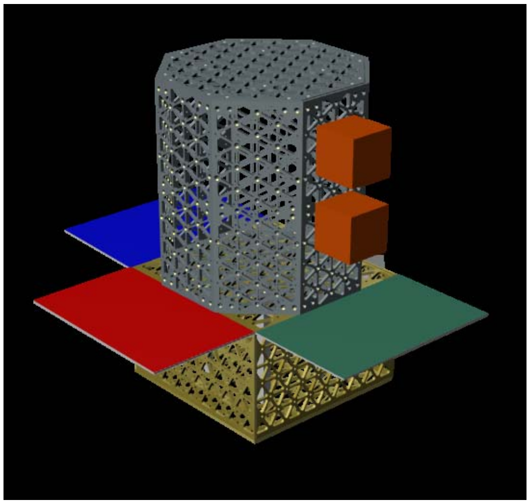

Figure 4: Telescope Calibration Module Concept

Once in orbit, the Oculus will fly over ground stations at a known attitude – chosen by the customer – thereby allowing ground stations to view the vehicle and characterize the materials on it. Attitude truth histories will be recorded by the Oculus and provided to customers after each pass. Ground observers will then be able to compare the measurements taken during the viewing with light curve predictions based on pre-launch characterization of the vehicle, solar angle, and viewing angle.

The side panels, when deployed, will alter the shape of the vehicle in such a way that should be detectable by ground telescopes. This gives customers an opportunity to detect the change in measurements from their instruments and correlate it with the vehicle's change in shape. Each of three side panels can be released individually, providing multiple opportunities for ground observers to recognize a change in the vehicle's dimensions. Michigan Tech's Amjoch Observatory, pictured in Figure 5, is equipped to perform the observations needed to complete these ground-imager calibration mission objectives.

For additional functionality of the Oculus vehicle, as well as added calibration opportunities for the ground-based telescopes, the fourth side of the module will be outfitted with a corner cube retro-reflector. The corner cube will be used for ranging and altitude determination from a ground station. These measurements will then be compared to the known altitude of the vehicle. An exploded view of the module that will be added to the Oculus can be seen in Figure 6.

Figure 5: Michigan Tech's Amjoch Observatory

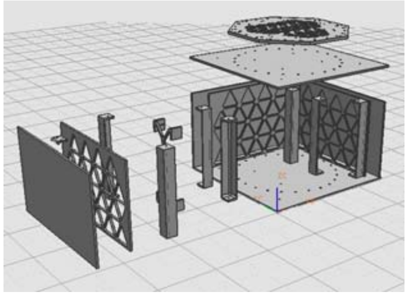

Figure 6: Module and Corner Cube Concept

VEHICLE DESIGN

The design of the Oculus vehicle was driven by the mission-critical requirements which were used to flow down into system-level and subsequent subsystem requirements. Hardware was selected to fulfill subsystem requirements and integrate with other SSA mission specific hardware.

Approximately sixty students are currently working on the Oculus vehicle. These students are from a wide variety of majors, providing students with an educational experience that allows them to work in multidisciplinary teams. Work on the Oculus vehicle is divided into the five subsystems, detailed below. Team leaders from these subsystems meet weekly and act as a systems engineering team to handle integration issues, resolve hardware issues, and regularly review the project to ensure that it is achieving mission goals.

The Oculus project received aid from numerous sponsors who provided the team with both imagers, Li-ion batteries, a fluxgate magnetometer, multi-layer insulation, and development software. However, the Oculus' limited budget necessitated commercial-off-the-shelf (COTS) components as well as in-house development and construction of hardware. As a result, students benefitted from unparalleled opportunities to become educated in all aspects of satellite design and fabrication.

Michigan Tech's facilities will aid in-house hardware development and system-wide testing. These facilities include an advanced controls laboratory with a 6-degree-of-freedom table for hardware-in-the-loop control systems testing, an anechoic chamber for radio testing, a shaker table and experimental modal test equipment, student accessible CNC machine shop, and an electronics fabrication and testing laboratory. Additionally, the Ion Space Propulsion (ISP) Lab at Michigan Tech, pictured in Figure 7, includes vacuum chambers with a cold box and radiation lamp that can be utilized to perform the thermal vacuum and "day-in-the-life" tests.

