Deep Space Habitat Wireless Smart Plug

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***Abstract* – NASA has been interested in technology development for deep space exploration, and one avenue of developing these technologies is via the eXploration Habitat (X-Hab) Academic Innovation Challenge. In 2013, NASA's Deep Space Habitat (DSH) project was in need of sensors that could monitor the power consumption of various devices in the habitat with added capability to control the power to these devices for load shedding in emergency situations. Texas A&M University's Electronic Systems Engineering Technology Program (ESET) in conjunction with their Mobile Integrated Solutions Laboratory (MISL) accepted this challenge, and over the course of 2013, several undergraduate students in a Capstone design course developed five wireless DC Smart Plugs for NASA. The wireless DC Smart Plugs developed by Texas A&M in conjunction with NASA's Deep Space Habitat team is a first step in developing wireless instrumentation for future flight hardware. This paper will further discuss the X-Hab challenge and requirements set out by NASA, the detailed design and testing performed by Texas A&M, challenges faced by the team and lessons learned, and potential future work on this design.**

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1. INTRODUCTION

NASA has been focusing on deep space missions, and new technologies are necessary to make this feasible. The Deep Space Habitat (DSH) project [1] was a project through the Advanced Exploration Systems program [2] to focus on the development of these technologies that would be needed for human survival on a long-duration habitat in deep space. The DSH project has been in existence for four years [3] and has evolved over those years from a pressurized excursion module configuration to a fully configured deep space habitat in 2012. In 2013, the project transitioned to focusing on different potential habitat design configurations for various mission locations, and the continued development of hardware in NASA's habitat testbed.

Power Monitoring and Control

Power monitoring is a critical aspect for the reliable operation of the DSH power system. Ideally each load on the system would have a sensor capable of monitoring the power consumption of the load by providing information to the main control system on the load's operating power level, average and peak power consumption, and power consumption profile throughout the day. The sensor would also be capable of shutting off power to the load in case of a fault or excessively high current demand from the load. The main control system would use the information collected by these sensors to optimize the distribution of power and dynamically schedule the operation of the loads on the system to remain within the capabilities of the power system's output.

The first step toward meeting this power monitoring and control capability was the integration of off-the-shelf current sensors into the 2010 [4] and 2011 DSH demonstration unit. For this initial application the majority of the loads within the DSH were AC powered. Therefore, AC current monitors as shown in Figure 1 from Digikey, based on the ZigBee wireless networking protocol, were used. These sensors provided information of current draw from an outlet to the load, or loads, plugged into it. These sensors also allowed on/off control of the outlet. A total of 14 sensors were utilized within the DSH. These sensors were connected to various outlets on the power distribution units within the DSH, as illustrated in Figure 2, and provided data wirelessly to the control system. The sensors became an integral part of monitoring and controlling the operation of the loads within the DSH.

Figure 1 – Digi wireless current sensor

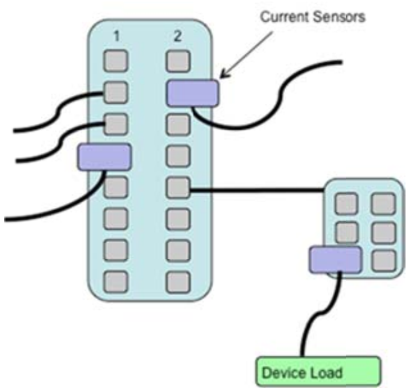


Figure 2 – Illustration of current sensor layout

The next evolution in the DSH power system was to transition from the mainly AC based system to a DC system. The selected voltage for the DC power system was 120 VDC. The DC system needed to have the same or better operational control as the AC system had. To achieve this requirement, a main bus switching unit (MBSU) and power distribution units (PDUs) were developed that provided switching and current monitoring. There was also a need to provide information and control on loads further downstream from the PDUs. Thus, switchable, wireless, current sensors, similar to the AC ones previously used, were needed. However, these types of sensors were not commercially available for a 120 VDC-based power system. Therefore, to meet this requirement, new sensors needed to be developed.

