The IRIS Nanosatellite for Autonomous Multi-System Responsive Space Operations and High Spectral Resolution Earth Imaging

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ABSTRACT
Santa Clara University's Robotic Systems Laboratory is developing the Intelligent Responsive Imaging Spacecraft (IRIS) for autonomous multi-system responsive operations and high spectral resolution Earth imaging. IRIS will interact with an extended system of land, sea, air, and space-based robotic and human elements to observe transient events on the ground. Specifically, IRIS will provide critical imaging and communications services to detect, monitor, and respond to harmful algal blooms in shallow water regions. Students are responsible for all aspects of development. This paper will describe the mission concept and its use of advanced small satellite technologies to perform multi-system responsive space operations.

INTRODUCTION
Santa Clara University's Robotic Systems Laboratory (SCU RSL) is developing the Intelligent Responsive Imaging Spacecraft (IRIS) for autonomous multi-system responsive operations and high spectral resolution Earth imaging. IRIS will contribute to coastal marine science and ecology by performing critical imaging and communications services for the SCU / University of Alaska – Fairbanks RETINA program and the Monterey Bay Aquarium Research Institute Controlled, Agile, and Novel Observing Network (MBARI CANON).

In achieving these objectives, IRIS will adopt several functions fundamental to military responsive space operations, including a) remote sensing of regions of interest using high spectral resolution imaging, b) the ability to communicate with mobile manned communication stations and isolated low-power field stations, and c) the ability to respond to high priority transient events by autonomously and intelligently retasking the satellite system based upon alerts/requests from field stations. Specifically, IRIS shall receive alerts of transient shallow-water events such as algal blooms from static instrument buoys, autonomously retask itself to photograph the area of interest, process the data, and deliver the results to mobile ground assets; these assets shall respond by investigating the phenomena at close range.

IRIS is one element of the Robotic Systems Laboratory's multi-system suite of land, sea, air, and space robots. These platforms make up the RETINA System of Systems (SoS) remote ocean observatory. By interacting autonomously and cooperatively, the systems within the SoS obtain data products that an independent system cannot. The IRIS spacecraft incorporates several of these systems, demonstrating responsive operations between both human and robotic and local and remote ground assets.

Students are responsible for all aspects of development, including the IRIS spacecraft and its extended RETINA systems. IRIS is in the initial stages of development.

ONE SYSTEM WITHIN A SYSTEM OF SYSTEMS
The purpose of the IRIS spacecraft is to produce viable scientific data products while demonstrating core elements of military responsive space operations. The spacecraft shall operate in concert with multiple manned and unmanned systems, and in doing so, obtain data products that it could not get alone.
The RETINA System of Systems

IRIS is one element of the RETINA remote ocean observatory sponsored by SCU and the University of Alaska - Fairbanks. RETINA incorporates multiple robotic systems, including underwater robots, surface vessels, terrestrial rovers, ground communication stations, aircraft, and spacecraft, to conduct integrated field studies of estuaries, coastal waters, lakes, and their surrounding ecosystems, as seen in Figure 1. Science objectives include characterization of deep-water hydrothermal vents and the biological, chemical, and geological evolution of littoral environments.²⁻³

The RETINA systems are designed to work together to provide persistent, real-time, high resolution data on the state of estuarine environments using both in situ and remote sensing observation. Observatories are being developed for San Francisco Bay in California and the Kasitsna and Kachemak Bays in Alaska. Systems within the observatory are automated so that they can operate in remote regions, like the Bays in Alaska, where manned support is limited, and so that data can be collected continuously over long periods of time.

