

## Plug-and-Play for Creating “Instant” GN&C Solutions

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### ABSTRACT

Small satellites provide an excellent, near-term platform for demonstrating a responsive capability highlighting missions that necessitate quick launch, quick operational capability, with an attendant, very short development schedule. To achieve this rapid response capability, there is the implication that spacecraft will need to embrace the PC-based concept of Plug-and-Play (PnP), where the user plugs a device into a USB socket, invoking the operating system to find the correct driver, configure the system parameters, and seamlessly makes the device an available resource. Creating a truly modular, PnP spacecraft capability will stretch the industry, particularly in terms of developing guidance, navigation and control (GN&C) systems which are traditionally customized for each specific mission and payload. To facilitate the creation of a PnP GN&C system, a set of generic algorithms can be created that are not dependent on the sensor suite, or the actuator suite, or the vehicle characteristics. This antithetical approach to the traditional development of GN&C solutions can be viewed as a disruptive technology, where an upfront investment can result in monumental rewards. This paper will present a mechanism for creating an instant GN&C solution, using the PnP paradigm, to create small satellites that can support new and emerging mission needs.

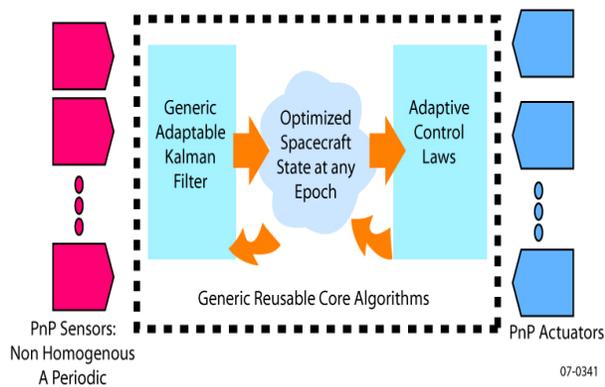
### AN INSTANT GN&C SYSTEM

Small satellites provide an excellent, near-term test platform for proving new spacecraft technologies. They can also provide a responsive capability for missions that necessitate quick launch, quick operational capability, with an attendant, very short development schedule and thus, lower mission costs. New missions for space assets are evolving, particularly in terms of operationally responsive space. Operationally responsive space implies a quick cycle from identifying a mission need which current assets will not meet, to designing and implementing a solution, and on to deploying the solution, ultimately meeting the mission need. Creating a truly modular, PnP spacecraft capability will allow development cycle times to shrink to the order of a few months instead of the usual few years, which will enable rapid testing of new space hardware, as well as the creation of highly responsive space systems.

To enable such a rapid response mission, a “built-to-inventory” cadre of space assets, constructed from off-the-shelf components (and rapidly integrated with payloads) is implied. To produce this inventory of

spacecraft, both hardware and software off-the-shelf components are needed and this indicates the need for a high level of innovation, which might include plug-and-play (PnP) and/or reusable components. In terms of PnP hardware, the Air Force Research Laboratory (AFRL) in their Responsive Space Testbed (RST) and PnPSat are making great strides toward a standardized spacecraft PnP avionics (SPA) protocol and acceptance of traditional commercial PnP practices as viable in the spacecraft industry are starting to be embraced by the spacecraft community. In terms of PnP or reusable software, innovation in development is required, ranging from process oriented enhancements to actual software implementations that facilitate new mission, including operationally responsive space. Specifically, the reuse of off-the-shelf modules is highly desirable. Additionally, the core algorithms must be designed to be generic and the software must be developed and tested, before the specifics of the mission may have been identified. Mission parameters associated with the vehicle configuration and characteristics must be easily tailored without requiring additional testing to facilitate the reuse of these generic core algorithms.