The wireless data and control capability of these desired sensors is a critical aspect to their integration into the overall power and control system architecture. For space applications, wire weight is a significant mass penalty on the vehicle. Another competing requirement is the ever-increasing need to gather information on the status and operation of the equipment within the habitat or vehicle. Increasing the number of sensors provides greater resolution and control. This increased capability is needed as more intelligent control systems are utilized to operate the habitat or spacecraft. Wireless sensors allow for this ability to gather large amounts of information without the wiring penalty associated with most present day sensors. As long as standard interfaces are used, these types of sensors can be utilized or reutilized at different locations within the DSH as operating conditions change, providing both inherent redundancy and the ability to adapt the control system to unforeseen circumstances. Thus, the development of these sensors was submitted to the X-hab Challenge Program as a need for the DSH Project.

X-hab Challenge

In 2011, a challenge was formed as part of the DSH project to enable universities to participate in the design and development process, providing hands-on and real-world experience to the students, while simultaneously solving challenges on the DSH project. This challenge became known as the X-Hab Academic Innovative Challenge [5, 6]. NASA engineers working on the DSH project provide potential projects for the X-Hab Challenge and universities present proposals that would meet the demands of the challenge presented. The outcome of the work must be some sort of hardware or prototype that can be physically tested, rather than theoretical or paper design studies. The best proposals are selected and the winning universities are paired with NASA technical points of contact to aid and guide the universities' developments. As part of the challenge, a university must complete a Requirements and System Definition review, Preliminary Design Review, Critical Design Review, progress checkpoints, acceptance testing, and final review and demonstration to NASA management.

TAMU Concept

The Electronics Systems Engineering Technology (ESET) program at Texas A&M University has an experiential learning-based curriculum that prepares undergraduate students for electronic product and system development jobs in the public and private sectors upon graduation [7]. While the actual curriculum prepares students with background in analog/digital circuit design, data communications, embedded system design and topics in product development, an essential part of an undergraduate's learning experience is through participation in open-ended, real world, funded applied research and product development projects [8].

The primary mechanism for achieving this goal is through the Capstone experience. A sequence of two courses, Capstone is an experiential learning environment where undergraduates apply their classroom knowledge to a real-world challenge [9]. Over a period of nine months, students form three to four person pseudo start-up companies, find a customer with funding and a product idea, develop a preliminary design (first semester), and implement/document a functional, professional prototype (second semester). This experience is integral to their education and must be completed successfully in order to graduate. To ensure the students have the resources necessary to complete Capstone, they are given access to the Product Innovation Cellar (PIC), a 3400 square foot facility

(Figure 3) that houses a reconfigurable work area, design suite, a mechanical fab with 3D printer and CNC router, an electronics/test fab with PCB fabrication/testing equipment, and an industry collaboration room that supports weekly on-site or remote interactions with customers [8]. Using PIC's rapid-prototyping resources, students can now easily produce highly professional, alpha version products over the course of their Capstone experience.

Figure 3. Product Innovation Cellar. Top to bottom: reconfigurable work area, design suite, mechanical fab, electronic/test fab, industry collaboration room.

In addition to Capstone, the faculty is very involved in providing extracurricular research experiences for the students. To this end, the faculty focuses on working with ESET students through their respective research laboratories and funded projects. A recent survey done by the ESET program showed that at any given point in time over 60% of the ESET students have participated in at least one funded research activity outside of the classroom. An example of one of these laboratories is the Mobile Integrated Solutions Laboratory (MISL). MISL's mission is to solve industry and applied research problems through the development of mobile, embedded systems-based solutions. Each semester between five and ten ESET students are employed by MISL and work on a diverse set of problems in areas such as robotics, emergency preparedness and energy management. A recent research model which has worked well is to seek industry funded hybrid projects that contain both a sponsored project through a faculty research lab and a subcontract to fund a related Capstone project. This allows students to be involved in research both through paid, extracurricular activities as well as a through their classroom experiences.

