Flexible Closed Loop Feedback Control Architecture for SDA Payloads

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To enable effective onboard, automated tracking as part of an integrated tasking loop, closed loop tracking algorithms are necessary to engage pointing hardware such as gimbals, steering mirror assemblies, or body-pointed spacecraft adjustments. For mission flexibility, Ball has developed and demonstrated a modular software architecture for closed loop detection, tracking, and pointing allowing for regular updates to the code base for active mission tuning. The target use case includes regular updates to mission data level 0 chip processing parameters which govern detection. This includes photometric calibration for greater dim target detection and discrimination, image quality assessments, multi-sensor input tuning, enhanced velocity matched filtering, and pose and range estimation techniques.

1. MISSION

Onboard Mission Data Processing is heart of a space domain awareness (SDA) / space situation awareness (SSA) capable space vehicle (SV), providing interface management, mission data routing, mission data pre-processing and onboard post-processing (OD, catalog maintenance) and decision analysis. Our reference mission to develop an autonomous, self-tasking space domain awareness sensor is presented in Figure 1. In this example, a small spacecraft is performing in situ measurements across a large volume using multiple sensors with varying performance characteristics. In concert with ground tasking and analysis, two ultra-wide field of view cameras of approximately 45 degrees provide domain awareness in plane along the velocity and anti-velocity vector. Additionally, a high performing sensor wide field of view sensor with dynamic range > 50000 DN and sensitivity dimmer than 15Mv with an adjustable line of sight based on closed loop targeting feedback within the scene.

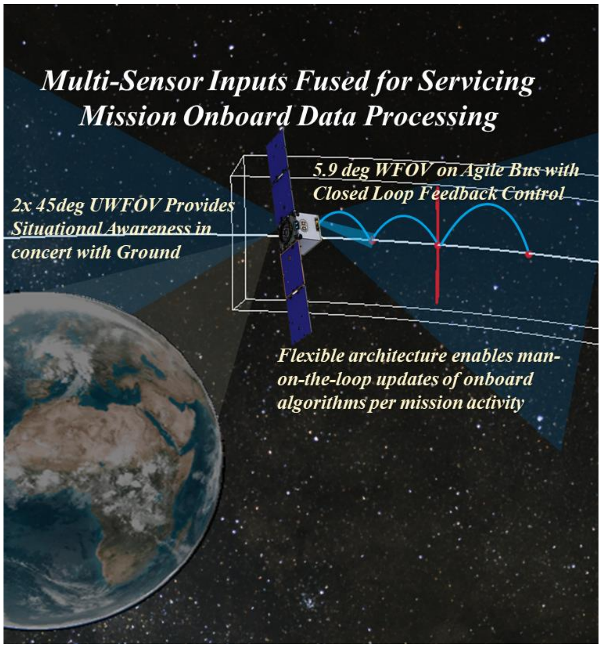

Figure 1. Onboard Mission Data Processing Design Reference Mission

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With this sensor set, Local Domain Awareness can be performed to monitor spacecraft's neighbors and its own nearby space to detect anomalies and potential threats. Platforms may use tasking guidance to automatically configure for detecting the subtle observables while remaining nimble to competing information needs. To enable tactical responsiveness, one needs to consider techniques to transfer ground-based data processing to on-orbit processing. This transition permits a reduction in downlink and onboard storage utilization, thus reducing RF bandwidth costs, and will enable commanders to make decisions from a robust near-real time space-based data architecture.

To accomplish this onboard processing, a processing hardware significant technology gap exists which is required to maintain space superiority. Ball is developing and demonstrating a flexible, modular hardware and software architecture which can facilitate block upgrades and leverage ground and flight-based implement machine learning for on-the-fly, per mission adjustments to mission planning or course of action rulesets. This can be combined with mission toolsets such as Ball's PROXOR resolved and unresolved imagery generation as a training basis for on-orbit imagery. These toolsets enable non-standard detection and tracking (e.g., dim object, fast moving object, or flickering object detection). The data processing nodes in the ground systems compute the likely strategic actions and mitigations to be converted into new self-generated algorithms and parameters to load into the onboard mission data processing stack as shown in Figure 2.