From the perspective of traditional guidance, navigation and control (GN&C) system design, this represents an antithetical approach. Traditional systems involve fine tuning the data elements and deterministic timing between the sensors, the algorithms and the actuators. In a PnP system, the set of sensor outputs and actuator inputs must be discovered at run-time and any and all types of available (discovered) information must be usable by a generic set of algorithms. The overall PnP paradigm allows for the rapid integration of non-homogeneous sensors and actuators into this core set of generic GN&C algorithms. By forming a mechanism or framework for including all available sensed information into a synthesized determination of the spacecraft position and attitude, the quality of the inputs to a generic core can be enhanced. The performance of the core control algorithms will be maximized as the quality of the “known state” is optimized. Thus, a key component to improving overall system performance is the inclusion of a generic, adaptable, Kalman Filter that uses available data, even if it is variable or a periodic, to create the best estimate of spacecraft current state, at any time epoch desired. With PnP sensors and actuators, a generic set of core control algorithms that is tailored based on mission and vehicle configuration data, in concert with a generic adaptable Kalman Filter, a spacecraft GN&C system can be quickly configured, creating an “instant GN&C system”. The basic architecture for this “instant” GN&C system is shown in Figure 1.



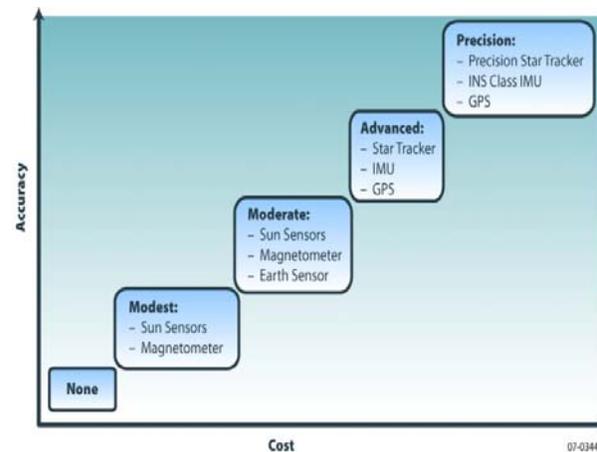
**Figure 1: The architecture of an instant GN&C system: PnP sensors and actuators integrated with a set of generic reusable core algorithms allow the GN&C system to be “assembled” multiple times rather than developed specifically several times.**

The caricature, shown in Figure 2, illustrates that there is a balance between the number and quality of sensors integrated into a system, which is ultimately measured in cost, and the performance that is needed to meet the mission requirements. The overall performance of the

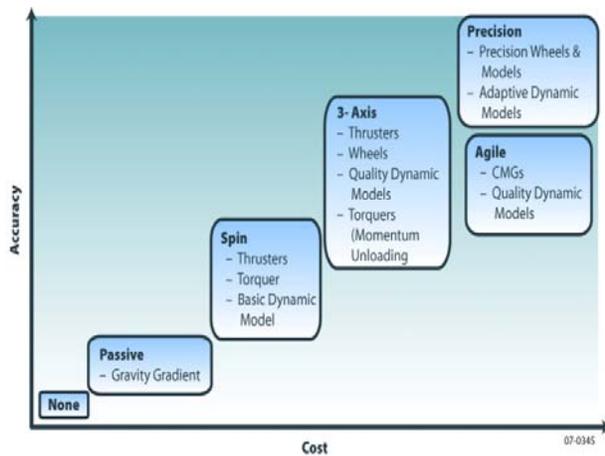
instant GN&C system can remain “as good” as traditional system through the use of these new approaches for spacecraft software development such as PnP and reuse modules. The overarching concept is that vehicle control is driven by both vehicle state knowledge, directly linked to the quality of sensed information and the ability to assimilate that information, and the actuator suite configuration. In the PnP spacecraft build process, the selection of the “correct” vehicle sensors is the initial driver to meeting the mission requirements. Figure 3 illustrates the idea that by adding more and better sensors in the vehicle configuration, better knowledge can be gained. Taken together with the generic adaptable Kalman Filter, spacecraft state knowledge is optimized. Figure 4 highlights the concept that once knowledge is optimized, the selection of the correct actuator suite will lead to optimal control.