Figure 7: Ion Space Propulsion Lab

The orbit constraints for the vehicle are based on the capabilities of the imager, optimal conditions for ground station coverage, and requirements for ground imager mission objectives. The Oculus can perform its mission and communicate with and be observed by Michigan Technological University's ground stations at a minimum inclination of 36 degrees and an altitude range between 320 and 900km, however, an inclination over 60 degrees is desired to maximize ground station talk time and an altitude around 360km is desired to provide the most ISS viewing opportunities. Additionally, Oculus should not be placed in a sun-synchronous orbit due to constraints this would place on ground observation opportunities.

Guidance Navigation and Control

The Guidance Navigation and Control (GNC) team was tasked with providing the satellite bus with the maneuverability to complete the SSA objectives of ground-to-space imaging and RSO space-to-space imaging. The primary requirement for both objectives was three-axis attitude control. General orbit requirements imposed by the ground observatories require the Oculus to be fully functional in an orbit altitude range between 320km to 900km and 40 to 70 degrees of inclination. The 3-axis control system accuracy must be able to know and command the actual satellite attitude within +/-2 degrees, detumble after release from the launch vehicle, counter disturbance torques for one full orbit, and rotate the satellite at $1.5\,\deg/s$ velocity and $0.1\,\deg/s^2$ acceleration for ground station flyover maneuvers and $10\,\deg/s$ velocity and $0.5\,\deg/s^2$ acceleration for imaging RSOs.

In order to accomplish these agile and precise maneuvers in the simplest and most robust fashion, the Oculus was designed to include reaction wheels and magnetic torque rods (magnetorquers). Three orthogonally-mounted reaction wheels will provide abundant torque to perform agile slew maneuvers and precise attitude adjustments, while the three orthogonally-mounted magnetorquers will desaturate the reaction wheels and neutralize disturbance torques when the reaction wheels are off. Aided by an inclined orbit, a three-axis magnetometer and three-axis angular rate gyroscopes (gyros) will inertially reference the satellite's attitude. An advanced 3-axis control system running on an onboard computer will autonomously command the GNC system to perform all queued commands which will be uploaded from a ground station.

Component performance specifications were derived based on attitude control requirements: overall vehicle mass, size, and power estimates, and predicted disturbance torques for the desired orbital range [7]. Overall design specifications are listed in Table 3. Acquiring COTS space-rated GNC components to meet the required design specifications was outside the budget for the Oculus, so creative, in-house solutions were pursued and sponsors were identified.

Table 3: GNC Component Requirements

Reaction Wheels	Primary Inertia	$\geq 320\, kg \cdot mm^2$
	Top Speed	$\geq 10{,}000\, rpm$
	Torque	$\geq 0.01\, N \cdot m$
Magnetorquers	Powered Dipole	$\geq 6\, amp \cdot turn \cdot m^2$
	Residual Dipole	$\leq 0.15\, amp \cdot m^2$
Magnetometer	Magnetic Field Angular Sensing Error	$\leq 1.0\, deg$
Gyroscopes	Drift	$\leq 5\, deg/min$
GNC System	Total Mass	$\leq 10\, kg$

The reaction wheels were designed and built at Michigan Technological University. The mechanical mounting and configuration took several design, fabrication, and testing iterations before finalizing. Final design consisted of an $84\, mm$ diameter brass wheel with $385\, kg \cdot mm^2$ inertia press fit onto a Faulhaber 3056B 12v brushless motor lubricated with braycote 805 vacuum grease by Castrol. A US Digital E2 optical encoder and Maxon EPOS 24/1 controller will command the motor. Some components are shown in Figure 8. Wheels will interface via a serial RS232 interface with the onboard computer. Before assembly, wheels will be balanced by Precision Balancing Company; analysis has shown that balancing to at least 0.1 grams on center will guarantee the worst case jitter induced by the reaction wheels operating at maximum speed, matching an assumed resonance mode of the satellite structure to result in less than one pixel of blur on either onboard camera.

Figure 8: Reaction Wheel Components

The magnetorquers were also designed, built, and tested at Michigan Tech. Hiperco 50A was chosen as the core material because of its low remanence and high permeability. Cores were machined in-house and annealed by the Joint Magnetic Research Laboratory at Florida State University and Los Alamos National Laboratory. The completed rods have approximately 2000 turns, which when subjected to $300\, mA$ current generate a $10.0\, amp \cdot turn \cdot m^2$ maximum powered dipole with a $0.125\, amp \cdot m^2$ remnant dipole. A pulse width modulation amplifier, that interfaces via an RS232 serial port with the onboard computer, was designed and built at Michigan Tech as a current-controlled, commandable power supply for the magnetorquers. Both the circuit and one core can be seen in Figure 9.