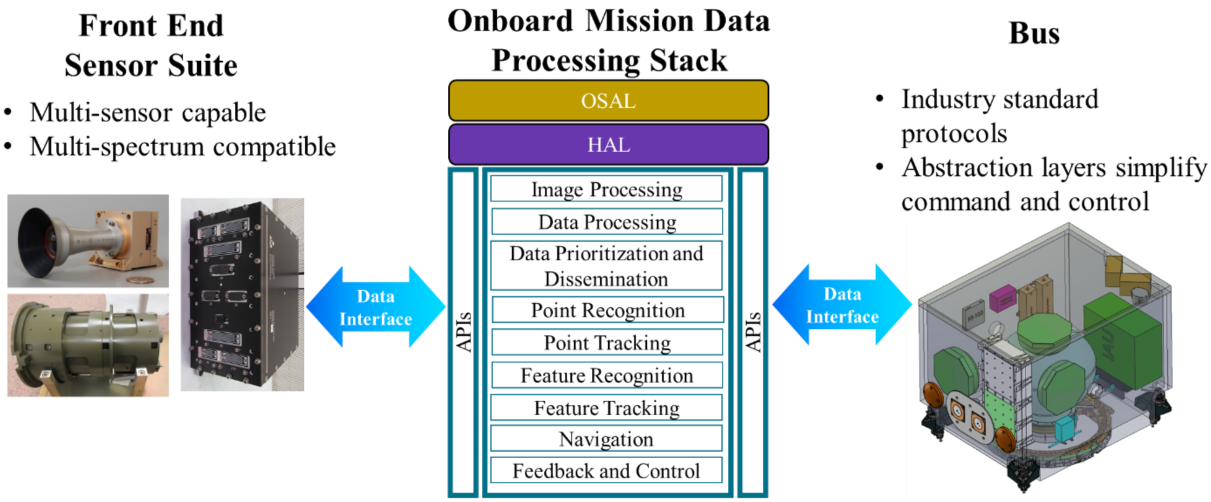

Figure 2. Flexible Onboard Mission Data Processing with Application [1]

With a flexible onboard mission data processing stack, multi-sensor inputs compliant with a sensor specific hardware abstraction layer (HAL) and a data specific application programming interface (API). Ball has created a standardized abstraction layer and ported our mission data processing stack into the framework.

2. ALGORITHMS AND SOFTWARE

Fundamentally, Onboard Mission Data Processing can be separated into four core functions: 1) the Framework and Architecture, 2) the Algorithms representing the functional logic, 3) the software applications and enabling overhead functions for the processor, and 4) the processing hardware as described in Figure 3. Ball is leveraging our abstraction layers for hardware and operating systems to provide a construct for new, novel algorithms and software applications.

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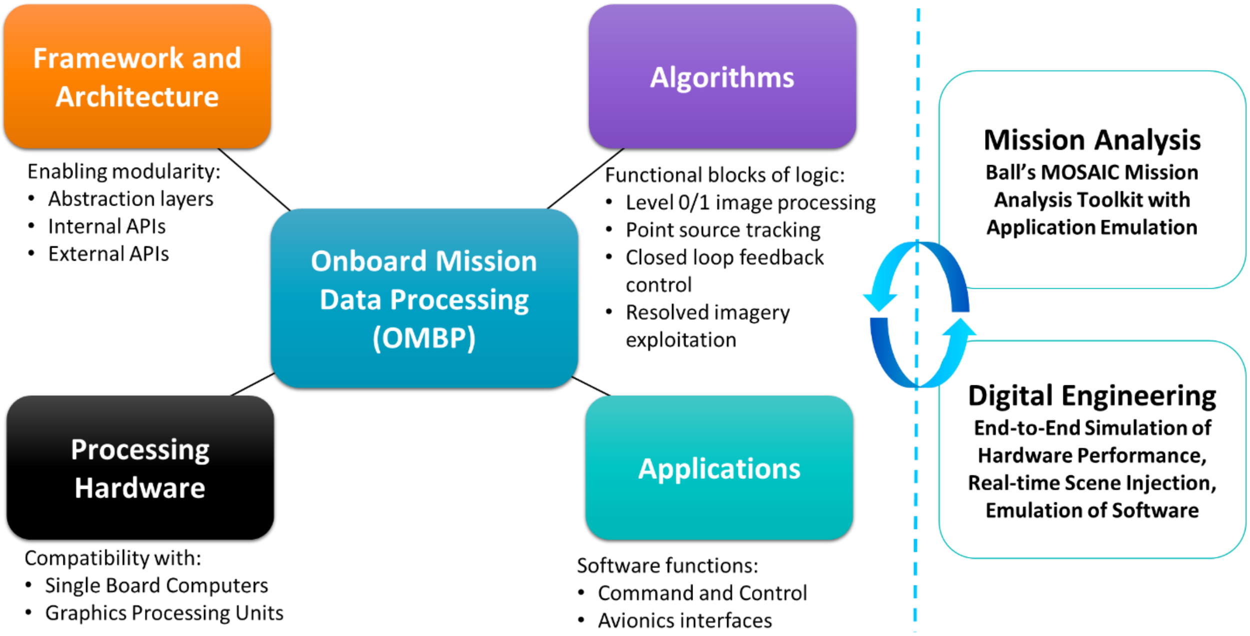