Moreover, the observatories are being developed with the ability to respond to transient events of high scientific and/or environmental interest. These events typically occur over a region too large and a spatial resolution too high for a network of static sensors to thoroughly characterize. Examples include algal blooms, which may be indicative of certain combinations of ocean processes; red tides, which can have devastating effects on aquaculture and recreation;

Figure 1. Example systems in the RETINA System of Systems, including the IRIS spacecraft in the top right corner. The communication rings indicate the two primary communication styles: (1) high-throughput links between major systems and a central control station and (2) low-throughput direct links between systems. IRIS specifically receives alerts from static sensors, transmits critical data results to remote mobile units, and relays all telemetry and minimally-processed data to the central control station. Graphic credit: Steven Li and Erin Beck, 2009.
local anoxic conditions, which may be linked to climate warming; and sudden introductions of toxic pollutants, like oil spills. While researchers possess a wealth of mobile platforms to study these events, they lack a timely and reliable identification and notification method.4

Platforms that are traditionally used for high spatial resolution observation over large regions are aircraft and spacecraft. Aircraft achieve higher resolution but cover less area. They may also be available only a few times per year due to expense and scheduling. Spacecraft may pass over an area several times per day, but most organizations must wait at least several days to receive data products. In both cases, results are not timely or reliable enough to activate mobile units during the early stages of the event, if at all.5

The IRIS spacecraft contributes a solution to these shortcomings in two ways. First, it is a dedicated, continuous observer of coastal conditions. Second, it is directly networked to additional RETINA systems. IRIS shall perform some data processing on-board and react to changes in water composition by transmitting the results to mobile ground units for immediate or near-immediate deployment, depending on the level of autonomy of the ground units. And, IRIS shall respond to alerts from local ground sensors to collect regional data of the surrounding area.

In both cases, the earliest stages of the event are supported both regionally and locally because the systems share information and respond autonomously. The RETINA System of Systems has the emergent property that it can collect data that would otherwise be missed by an independent system. Emergent in this context, and for the remainder of the paper, shall refer to the SoS notion of added capabilities of the SoS beyond the abilities of the constituent systems. IRIS plays the critical regional role in the SoS.

Several oceanographic institutions, including MBARI through the CANON initiative, are pursuing system of systems architectures for marine research. MBARI is located in Moss Landing, California on Monterey Bay. The CANON program, adopted as an initiative in 2009, is examining algal blooms and red tides using autonomous underwater vessels, manned cruise ships, and information-sharing radio networks. SCU RSL and MBARI are collaborating to integrate certain systems into both RETINA and CANON. IRIS will be the first system to participate in both SoS's and will provide supplementary regional support for CANON.

Science Application: Harmful Algal Blooms

In accordance with both RETINA and CANON science objectives, IRIS shall investigate transient, shallow-water events in coastal and estuarine regions. The selected target is harmful algal blooms (HABs), often called red tides. The primary region of interest is Monterey Bay, seen in Figure 2; secondary regions are San Francisco Bay and Kasitsna Bay.

Figure 2. IRIS captures regional hyperspectral images at better than 5 nm spectral resolution from 350 - 750 nm at better than 1 km spatial resolution. The regions of interest are Monterey Bay and San Francisco Bay, CA and Kasitsna Bay, AS. Here, IRIS is shown with the swath of a sample imager over Monterey Bay and the Santa Clara University central command station. Graphic credit: Ignacio Mas, 2009.
HABs grow and dissolve rapidly over a large area, from one to several hundred square kilometers over a couple weeks in spring and fall.\textsuperscript{6} Scientists are generally unable to monitor a large enough region to identify HABs in their early stages; many are responded to late or not at all. As a result, the relatively common marine phenomena and the ocean processes that affect them are not well understood.

An algal bloom is a rapid increase in the population of algae (phytoplankton) in a marine, estuarine, or freshwater system. If some or all of the phytoplankton in a bloom exhibit a harmful trait, the bloom is classified as a Harmful Algal Bloom.\textsuperscript{7} HABs cause harm through two primary mechanisms. First is the production of toxins, which may kill fish or shellfish directly or may cause human illness following ingestion of contaminated seafood. These blooms are colloquially called red tides, though a toxic bloom is not necessarily red, and red blooms are not necessarily toxic. Second is high biomass accumulation that leads to environmental degradation such as light attenuation, oxygen depletion, or clogging of fish gills.\textsuperscript{8} In one instance in Monterey Bay in 2008, large numbers of seabirds died of hypothermia when their feathers became saturated with the slime of a decomposing algal bloom and became non-insulating.\textsuperscript{5} Examples of HABs and their effects are shown in Figure 3.