Figure 9: Magnetorquer Cores and Circuit

A space-rated fluxgate magnetometer with LEO flight history by NASA, shown in Figure 10, was generously donated from Bartington Instruments. This magnetometer can sense the direction of the Earth's magnetic field within less than one degree of angular error with adequate bandwidth for the discrete control system and interfaces to the onboard computer via analog input channels.

Figure 10: Bartington Instruments Magnetometer

Radiation tested microelectromechanical system (MEMS) angular rate gyros with flight history from the European Space Agency were purchased from Silicon Sensing. Additionally, redundant MEMS gyroscopes, donated by Analog Devices, were incorporated into the design. Silicon Sensing gyroscopes interface via analog input channels while the Analog Devices gyroscope interfaces via an SPI and RS232 serial port with the onboard computer. Both gyro sets can be seen in Figure 11 below.

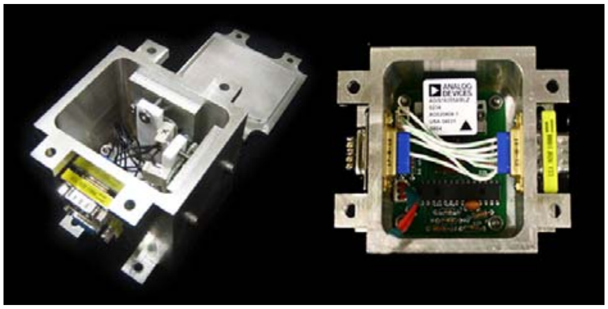

Figure 11: Gyroscopes

An advanced three-axis control system was developed at Michigan Tech based on established reaction wheel and magnetorquer control laws [8] [9] and a Kalman-filter-driven attitude estimator [10]. Hardware- and Software-In-The-Loop (HIL and SIL) testing was conducted throughout the development process to prove the control system's functionality and reliability.

The Oculus satellite will have an onboard orbital model SGP4 of its current position and World Magnetic Field Model (WMM-2010) of the Earth. A Kalman filter attitude estimator will couple these two models along with the magnetometer and gyroscope readings to inertially reference the Oculus' attitude. Additionally an Earth model and orbit propagator will provide the Oculus with a reference to objects fixed on the ground and to resident space objects in orbit respectively.

An onboard scheduler will determine which control law should be in effect at any given time based on commanded maneuvers uploaded from the ground. The reaction wheel control law takes in a desired attitude or rotational velocity and drives the wheels to match that orientation based on the instantaneous craft orientation and wheel speed. The magnetorquer control law also takes in a desired attitude or rotational velocity and creates a net magnetic dipole based on the instantaneous direction of the Earth's magnetic field. Also, it will autonomously monitor the reaction wheel speed to determine when momentum dumping should occur.

Initial detumbling of the satellite will occur using the magnetic torque rods. The control system will read in magnetometer data and use this to control the torque rods to drive the gyroscope rotation rate readings to zero thereby stabilizing the craft. Because of launch vehicle uncertainties, the vehicle orbit will be unknown to the craft when launched. Omnidirectional antennas will allow the stabilized craft in most orientations to communicate with a line of sight ground station. The first uploaded command to the satellite will synchronize its clock and orbital position based on ephemeris two-line element (TLE) data from NORAD. From this point on the satellite will know its inertial attitude.

Imaging any RSO will always follow a similar control path. First, the satellite will use the reaction wheels to point its imagers at an expected target and start capturing images. The images will be analyzed autonomously by onboard image recognition and tracking software. Once an object is identified and recognized, the 3-axis control system will transition from being inertially referenced to being visually referenced. This handoff will change what is producing the attitude control error but will not change the control laws which govern the reaction wheels. Throughout the visual tracking operation, the control system will continually be saving images to disk while keeping the object centered in the cameras' field of view.

Downloading of images requires orienting the satellite's directional antenna at a ground station. This maneuver will be conducted multiple times throughout mission lifetime with the reaction wheels.

External disturbance torques will be detected as a standard attitude error by the control system and automatically mitigated. The magnetic torque rods will desaturate reaction wheels during non-manuevering operational times when reaction wheels have excessive momentum built up.