Figure 3. Core Functions of Onboard Processing and their Interactions with the Development Cycle

Fusing data from multiple sensors and phenomenologies with edge processing near the aperture helps shorten our Find-Fix-Track-Target-Engage-Assess timeline by answering time-critical questions of intent and attribution. On-orbit SDA processing can cover a range of capabilities, including pre-processing algorithms for increasing resident space object (RSO) signal-to-noise ratio (SNR); object-detection processing to register and track all RSOs; object discrimination to disambiguate RSOs from stars and other objects; and closed loop tracking (Auto-Track) of targets of interest or potential threats. Ball has developed and fielded onboard mission data processing for all of these types of on-orbit capabilities.

Auto-track capabilities provide an immediate use case for autonomous, closed loop feedback and onboard tasking. With this approach, as new objects are identified, the sensor can autonomously self-cue and start tracking the object, rather than having to rely on other assets for a tip/cue. Alternatively, the sensor can be given a cue from the ground, and we can close loop track a potentially maneuvering RSO to provide very timely measurements, since the ground will not be in the loop for every new desired LOS command. An overview of this functionality is provided in Figure 4.

Auto-track closed loop feedback requires Level 0 and Level 1 frame processing onboard. The data can be pre-processed to increase SNR or to perform data reduction. For frames that are aligned to within a small fraction of a pixel, coadding (frame stacking) can be applied directly to improve SNR in rate track mode. If frames are not reasonably well aligned, then we first register the images and then coadd. Coadding, or frame stacking, ideally can provide a SNR improvement in SNR since the signal adds linearly and the uncorrelated noise variance adds linearly. Improved SNR leads to detection of dimmer targets, and hence to better observations and improved ability to detect small threats. Windowing is another pre-processing technique that can be applied either in hardware or software. Windowing and spatial binning are data reduction techniques that help reduce the amount of data (pixels) that need to be processed for each frame.

With the raw data output from onboard frame processing, detection algorithms discriminate RSOs from other objects within a single scene. These detections can be fused onboard with other on- or off-board sensor to form a 3D track. This track is handed off to Auto-Track algorithms for autonomous closed loop tracking of targets of interest. As new objects are identified, the sensor is autonomously self-cued based on the onboard rules of engagement to start tracking the object. Alternatively, we can be given a cue from the ground, and we can close loop track a potentially maneuvering target to provide very timely measurements, since the ground will not be in the loop for every new desired LOS command. This system-of-systems approach enables responses in an agile manner to reduce the F2T2EA timeline.