**Figure 2: Performance of the PnP, reusable GN&C system is based on identifying the correct sensor / actuator configuration to balance the specific mission requirements with desired costs/schedule constraints.**



**Figure 3: Spacecraft Attitude and Position Knowledge is driven by mission requirements and can be met by optimizing the sensor selection – varying the number and quality of the sensors that are included in the configuration.**



**Figure 4: Spacecraft control performance is driven by the quality of the actual spacecraft state estimates (position and attitude) as well as the type, location, mounting accuracy, and plant model associated with the selected actuator suite.**

Control system performance is limited by the quality of the sensor suite, the capabilities of the actuator suite, and the quality of the dynamic models. The sensors provide a fundamental limit to the potential control system accuracy, and a common rule-of-thumb is that with good dynamic models and actuator choices, control errors can be kept to within a factor of 3 of the measurement errors. Early incarnations of PnP GN&C may not do quite as well due to the reduced energy put into modeling and metrology, however, as the paradigm begins to incorporate detailed models/transfer functions and adaptive approaches to reducing uncertainty in geometry and plant models, PnP will transition from “good-enough” to comparable to current practice – at a fraction of the cost and schedule.

During 2003, under a Phase II Small Business Innovative Research (SBIR) contract with the Air Force Research Laboratory (AFRL) at Kirtland Air Force Base (KAFB), Microcosm, in conjunction with partner HRP Systems, created a self-organizing network concept, leveraging commercial approaches to support responsive space avionics networks. By incorporating commercial off-the-shelf (COTS) networks, such as CANBus and Ethernet, a self-configuring, avionics network was created where the Microcosm team was able to demonstrate the viability of a GN&C self-configuring PnP system. In this environment, using COTS components, the system could be rapidly assembled with minimal need to write detailed, low-level code pertaining to the interface or usage of each element. Thus, the Microcosm team efficiently and effectively demonstrated both the viability of the PnP concept as well as the application of this rapid response approach to fault tolerance and graceful degradation.

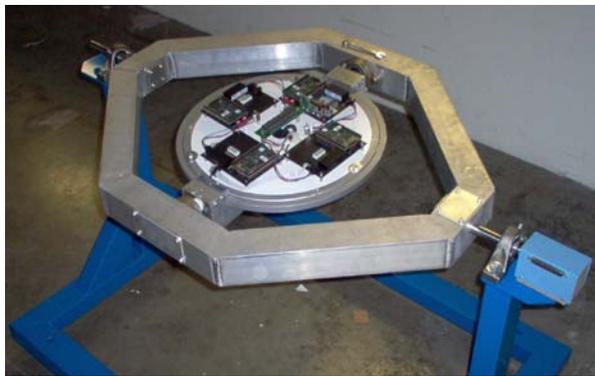
For applicability to future implementation in a spacecraft system, the demonstration architecture was defined with a focus on achieving support real-time performance in a dynamic environment. The goal was to create a demonstration that would be quickly attainable and easily reconfigurable so that proof-of-concept work could emphasize varying mission needs; thus, the use of COTS hardware and drivers, as well as the creation of simplified yet generic and reusable control algorithms. Specifically, the Microcosm PnP demonstration architecture was constructed to meet several high level requirements, summarized as follows:

1. Real-time (predictive, if not deterministic) performance
2. Support high availability, capable of fault tolerance
3. Scalable and extensible design (to both varying levels of network bandwidth and higher capability processors)
4. Low hardware overhead – size, weight, power
5. Compact software (to maximize the use of low cost microcontrollers)
6. Leverage existing technology (hardware, software, protocols)
7. Simplify system design and integration process
8. Maximize reuse (through well defined services and application program interfaces (APIs))
9. Maximize portability (through partitioning of platform dependent code)
10. Create a freely available, no royalty, open design specification

In addition to the hardware components, there were four primary modules associated with the software product: mission manager, resource manager, network manager, and the GN&C application software. The Mission Manager (MM) is the component of the system that understands the mission objectives, requirements, and success criteria. It is in this software that decisions are made regarding the mission phase and the algorithms that must execute at any given time during a mission. The Resource Manager (RM) understands the resource discovery process and maintains the information regarding data descriptions and the system configuration, as well as subsystem health and status. A component of the RM is the local RM that provides an API (application programming interface) to resident software applications by abstracting (partitioning for easy reconfiguration) the physical activity needed to access the data while providing a mechanism for error

handling and reporting. The Network Manager (NM) understands addressing, routing, protocol, and the interfaces associated with the medium over which data are being supplied. This is the component of the software that will be changed as different mediums and protocols are introduced. Finally, the GN&C application software understands the required sensor inputs, at an atomic level (e.g., acceleration value), and supports processing and outputs to the actuators (e.g., attitude control thrusters), based on mission mode control laws. Each of these elements is needed to make the overall PnP system operational.