Blooms occur when environmental conditions become more favorable to rapid phytoplankton growth. Possible favorable changes include: increase in limiting nutrients, change in temperature, change in the amount of light, turbulence in the water column, and deep-ocean upwelling.\textsuperscript{5} No single event or combination of events has been definitively identified as the cause of HABs or of any particular species of bloom. However, because blooms are clearly affected by these processes, it may be possible to use blooms as an indicator of certain events and combinations of events once the HAB phenomenon is well understood.

HABs negatively impact human health, recreation, and aquaculture and produce fundamental temporary changes in ecosystem structure and function.\textsuperscript{9} Because timely and complete characterization of HAB events is limited, estimates of economic impact vary widely by source. For example, the Committee on Environment and Natural Resources estimates the annual impact of

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HAB events and their effects; response capabilities to new events; accurate and rapid testing techniques for cell and toxin type; and physical, chemical, or biological intervention methods to eliminate or reduce harmful effects. Improved prediction and intervention methods will decrease the economic and cultural impact of HABs. Moreover, detailed understanding of how certain coastal events affect algal blooms will enable use of blooms as ocean process indicators, with implications in oceanography, carbon cycle research, and naval tracking.

**SPACE-BASED HYPERSONTRAL REMOTE SENSING**

IRIS, independent of the responsive space mission elements, will perform earth observation of coastal regions in support of HABs research. Because IRIS is a microscale satellite with limited power and processing, it will carry only a single imager. That imager shall produce data products of interest to the primary science customers while also demonstrating imaging techniques suitable to military application.

IRIS will carry a hyperspectral imager. The imager shall have better than 5 nm spectral resolution over the visible to very near infrared (VNIR) range at better than 1 km spatial resolution, with a goal of 0.5 km. The spectral requirements will allow marine researchers to discern type, concentration, and life stage of blooms over the entire region of interest. IRIS shall be sensitive to differences between the four primary bloom types in Monterey Bay: PSP, NSP, ASP, and DSP, or paralytic, neurotoxic, amnesic, and diarrheic shellfish poisoning. The spatial requirement exceeds currently available data products and allows researchers to identify specific sites of interest for closer investigation. These requirements were set through consultation with MBARI CANON.

**Ocean Color Research**

Harmful Algal Blooms are traditionally observed from space with trichromatic and multispectral imagers in the visible to near-infrared range. Algal blooms are detectable as an increase in chlorophyll backscatter between 445 - 565 nm, typically measured by the reflectance ratio of blue to green and increasing logarithmically with concentration. The type, stage, and concentration of the blooms will have various signatures within the visible to very near infrared range, 350 - 750 nm.

Trichromatic imagers can resolve regional variations in ocean color that may signify an algal bloom. Researchers may then deploy additional assets to verify the existence of the bloom, determine its type and life stage, measure its toxicity or potential for harm, and execute a response plan. However, these additional assets are localized and produce sample data points that may or may not be indicative of the entire region, which may be expanding rapidly.

Multispectral imagers provide improved regional awareness over trichromatic cameras. The Medium Resolution Imaging Spectrometer (MERIS) instrument measures ocean color of coastal zones in fifteen spectral bands in the visible and near infrared at 300 m spatial resolution from Low Earth Orbit (LEO). It is one of the premier ocean color observers, riding on the European Space Agency’s ENVISAT. Sample data and HAB-indicating bands are displayed in Figure 4. NASA's

<table>
<thead>
<tr>
<th>Band (nm)</th>
<th>Applications</th>
</tr>
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<tbody>
<tr>
<td>442.5</td>
<td>Chlorophyll absorption max</td>
</tr>
<tr>
<td>490</td>
<td>Chlorophyll and other pigments</td>
</tr>
<tr>
<td>510</td>
<td>Red tides</td>
</tr>
<tr>
<td>560</td>
<td>Chlorophyll absorption min</td>
</tr>
<tr>
<td>665</td>
<td>Chlorophyll absorption and fluorescence reference</td>
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<td>681.25</td>
<td>Chlorophyll fluorescence peak</td>
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<tr>
<td>708.75</td>
<td>Fluorescence reference</td>
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Figure 4. Annual average chlorophyll concentration in 2003 from the MERIS multispectral imager. MERIS designers selected the above seven bands for chlorophyll observation. Image and table credit: European Space Agency.
Sea-viewing Wide Field-of-View Sensor (SEAWiFS) on SeaStar in LEO is a similar ocean color instrument with eight bands. Researchers can access post-processed data by request, such as global average annual or monthly chlorophyll concentrations.