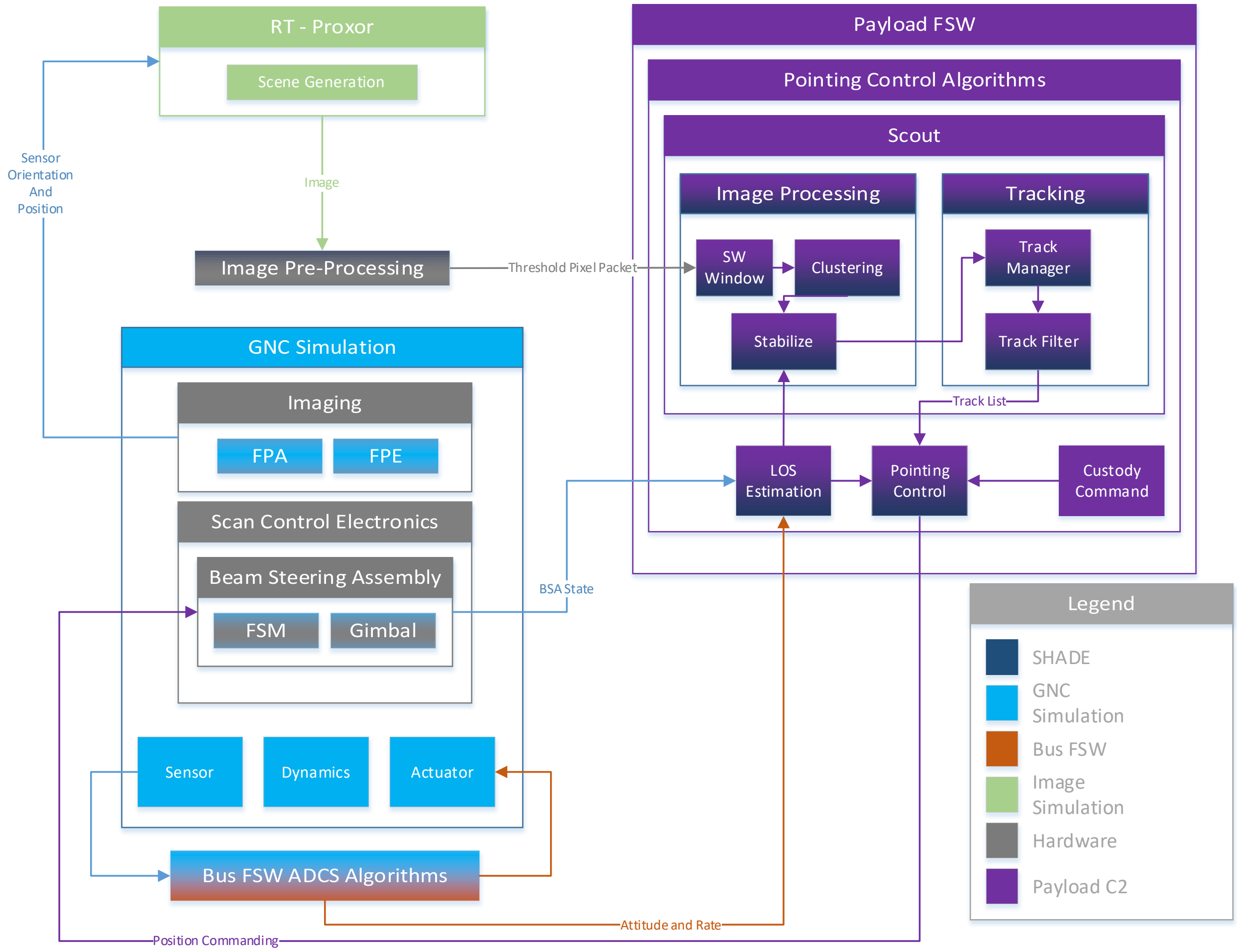

Figure 4. Ball's Closed Loop Autonomous Feedback Functional Diagram

The future of SDA processing utilizes a modular and flexible plug-in and play architecture that allows for heterogenous processing across a variety of algorithms. Our demonstration paves the way towards future Space Domain Awareness autonomous indications and warning, tracking, and threat identification.

3. HARDWARE

To realize the mission as described in Section 1 and effectively host algorithms shown in Section 2, a mission data processing system is needed. A gap in processing capability exists today based on several factors. More traditional processing systems relied exclusively on well characterized and rad-hard/tolerant processing modules. This was both for mission safety and for mission life considerations. These modules tent to be well behind state of the art for both commercial and tactical systems, and the gap appears to be widening [1].