The control system was modeled and developed with Simulink, a Matlab model-based design tool. First, a full dynamic model of the satellite was created for simulations and software-in-the-loop tests. The reaction wheel and magnetorquer control laws, autonomous scheduler, and the Kalman filter attitude estimator were all written in C-code and tested in Simulink. Once testing is complete, these C-code functions will be actual flight code ready for immediate deployment on the satellite computer. This implies that all simulations are truly SIL tests because flight code is being used in the test. This will also ensure coding mistakes do not result from porting the simulated control system to the embedded VxWorks realtime computer used for Oculus command and data handling.

Control system simulations were conducted of all the various types of maneuvers the satellite is expected to perform on orbit. Anomalies such as disturbance torques, sensor noise, and actuator nonlinearities were also incorporated into these simulations in order to prove the system stability and reliability. AGI's Satellite Toolkit (STK) was utilized to visualize simulations in real and accelerated-time.

Figure 12: Stewart Platform Setup

HIL tests were conducted by having individual components such as the imagers mounted to a 6-degree-of-freedom Stewart Platform seen in Figure 12 above [11] [12]. A simulated space environment with an RSO target was projected on a screen in front of the platform which was viewable by the imagers. Visual tracking maneuvers could then be simulated with the control system driving the orientation of the platform in lieu of actual reaction wheels, while feedback was incorporated from the flight image tracking software, which runs on the embedded PC104 computer, scanning frames from the imagers in the same manor as will occur on orbit.

Telecommunications

The telecommunications subsystem is responsible for transmitting data from the vehicle and receiving data from a ground station. This includes both command and control data and mission data, such as images. The telecommunications subsystem uses a combination of low and high bandwidth components to handle these transmissions. In accordance with AFRL guidelines, the Oculus utilizes amateur frequencies.

Little bandwidth is needed for sending commands to and from the Oculus and has therefore been referred to as the "low speed" system; however, it is more technically known as low bandwidth. In order to command the satellite and retrieve health data from it, about 600 bits per second (bps) throughput is needed. In the amateur band, there are a number of devices which transmit 600 bps or faster in the 2 meter to 70 centimeter range. Both of these frequencies were chosen for the command and control of the satellite. The satellite transmits on the 2 meter and receives on the 70 centimeter bandwidth.

Transmit and receive signals were chosen to be on separate bands to eliminate the possibility of the transmitter locking up the receiver located next to it. A transmit frequency of 2 meters was chosen for two main reasons: space loss and interference. The 2-meter wavelength experiences less space loss due to the longer wavelength (per the Friis Transmission Equation). This loss on the uplink can easily be made up by increasing the transmission power. A 2-meter wavelength was not selected for the receiver because there are numerous 2-meter transmitters in view of the satellite that could cause interference on the receiver when the ground station is attempting to communicate with it.

In order to establish contact with a ground station when initially released into orbit, the Oculus must be capable of receiving data while in almost any orientation. Two separate, static antennas for the command and control radios are mounted on the same side panel of the satellite, as seen in Figure 13. This aligns the nulls of both antennas. Therefore, the command and control radios share a null +/- 15 degree off bore sight and another at 180 degrees off bore sight. This permits communication with the satellite in almost any orientation, allowing the vehicle to easily receive the ephemeris data necessary to inertially reference itself with respect to the Earth.

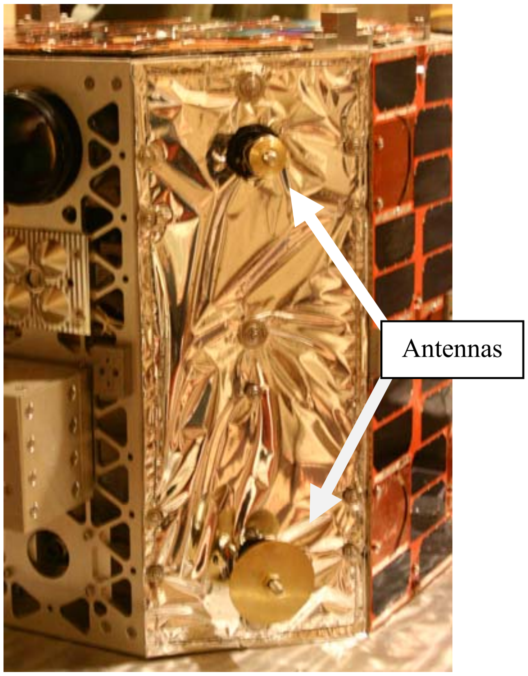

Figure 13: Command and Control Antennas

Michigan Tech does not have the facilities necessary to fully characterize and tune the antennas for the satellite. FirstRF has volunteered its services to help the

Michigan Tech team characterize, tune and ruggedize the Oculus' antennas for launch. Thus far, the command and control radio antennas have been modified from their original form to be space compatible. FirstRF is also tuning the antenna to provide a low standing wave ratio (SWR) at the desired frequency and ensuring that the antenna bandwidth is high enough for the Oculus' communication system needs.