The demonstration configuration, shown in Figure 5, included a simplified rate table to provide the mechanism to test the GN&C algorithms in a dynamic environment. The demonstration scenario included an initialization period, where first-time discovery through self-announcing by components occurs and the Resource Manager (RM) database is populated. Next, the GN&C algorithms demonstrated the ability of the system to sense motion, based on atomic level sensor data, which will ultimately cause the firing of actuators or the energizing of magnetic torquers. Several aspects of reconfigurability and graceful degradation were demonstrated through the failure of sensors. The addition of a new, more accurate, sensor demonstrated the real-time discovery mechanism.



**Figure 5: The Microcosm team initial PnP demonstration of GN&C with a two tier network approach, atomic data being sensed and basic bang-bang control laws.**

The process of populating the RM database demonstrated discovery and configuration, as well as resource management associated with the self-configuring network. The first step in the operational portion of the demonstration was to have the GN&C algorithms operate in a known, static state, making use of the “best available” atomic level data on either of the networks. Next the attitude state was changed, using the rate table dynamics. The GN&C algorithms noted the change in attitude, which prompted the use of

actuators, lighting the light emitting diodes (LEDs). A second adjustment of attitude returned the rate table to the original static state. Once again, the GN&C algorithms noted the change in attitude, eliminating the need to fire the actuators, demonstrated by turning off the LED(s), which also demonstrated the adaptability of the GN&C algorithms based on atomic level GN&C sensor inputs.

To demonstrate reconfigurability of the GN&C algorithms, a sensor failure was simulated. The 2-axis gyro sensor was disconnected, alerting the RM that these data were no longer available. The GN&C algorithms automatically reconfigured the system to make use of data from a different source, namely, the single-axis micro-electromechanical system (MEMS) gyros, demonstrating a graceful degradation of the overall system. While these data were less accurate, a solution was still achieved. The LED thrusters fired momentarily to account for the perceived change in attitude, due to less accurate sensor inputs. The first attitude adjustment was re-applied, and the GN&C algorithms fired the LED thrusters, demonstrating the continued operation of the system in a degraded condition. The attitude was returned to the original nominal, static state.

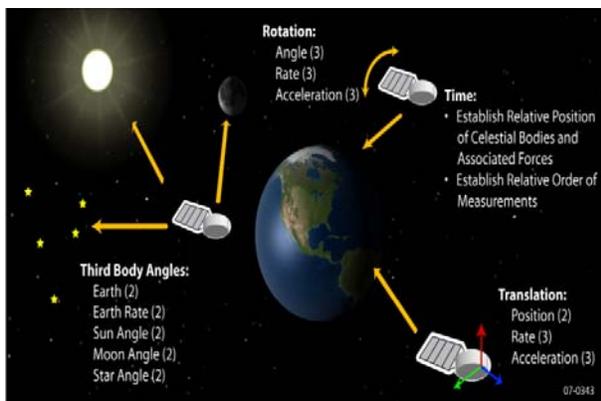
Finally, the demonstration included aspects of “real-time” discovery as a new sensor, a three-axis gyro, was “plugged” into the system. The component announced itself to the RM. The GN&C algorithms noted that a new, more accurate source of data was available and reconfigured to make use of these new data. Once again, the LED thrusters fired momentarily to account for the perceived change in attitude, due to more accurate sensor inputs. However, the system quickly reached equilibrium, concluding the demonstration.

This demonstration was the beginning of a commitment by the Microcosm team to create the prototype version of an instant GN&C system for flight demonstration on the AFRL PnP Sat. Continued work with AFRL, MDA, and NRL through various SBIR programs, has allowed Microcosm, and team members, to develop a PnP MEMS IMU and a very small, low-cost star sensor that has proven quite successful in the engineering model evaluation. Additionally, a combined GN&C sensor that includes the aforementioned IMU and star sensor, along with a GPS receiver from NavSys, has been prototyped and initial simulation and analysis are very positive. Finally, the Microcosm team is working to create PnP GN&C for demonstration in both the AFRL Responsive Space Testbed (RST) and the PnP Sat.