By selecting bands indicative of certain types of blooms, researchers can predict the type of bloom and its behavior before deploying assets. The type of instruments and platforms deployed can then be better optimized. By showing differences in bloom type throughout the region, multispectral images allow researchers to collect samples in each unique zone. However, multispectral imagers are limited to only a few pre-selected bands at low spectral resolution. High resolution data is still confined to localized data sets.

The hyperspectral imager provides high spectral resolution over a large spatial area. Direct comparison of panchromatic, multispectral, and hyperspectral data is shown in Figure 5. One major space-based hyperspectral imager, Hyperion, was flown on EO-1 in 2000 as a technical demonstration. Hyperion captures 220 bands at 10 nm spectral resolution and 30 m spatial resolution. Though data retrieval and processing is slow, NASA has extended the one-year mission through 2009 to continue data collection.

At better than 5 nm spectral resolution, changes in concentration and life stage can be deciphered in addition to bloom type over the entire region. The IRIS hyperspectral imager will increase the capabilities of existing bloom observation systems by tracking the entire bloom over its complete life cycle and integrating that data with traditional ground-based assets, thereby enabling optimized deployment of local instruments and high fidelity regional data.

**Military Surveillance**

Space-based hyperspectral imagery is a relatively new endeavor due to the extremely large image size. Each image contains information for on the order of one hundred wavelengths, an order of magnitude greater than multispectral and two orders greater than trichromatic. Processing the data on-board requires complex autonomous algorithms and large amounts of power and computing; however, downlinking raw data is equally cumbersome. The first Automated Target Recognition of military targets was achieved by the

Figure 5. Hyperspectral data contains an order of magnitude more wavelength information than multispectral data and two orders greater than trichromatic (red, green, blue) or panchromatic (black and white). This additional information is critical in military target detection. Image credit: GlobalSecurity.org, 2009.
Naval Research Laboratory’s airborne “Dark Horse” program just over a decade ago in 1997. It is traditionally sufficient to select a few bands only and fly a multispectral imager; however, as noted above, this strategy permanently limits the data set. This wavelength limitation is critical in military application, especially Camouflage, Concealment, and Deception. While it is common to mask visual and heat signals of objects and disturbances, it is presumably impossible to eliminate all electromagnetic signatures. High spectral resolution imagery in which wavelengths were accessible over large portions of the spectrum would make it possible to identify otherwise invisible targets.

Hyperspectral imaging can also be used for sub-pixel detection by identifying weak but retained signatures of objects smaller than the spatial resolution, shown in Figure 6. The strength of weakness of a signature within a pixel may indicate size or concentration.

Premier (unclassified) hyperspectral surveillance is currently confined to the Airborne Real-time Cueing Hyperspectral Enhanced Reconnaissance (ARCHER) airborne imager at 11.5 nm spectral resolution up to 960 nm and 1 m spatial resolution. ARCHER has high spatial resolution but limited range in comparison to a space-based platform. Its flight patterns could be optimized if informed by frequent regional updates via satellite.

Processing algorithms used on the IRIS spacecraft for autonomous detection of HABs may be adapted to military application. Example targets include: wreckage, by screening data for paint or oil signatures; agents of biological or chemical warfare, by screening for suspected compounds; foliage penetration; or terrain categorization, by observing outlines of disturbed soil or stressed vegetation.

Due to downlink constraints, at least some data must be processed on-board if the ground is to receive a high sample rate. IRIS shall provide daily updates to ground crews, with a goal of one update per pass. Exact data filtering and compression algorithms are to be determined.