The imaging data from the Oculus is much larger than the command and control data. In order to conserve bandwidth of the radio link and use a less expensive radio system, only a sampling of the pictures will be downloaded to the ground station. A large amount of bandwidth is still needed to transmit these compressed images. This throughput, about 160,000 bps, is much higher than COTS Very High Frequency (VHF) or Ultra High Frequency (UHF) equipment can provide. The command and control low-speed radios could not accommodate this requirement. The frequency for the image download radio was chosen to be 2.4 GHz. This frequency is high enough that COTS components with suitable bandwidth are readily available but low enough not to require excessive amounts of power to close the link. Amateurs have 1 GHz of bandwidth in this area and it is a useable frequency for satellites per the International Amateur Radio Union (IARU).

To establish a downlink with the radio used for transmitting images, a high-gain patch antenna is used. The patch antenna has four elements for 14dBi of gain. The beam width of this antenna is only +/- 15 degrees off of bore sight. The Oculus is able to use a single patch antenna with a narrow beam width because the satellite is 3-axis stabilized and has a pointing accuracy well within the -3dB beam width of the antenna.

To prevent unauthorized use of the Oculus' capabilities, transmissions to and from the Oculus must be authenticated and encrypted. All amateur frequencies licenses specify that only the command and control transmissions can be encrypted. Initially, RSA encryption was chosen for the Oculus' transmissions. However, to provide a more secure means of transmitting data, the Oculus upgraded to 128-bit Advanced Encryption Standard (AES). This AES encryption will ensure that external parties cannot hijack command or control of the satellite.

Power

The power team is tasked with the power generation, control, and distribution within the satellite. Power is generated through solar cells, stored in the batteries, and distributed by means of power control circuitry.

The solar strings utilize 16 Emcore Advanced Triple Junction cells for a string voltage of 38V and current of 0.45A at maximum power. The panels of the satellite consist of vented eighth inch aluminum honeycomb sized to fit on the respective locations of each of the strings. In order to insulate the solar cells from this substrate, they are covered in a layer of Kapton film. The strings themselves are then attached to the Kapton using a controlled volatility epoxy made by NuSil. The panels are designed to be the last thing attached to the structure of the satellite. They are mounted at a 7mm standoff from the structural isogrids leaving space for a layer of thermal insulation around the vehicle.

The battery onboard Oculus was donated by ABSL Power and consists of three parallel strings of Lithium-Ion cells. The strings consist of eight 4.2 V, $1.5\, amp \cdot hr$ Sony 18650HC cells. This design results in a 33.6 V, $4.5\, amp \cdot hr$ battery with a total usable capacity upwards of $125\, watt \cdot hrs$. In an overvoltage situation, a pressure-fitted aluminum disk will pop out of place, disconnecting the battery from the circuit. This prevents the overcharging of the battery, but permanently cuts the string of cells from the circuit. Each cell also contains a pressure release vent, and positive temperature coefficient (PTC) fusing to further prevent malfunction and external damage. Charging of the battery is controlled using an 8-cell Taper charge circuitry which supplies a constant current to the battery until the fully charged rated voltage of 33.6 V is obtained. Once this is achieved, the voltage is clamped and the current is decreased to zero. At this point, the batteries have achieved a full charge.

The power distribution system takes the bus voltage of the battery, and regulates it down to the various voltages needed by different systems of the satellite. The supplied regulated voltages are 3.3 V, 5 V, 12 V and 24 V. Additionally, the power on and off state of each subsystem is controlled by the computer through the digital operation of solid state relays on the power distribution boards. Each line is PTC fuse protected for further over-current protection to each device.

On Board Data and Command

On Board Data and Command (OBDC) is the "brains" of the satellite. OBDC is tasked with developing and obtaining computer hardware and software to command, control, and monitor the health of all components on the satellite in order to properly complete mission objectives. Additionally, the OBDC hardware must run GNC control system and image tracking algorithms.