The instant GN&C system comes to fruition through acceptance of the notion that by removing traditional

subsystem boundaries and creating an architecture that is data centric, generic control laws can be developed that are self-configuring, based on the availability of sensed information within the system along with the commanded torque authority provided by self-announced actuation sources. The data centric architecture is rooted in the concept that if all inputs and outputs are abstracted from the actual components, all that remains is the physics of the measurements and/or the movements or *atomic data elements*. An investment in understanding the atomic level data of sensors and actuators is necessary to architect algorithms that respond in a general way to these data centric measurement components.

Figure 6 shows how measured or sensed atomic data has a direct tie to physics and geometry, rather than subsystems or components. For example, spacecraft motion, rates, expressed in body coordinates. These would be considered atomic level data rather than velocities measured in sensor coordinates via an inertial measurement unit (IMU). Another example is a vector (line of sight) and clock angle to the sun, in spacecraft coordinates, rather than an intensity measurement of light on a sun sensor in sensor coordinates. In terms of outputs from core GN&C processing, desired rate, imparted on the spacecraft in spacecraft coordinates rather than a torque (which includes vehicle mass properties) or worse, on/off time for a thruster. When the GN&C system is developed from the first principles of physics, using atomic data elements, it can be created in such a way that it will be extensible and reusable under varying conditions.



**Figure 6: Sensed atomic data elements have a direct tie to physics rather than the subsystem or avionics component that took the measurement.**

Specifically, for a low earth orbiting (LEO) space vehicle, the set of sensor and actuator atomic data elements would include the following:

### Sensors

1. Time — time stamp
2. Rotation measurements — rotation angles (3 components), rotation rates (3), rotation accelerations (3)
3. Translation measurements — translation position (3), translation rates (3), translation accelerations (3)
4. Third body angles — Earth angle (2 components), Earth angle rate (2), Sun angle (2), Moon angle (2), and star angle(s) (2 components for each star in the field-of-view).

### Actuators

1. Requested thruster force (3 components)
2. Requested thruster torque (3)
3. Wheel (or CMG) momentum (3)
4. Wheel (or CMG) torque (3)
5. Magnetic torquer torque (3)

The design and architecture of the instant GN&C system software has been predicated on the abstraction of the core software components from the specific sensor and actuator suites, by establishing atomic data elements. The concept of atomic data elements is augmented with the addition of helper application software modules (helper apps) that use vehicle configuration information (mounting locations and transformation, etc.) along with mass properties (center of mass and pressure, etc.) to integrate newly discovered sensors and actuators into the GN&C concept. Helper apps can include typical library functions such as coordinate transformations (sensor to body, earth centered earth fixed - ECEF to earth centered inertial - ECI, etc.) and time conversions (J2000, GPS time, etc.), or translations of new or different devices to “standard” data elements such as GPS pseudo-range augmented to create position/velocity. Additionally, helper apps might include keep-out zones for payloads or instruments, orbit and attitude propagation, and the environmental models associated with that propagation. Figure 7 shows a prototypical architecture for the PnP GN&C software that includes a data flow from an “undefined” set of sensors, sensor helper apps, core GN&C algorithms, actuator helper apps, output to an “undefined” actuator suite. Even a Kalman Filter could be considered a helper app as it makes use of atomic data elements that are available in the system and enhances them to create an optimal estimation of the vehicle state.



include this real-time knowledge. Vehicle mass properties can be updated in a similar fashion to account for initial uncertainties, propellant usage and other potential changes to the vehicle launch configuration.

While the performance achieved with these self-configuring systems may not be optimized for the particular vehicle configuration, the goal is that the solution will be “good enough”, which when added to the “instant” availability, makes the complete system revolutionary in terms of providing an enabling capability that moves small satellites into the mainstream of the responsive space arena. The approach suggested and discussed here is a first cut at creating such a system and includes significant innovation. The process of developing, implementing, testing, and receiving acceptance of these new algorithm technologies will require a long term view and may require more effort to implement initially than traditional approaches, but with optimum payoff in the long term. It is anticipated that re-usable GN&C software modules, that can be thoroughly tested, instantly configured, and rapidly integrated as needed, will be created and accepted in much the way hardware components are currently established. If all of this comes to fruition, many of the typical missions that small satellites are used for, as well as the emerging new missions, can take advantage of this instant GN&C system for quick integration and rapid response.