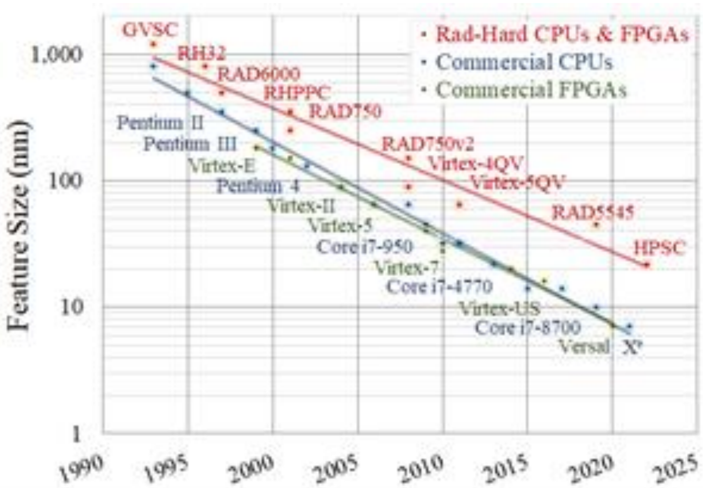

Figure 5. Trends of Rad-hard devices versus commercial for multiple architectures

These traditional systems were also built around highly specific and optimized monolithic software and firmware approaches. While well understood and characterized at built-time, there was little option for rapid on-orbit SW updates, swapping of algorithms, application stores, or other technology that is quite common now in commercial spaces. Adding to this is the advent of ubiquitous space communication layers. No longer restricted to short contacts a few times per orbit, using ground stations as a service and cross link providers, many satellite systems can achieve almost continuous connectivity. This opens up new possibilities for group and space interactions, data exchange, and movement of where processing takes place.

To meet these new architectures, a better way to design and build electronics for data processing is needed. Ball has been at the forefront of these innovations under multiple efforts. Notably to this paper is the Heterogenous On-orbit Processing Engine (HOPE) being designed in concert with AFRL/RV [1]. This system allows use of a spectrum of processing modules in a way that is safe and controllable. The notional architecture of HOPE is seen in the figure below, and consists of several key sections.

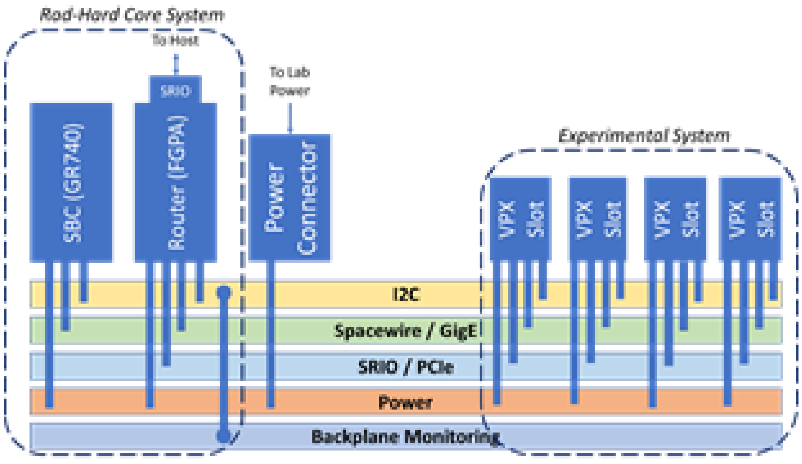

Figure 6. Notional HOPE Architecture

HOPE assembles a heterogeneous mix of commercial processor boards, interconnected over a protocol-agnostic high-speed backplane. A proven rad-hard supervisor implements mitigation functions to maximize survivability of the commercial boards to provide sufficient reliability for moderate radiation environments. It was postulated that such an architecture would rapidly accelerate adaptation of advanced commercial electronics into space systems, thereby dramatically improving on-orbit processing performance. Specifically, the HOPE architecture has the potential to provide (1) new experimental insights and (2) increased operational capability to keep pace with growing mission requirements. First, the monitoring and data-logging services of the supervisor will enable detailed study of the spaceflight capabilities of SOTA commercial electronics. A well-planned ground-based radiation testing campaign can provide a lot of insight into the expected performance of electronics in a space environment. However, accurately emulating the combined impact of total ionizing dose (TID) and single-event effects (SEEs) at the system level is difficult. There is no substitute for collecting in situ experimental data while the electronics are operating on-orbit under the relevant SWaP constraints. Second, the HOPE design would allow engineering teams to quickly compose a high-performance processing unit to support satellite mission needs. This could include a heterogeneous mix of computing architectures or redundant pairs of the same architecture for added reliability. A protocol-agnostic backplane, over a standard SpaceVPX framework is expected to accelerate integration of commercial boards into HOPE and potentially enable interoperability between them.