OBDC is configured with two computers, one dedicated for image handling and one for GNC algorithms, health and all other component command and communication. The MIP405 model computer was chosen because its processing power, versatility, and interfacing capabilities allow it to be used for both computers. The computer's PC104+ form-factor has both ISA (Industry Standard Architecture) and PCI (Peripheral Component Interconnect) buses to communicate with necessary add-on boards. Additionally the MIP405 has been radiation tested and used on the International Space Station. Table 4 highlights some of the key features of the MIP405.

Table 4: MIP405 Features

Form Factor	PC104+
Processor	PowerPC 608 MIPS @ 400 MHz
RAM	128 MB ECC
Buses	PCI, ISA
Ports	Ethernet, Serial, IDE
Clock Features	Real Time backed with battery Independent Watchdog Timer
Operating System Support	VxWorks, Real Time Linux

The image processing computer, shown in Figure 14, consists of an MIP405 connected to an FPGA (field-programmable gate array), a 32 GB solid state hard drive, and two frame grabbers, one for each camera. Real Time Linux was selected as the operating system because of its driver support for both cameras and the FPGA. Because of all of the processing power that is needed, an FPGA runs advanced image tracking software than can differentiate between multiple objects in a single field of view and predict object position for intelligent spacecraft control. Frame grabbers will communicate with the WFOV and NFOV cameras to set camera configuration, take pictures, and download frames. These image frames will be sent to the FPGA where they will be analyzed and processed, before being saved to non-volatile memory. Output from the image processing will be sent across a serial port to the main processing computer for use by the GNC control system. Compressed frames will later be sent back to Earth when requested by a ground station.

The second MIP405 is used as the main processing computer. This computer has an octal serial card for GNC components and radios, and two expansion cards supplying numerous digital and analog I/O for controlling component on-off state, monitoring component power draw and temperature, and reading data from analog devices. The GNC control system, health, and telecommunication processes all reside on this computer. VxWorks was selected as the operating system because its advanced real-time, multi-task capabilities allow the GNC control system to reliably operate in real-time in parallel with device communication, health, and telecommunication processes. An Ethernet port on the computer provides communication with ground support equipment for development and testing use. Commands and new software code can be uploaded through the network port or radio system.

Figure 14: OBDC Computer Stack

To provide structural support for the computer stack, braces are attached throughout the stack as it is assembled into an aluminum box. This aluminum box is then mounted centrally in the Oculus for ease of wiring.

Structures

The structures team is tasked with designing, modeling, machining, and testing the frame, panels, and boxes used for housing all the components of the vehicle. Testing includes finite element analysis, thermal analysis, and experimental modal vibration testing. Additionally, the structures team has designed the separation mechanism for the two releasable payloads.

The main external structure of the Oculus is shaped like an octagonal prism composed of isogrids which provide a high strength-to-weight ratio while allowing for multiple mounting points. Internal bracing adds structural support and rigidity to the satellite as well as mount points for additional component boxes. These features can be seen below Figure 15. The additional module with deployable panels, shown in Figure 6, mounts to the bottom of the octagonal prism. The overall structure is composed primarily of alodined aluminum 6061 and is fastened with stainless steel bolts and lock nuts.

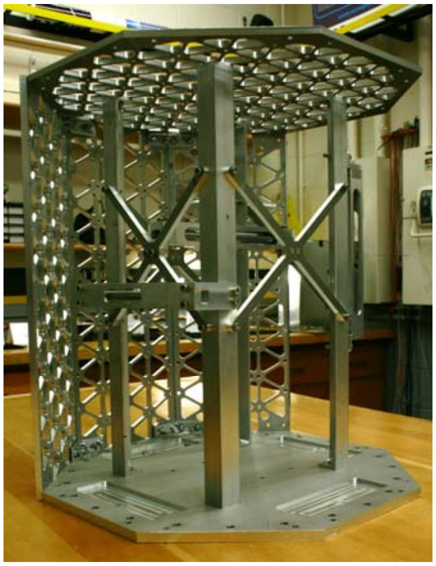

Figure 15: Isogrids and Internal Structure

The Oculus is able to guarantee viewing opportunities of a local vicinity RSO in order to demonstrate its imaging and tracking capabilities by having releasable payloads attached to the vehicle. The two payloads are each attached with a Non-Explosive Actuator (NEA) release mechanism. The mechanism utilizes a separation nut which consists of a split-spool and a fuse wire that clamps onto spring loaded payload mounting bolt. This system has a history of being used in space applications.