**INTER-SYSTEM COMMUNICATION**

The first piece in integrating multiple systems into a system of systems is passing information from one system to another. Presently, most system of systems research is concentrated on establishing real-time (or near-real-time) communications between platforms. Information may include commands, position, health and status telemetry, and processed or unprocessed science data. Communication may happen between each system and a central control station and/or between the systems themselves.

The RETINA System of Systems will consist of a high-power, high-bandwidth, semi-autonomous manned central control station with a link to each system, and low-power, low-bandwidth radio links between select systems. The central control station will be manned as a typical ground station operations center. A manned team shall transmit commands and receive telemetry and data from each system. In baseline operations, the team shall perform complex data processing and analysis and coordinate actions between the systems. In autonomous operations, the station shall perform any or all of the manned team’s functions. Figure 7 shows examples of operational SCU RSL central control centers.

Figure 6. Hyperspectral imaging can be used for sub-pixel target identification because even weak signatures are retained in the data. Image credit: GlobalSecurity.org, 2009.
While the central control station acts as a relay between all systems, select systems shall have direct links between them. These low-power, low-bandwidth connections will relay critical information such as position or data results that affect the real-time actions of the systems. For example, a constellation of systems may relay real-time position for formation control. Or, a marine buoy may transmit a bloom alert to neighboring systems if its instruments detect a positive change in water composition.

The IRIS spacecraft shall have the ability to communicate with the central command station, mobile manned communication stations, and isolated low-power field stations. These capabilities represent three scenarios. First, the spacecraft shall downlink minimally-processed science data to the central command station for complex processing and distribution to other systems. The central command station shall also be responsible for regular maintenance of the spacecraft. This represents a traditional spacecraft communications scenario.

Second, the spacecraft shall isolate critical data onboard, such as the spatial outline of a bloom, and transmit that information to mobile manned units. The mobile manned unit would be a team in the field with limited communication abilities, either deployed on a cruise or along the shore, that would not have access to the central command station or that would benefit from alerts as the spacecraft passed overhead rather than waiting for the central station. In addition to being a practical application for multi-system HAB observation, this scenario is an analog for an isolated manned military unit in need of situational update. Such a unit could receive minor but critical alerts every time the satellite was in view.

Third, the spacecraft shall receive alerts from low-power field stations. A low-power field station may be the marine buoy described earlier. Should the buoy detect a positive change in water conditions, it would transmit a “Look at me!” beacon at regular intervals. The spacecraft would receive this beacon and prioritize imaging of that site in its command queue. Rather than waiting for an alert to be relayed through the central command station, which may be positioned farther down range in the satellite’s path than the region of interest, the spacecraft is alerted of the beginning bloom while directly overhead. The spacecraft can capture the earliest stages most often missed by scientists. Again in addition to being practical for HABs, this scenario is an analog for an isolated warfighter in the field requesting imagery from a passing satellite. In this instance, that imagery would be of the immediate area and would be returned via one of the first two scenarios. In extended applications, the warfighter may be able to specify, “Look at this other place!” in addition to, “Look at me!”

IRIS shall have one high-power, high-bandwidth, narrow-beamwidth S-band radio system and one low-
power, low-bandwidth, high-beamwidth 70 cm-band radio system to accommodate the above three scenarios.

INTELLIGENT RESPONSE AND OPTIMIZATION

Communication between multiple systems is nontrivial. However, the great potential of the system of systems architecture lies in (1) exploiting the emergent properties of the combined systems, and (2) optimizing the use of those systems in performing a task.

The RETINA System of Systems satisfies the first criteria by using data from one system to position other systems for data that would otherwise have been missed. IRIS shall have the ability to respond to high priority transient events by autonomously and intelligently retasking the satellite system based upon alerts or requests from field stations. IRIS shall receive automated beacon alerts from sensors on the ground and prioritize its imaging schedule to focus on that site. Those alerts or commands may also come from mobile manned units in need of a situational update or from the central control station. Figure 8 shows example RETINA extended systems.

The next criteria is to optimize the system for greatest efficiency and data quality; IRIS is one element of this demonstration.