The basic premise of the electrical architecture is to provide a standard set of radiation-tolerant services which can interface with any configuration of experimental boards. This is accomplished with three key pieces of technology. The first is an active backplane with intelligent power monitoring and control features, the second is the rad-hard supervisor single-board computer (SBC) running experiment management software, and the third is an FPGA-based high-speed data router with protocol translation. The HOPE backplane will be based on the ANSI/VITA 78-2015 SpaceVPX standard which supports popular space data protocols such as Serial Rapid IO (SRIO) and SpaceWire and adds redundancy to the utility plane for improved fault tolerance. Additionally, the HOPE backplane may include support for the ANSI/VITA 65-2019 OpenVPX standard to maximize compatibility with space and commercial VPX boards currently under development. VPX provides both connector and electrical interconnect specifications and supports both 3U and 6U board configurations. The initial HOPE assembly will use the 100mm×160mm 3U form factor. Main system power is achieved in two ways. For laboratory experiments, regulated power can be applied directly to the backplane with a simple connectorized cable, allowing for many different total power scenarios without needing to define current and voltage power requirements. For spaceflight scenarios, the final hardware configuration will be known and a flight LVPS can be specified and procured based on specific mission needs. Of particular interest for HOPE is the ability to run different protocols over the standard-specific physical planes to enable integration of a variety of processor boards. Due to the use of COTS type processors, the radiation environment must be assessed for each space mission utilizing this architecture. There is a potential need for updated chassis designs or spot shielding based on expected performance of each COTS device. The risk posture of each program, orbit, service life, and other specific factors must be accounted for as well. The current design focuses on a lab-based demonstration to show the usefulness of the architecture in general, so research into more specific radiation requirements should be done at a later time.

Of particular interest to SDA concepts is the ability to specify compute modules which can host high end algorithms and adjust or change running applications on the fly. We look at the SOSA architecture concept for some help here. SOSA sections 2.1 and 2.3 define frame capture and pixel level processing with the goal of a standardized digital output at the exit of the 2.3 compliant hardware. Many camera systems may fit this need, including Ball built signal chains. So, in the SDA processing context we expect fully formed frames with processing such as non-uniformity correction, bad pixel replacement, bidding, or co-adding to have occurred. The OBMP then takes these frames and processes based on the mission algorithms presented above. Algorithms and other applications live in the SOSA section 3.X realm. Here there is a separation between the software and the hardware. These applications process incoming sensor data, send messages or other data between algorithms, make requests of the system (such as pointing updates).

Given these HW design considerations, the final hardware need is the ability to rapidly prototype and test a representative instantiation of the chosen HW to understand algorithm performance. Ball's architecture allows for rapid standup of a lab-grade MDP using COTS processing modules. Our scene injection system can take real-time scene input or static rendered scenes and match the electrical interfaces and protocols to move frame data into the MDP. This includes SRIO, PCIexpress, and others. We utilize the Ball COSMOS C2 system [3] to capture telemetry data and send commands to the MDP, allowing testing with realistic host scenarios. The collected telemetry can be used to assess algorithm and HW performance versus a set of mission criteria.

In summary, commercial technology in both hardware and software for edge processing have rapidly outstripped what is currently available for space systems. The SDA missions of the near future will require significant onboard data processing for timeliness and data reduction. Commercial technologies such as containerization (Docker, Kubernetes, etc.), IOT, and edge processing frameworks, and new communications paths provide a good foundation for algorithm and software performance. Processing hardware must evolve to take advantage of these tools. Ball's

MDP architectures provide a flexible and modern platform that balances processing features and program risk to create individual mission solutions.

4. REFERENCES

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