A thermal model was used to predict the temperature conditions the satellite components will be subjected to in space and the effects this will have on the vehicle design and reliability. The analysis was conducted by identifying acceptable temperature ranges and expected heat generation, transmission, and dissipation of each component. Then simulations were generated based on the vehicle's expected orbit and component duty cycles during various mission operations to determine where insulation, heatsinks or heat sources needed to added to the vehicle. The overall vehicle temperature must remain within -20 to 50 degrees Celsius to prevent damaging any components. However, the EMCCD in the NFOV camera achieves optimum picture quality only in the temperature range of 18 to 30 degrees Celsius. Simulations were run with Thermal Desktop and checked with a simplified Matlab heat transfer code. Results indicated that Mylar thermal insulation should be included around the perimeter of the vehicle and that specific components on the NFOV camera required additional heat dissipation. On orbit, the satellite will utilize thermisters to monitor individual components for thermal health.

To ensure launch survivability, the first resonant mode of the Oculus must be above 100Hz [6]. Finite element analysis and experimental modal testing were conducted on the satellite structure as well as the individual components for design improvements and to verify and validate the vehicle structural integrity. Finite element analysis was conducted with Unigraphics Nastran NX solver. Impact hammer modal surveys taken of the fully assembled octagon structure with a fixed-fixed base condition showed the first resonance of the structure to be at 162 Hz. The fully assembled vehicle with the additional module for telescope calibration will have a slightly lower first mode that will still be comfortably above the 100 Hz limit. Additional shaker table tests will be conducted on each axis of the fully assembled vehicle with the table and mount shown in Figure 16 below. Conducting random vibration, sine burst, shock, and sine sweep tests with this table will further prove the vehicle's ability to survive launch.

Figure 16: Shaker Table Mount

RESULTS

The majority of the Oculus' hardware is currently complete. Specific components have been chosen and purchased, and the functionality of these individual components has been tested. Components which were fabricated by students at Michigan Tech have also been completed and have undergone testing. In all, the hardware for the vehicle's computer, telecommunications, attitude control, imaging, power, and computing subsystems is nearly finished.

The nanosatellite team at Michigan Tech has been given an additional two years in the University Nanosat Program to complete work on the Oculus' space-to-space imaging functionality as well as extend the Oculus' functionality to complete its telescope calibration mission. In this time, the bottom module with deployable panels will be fabricated for the ground-based telescope calibration portion of the mission. Module integration with the Oculus' octagonal section will conclude in 2010.

Control system development is in final testing stages; remaining software development currently underway includes health and telecommunications processes as well as user interfaces for the ground support equipment.

System integration and vehicle environmental testing has been started. Thermal vacuum tests, full vehicle vibrations tests, and "day-in-the-life" tests, where the vehicle is run in an isolated vacuum chamber through typical functions to be performed in a day on orbit, are on schedule to be completed through 2009 and 2010.

CONCLUSIONS

The Oculus project has shown that a team of dedicated, hard-working students is able to develop and build a functional nanosatellite. This achievement is important because it verifies that the University Nanosatellite Program has achieved its goal of preparing students for employment in fields related to small satellite development and space technology. Students participating in the University Nanosatellite Program have been able to use the experience to propel themselves into highly rewarding internships and careers in the aerospace industry. The students who devoted immeasurable amounts of time and effort into the Oculus will have the skills and knowledge necessary to participate in the next generation of satellite development.

The Oculus itself has the potential to aid in the advancement of U.S. Space Situational Awareness. First, it will demonstrate 3-axis attitude control on a nanosatellite platform. Such an attitude control system could be vital in many future small satellite applications. Second, it will help to confirm the viability of a space-based system of small satellites with the capability to image, track, and monitor resident space objects. This network of small satellites would be a key component in a more effective SSA program, complimenting an array of ground-based telescopes. Finally, the Oculus would serve as an imaging target with well-known spectral and photometric signatures. A target like this is necessary for the calibration of ground telescopes.

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Other sponsors include:

Aerophysics
AGI
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Analog Devices
Bartington Instruments
C&R Technologies
Connect Tech Inc.
Dunmore Corporation
Integrity Applications Incorporated
Systems Integration Plus Inc.
Tyco Electronics
Wind River

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