System of Systems Engineering

Enhanced military situational awareness and response are dependent upon constant and current communication and data exchange between independent systems. These assets may be manned or robotic with varying degrees of autonomy, including airborne regional sensors, low-power ground sensors, unmanned relay stations, deployed manned units, or command centers.

A system of systems may be described as “a set of several independently acquired systems, each under a nominal systems engineering process; these systems are interdependent and form in their combined operation a multifunctional solution to an overall coherent mission. The optimization of each system does not guarantee the optimization of the overall system of systems.”17 As will be described later, optimization of the SoS is dependent on its constituent systems and their combined properties.

Eight criteria have been proposed to describe a system of systems:

1. Operational independence of assets
2. Managerial independence of assets
3. Evolutionary development
4. Emergent behavior
5. Geographical distribution of assets
6. Inter-disciplinary study
7. Heterogeneity of assets
8. Network of assets

The first five are known as Maier’s criteria.18 The final three have been proposed from the study of mathematical implications of modeling and analyzing

Figure 8. Several RETINA static and mobile assets. Above left, this in situ static sensor may be deployed on a buoy. Above right, an aerial photo from an Unmanned Aerial Vehicle. Below, a the SeaWASP Small Waterplane Area Twin Hull Autonomous Surface Vessel for shallow water bathymetry. Photo credit: RSL 2009.
SoS’s by Dr. Daniel DeLaurentis and collaborators at Purdue University.\textsuperscript{19}

This is the SoS concept being adapted by oceanographic research centers like MBARI for the study of complex ocean processes requiring high spatial resolution sensing over large regions with multiple instrument types.

Presently, multiple sensors on multiple platforms are/may be used to investigate coastal phenomena. However, these sensors do not interact; each collects data, and that data is compiled by the scientist. The scientist must be responsible for choosing, placing, and tasking each system. Furthermore, data is generally collected locally due to the cost and availability of airplanes and satellites for regional imagery. As a result, time-critical data may be lost because phenomena are simply missed or responded to too late.

A system of systems which (1) supply regional data as well as local and which (2) interact with each other as well as the scientist would enhance the study of transient coastal events by enabling timely, resource-efficient investigation.

\textbf{Optimal Controls Architecture}

The IRIS / RETINA SoS architecture scheme is to model the SoS like a controls system.\textsuperscript{20-22} The location and task of each asset is controlled to optimize performance, time, and/or cost given sensor input from the systems and to adapt to the systems available.

In addition to deploying assets and enabling data exchange, we may answer several more compelling questions: Which sensors are best for the event? Which platforms are best for the event? Based on knowledge of the type, size, and growth-rate of the event, how should those sensors and platforms be arranged? If one is not available, how shall the others compensate? Based on the time, personnel, and financial cost of deploying each asset, what is the most resource-efficient configuration to achieve good science? The answers to these questions may change as the event state and scientists' knowledge of the event state changes. The SoS must take in new knowledge from each asset and intelligently distribute the assets for quality and efficiency.

We hypothesize that we can assign certain core parameters to each system and write a control script that optimizes their behavior within the SoS. Platform parameters include cost to deploy, speed of deployment, manned supervision requirements, spatial coverage, sample rate, and communication abilities. Sensor parameters include measurement type, sample rate, spatial resolution, spectral resolution, and processing needs. The qualities of a given sensor and a given platform shall be combined to produce the core parameters of a system. Additional parameters that shall be considered are estimators (data processing) and communication (link between systems).

The SoS would be governed by control scripts that optimize these attributes. The performance index may be based on data quality, range, cost of deployment, time efficiency, or power efficiency, for example.

In the same way that a spacecraft has emergent functions as a result of its combined systems, the SoS has emergent properties based on its collaborative elements. However, unlike spacecraft subsystems that are largely independent (i.e. the power subsystem does not and cannot perform the same functions as the communications subsystem), full-system elements of an SoS may overlap each other considerably.

An ideal SoS would be composed of systems with orthogonal capabilities. For example, a spacecraft platform with a regional imager would be complementary to a static buoy platform with a local sensor. However, the SoS may also have access to an airplane with a regional imager. The optimization strategy of which platform to choose must be based on parameters such as cost and availability. As in, the plane has higher spatial resolution than the satellite; however, the spacecraft is available daily, while the plane is available for one day every six months. The plane is expensive to rent and the spacecraft data is, in this case, free; however, the one-time cost of building the launching the satellite is two orders of magnitude higher than running the plane.

IRIS’s optimization scheme is in development. First, the parameters of the platforms and sensors within the SoS will be defined and each asset within RETINA will be assigned values for each parameter. We will begin by balancing parameters and analyzing emergent
properties of a two-asset SoS, such as the spacecraft and central command station. We will then build up to an n-asset SoS, both generally and specific to RETINA. The goal is to design a controls structure for which any asset “plant” can be inserted and the SoS will adjust accordingly.

A likely optimization scheme is to maximize data quality while minimizing time, personnel, cost, and distance traveled. However, the weighting of each element is critical. Another optimization scheme may be to maximize the orthogonality between as many systems as possible.

CONCLUSION

Santa Clara University’s Robotic Systems Laboratory is developing the Intelligent Responsive Imaging Spacecraft for autonomous multi-system responsive operations and high spectral resolution Earth imaging. IRIS shall produce viable scientific data products while demonstrating elements of military responsive space operations. It accomplishes both of these goals by participating in the RETINA System of Systems collaboration of land, sea, and space robots.

The RETINA SoS uses the collective data from all systems to optimally control the deployment of assets, thereby enabling acquisition of data products unobtainable by a single asset. IRIS is one element of the SoS. The spacecraft performs critical regional hyperspectral imagery of transient shallow water phenomena at a daily sample rate, specifically harmful algal blooms. It responds to new events by networking with static and mobile, manned and unmanned, local ground-based assets.

IRIS will scientifically contribute to the understanding of the full life-cycle of algal blooms and the ocean processes that affect their formation, with strong implications in aquaculture, recreation, ecosystem health, and carbon cycle and climate change research. IRIS will technologically contribute to the on-board processing of hyperspectral image data, autonomous event detection, system of systems controls and optimization techniques, and the demonstration of an applied system of systems.

Student Participation

Students are directly responsible for all aspects of development, including concept, design, fabrication, integration, testing, operations, and management of both IRIS and RETINA, as in Figure 9. The IRIS project is driven by the University Nanosat Program’s two-year competition cycle, such that all students may work in all phases of the spacecraft’s life cycle within their academic lifetime.

The IRIS team consists of over twenty graduate and undergraduate students from all engineering disciplines, with an emphasis in mechanical engineering, controls, and operations. Leadership is earned based on knowledge, ambition, and enthusiasm, irrespective of age or major. As such, 70% of the core ten students are undergraduates, including the Lead Systems Engineer.

![Figure 9. Students are responsible for all project elements of both IRIS and RETINA. Here, sophomore through graduate student engineers are shown in the Santa Clara University central control center and operating the Remotely Operated Vehicle, Triton. Photo credit: SCU RSL, 2009.](image)
All additional elements of the RETINA remote ocean observatory were also developed, or are being developed, by students of the Robotic Systems Laboratory. Because the IRIS mission is highly dependent on the RETINA SOS architecture, several students participate in both the spacecraft and oceancraft or aircraft development. Students are trained in full-system engineering in several extreme environments and multiple research industries, gaining the IRIS team a wide range of experience and skills.

ACKNOWLEDGEMENTS

The IRIS mission is a highly complex student endeavor requiring expertise in military responsive space applications, controls engineering, remote sensing, image processing, marine biology, and oceanography, in addition to spacecraft subsystem design and implementation. RSL has formed close partnerships with external organizations in order to expand our core competencies, oversee the development process, and provide general training and mentorship to the student team. These relationships are critical to the success of the program.

We would like to acknowledge the University of Alaska – Fairbanks and the RETINA program, the Monterey Bay Aquarium Research Institute and the CANON Initiative, NASA Ames Research Center, and the Air Force Research Laboratory and the University Nanosatellite Program. Also thanks to the University of Colorado – Boulder, Moss Landing Marine Laboratories, Headwall Photonics, and the Elkhorn Slough National Estuarine Research Reserve.

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