The power and monitoring problem posed by NASA's X-Hab Challenge is an excellent example of one such hybrid project. Responding to the NASA request for proposals, the faculty broke the work down so that preliminary research and requirements development was done by researchers in the Mobile Integrated Solutions Laboratory at the beginning of the Fall 2012. This allowed a Capstone project to be specified through a set of customer requirements. These specifications were then subcontracted to a Capstone group, who took the customer requirements and through continued interactions with the NASA customer, developed functional requirements, performance specifications, a project management plan, and a preliminary design. The group used the Spring semester to implement a functional prototype. This prototype was delivered to the MISL researchers who used the summer of 2013 to perform functional testing and final design. Finally, five Wireless Smart Plug units were delivered to NASA for further testing and acceptance. The project was completed on time and within the provided budget.

2. SYSTEM REQUIREMENTS/ SPECIFICATIONS

There were several requirements levied on the students. Spacecraft require DC power and the DSH used both 120 V DC and 28 V DC power. Additionally, the International Space Station (ISS) is known to have cases where both 120 and 28 V DC are available from the same outlet. Thus, the smart plugs needed to support 120 and 28 V DC power, with the possibility of also having both voltages. Furthermore, the smart plugs were required to use cannon type connectors, similar to what is in use on the ISS. In the case of an overcurrent situation, NASA engineers needed the capability to disconnect a load from the power system. Therefore, the smart plugs needed to also provide control capabilities. The smart plugs were required to provide near real-time monitoring, collecting data at a minimum of one sample per second and providing data up to 5 Amps. The data collection and command and control functions were required to be wireless to allow for reconfiguration of the sensors and to provide the greatest flexibility. Moreover, given that the DSH already contained a wireless mesh network, the NASA engineers wanted to maintain commonality to reduce problems of interference, and required that Nivis hardware was used (ISA 100.11a protocol). The smart plugs were also required to have minimal power consumption and use a small form factor. To provide the most use to the DSH Project, the smart plugs needed to be able to integrate into the DSH testbed, however, full integration with the avionics and software was not possible at the time. Thus, the smart plug was required to have a standalone application on a Windows-based Master Control Unit that provided a graphical user interface. The team was also required to deliver a minimum of five units to the DSH project for evaluation.

3. DEVELOPMENT APPROACH

The ESET Principle Investigators proposed a highly unique development, test and validation approach in their response to the NASA X-Hab Challenge solicitation. The faculty members proposed to sponsor a Capstone Design project as part of the funded research effort. This approach, although somewhat riskier than a standard research project, allowed the overall project costs to be reduced to a level that was within the allotted budget for the project. If standard salaries for all the work completed would have been included in the proposed budget, the total costs would have exceeded the NASA budget for the project. By using a Capstone Design team approach for the design, development and test activities, the Capstone team was offered the opportunity to work on an exciting and challenging project while providing a cost effective method to accomplish these initial project elements.

The Capstone team began planning the initial design activities during the Fall 2013 semester and completed final prototype demonstration, project presentation and documentation in May 2014. The ESET Product Innovation Cellar (or PIC) was just coming on line at the beginning of the project and provided the Capstone team a resource for all aspects of their project from design, through development, fabrication and testing. Because the Capstone team members graduated in early May, they were not available to assist the PIs in the installation and validation testing/acceptance of five unit system by the Deep Space Habitat engineers at NASA-JSC.

Knowing that this would be the case, the PIs had a second team of junior-level students working within the Mobile Integrated Solutions Laboratory (MISL) shadowing the Capstone Design team. They attended all presentations made by the Capstone team which included the System Design Review (SDR), Preliminary Design Review (PDR), Critical Design Review (CDR), Project Checkpoint 1, Checkpoint 2, and final project demonstration and presentation. The MISL student team also participated in all testing activities conducted by the Capstone team.

Working with the DSH engineer, the MISL student team installed and configured the NWSP five unit system into the DSH wireless network and transferred the graphical configuration, control and monitoring software to a NASA computer. Following these activities, the MISL student team participated in the execution of eight of the nine acceptance tests contained in the NASA-approved test plan. The final test, endurance, was conducted solely by the NASA DSH engineer. The test required the NWSP system to operate continuously for seven days without human intervention. The NWSP system passed all testing requirements including the seven-day endurance test.

This unique approach proved to be an excellent method of combining the innovative minds and motivated efforts of ESET Capstone team members with the longer-term access to lower-level student workers who would be available to complete the project over the summer months. Neither team could have accomplished the project on their own, but the synergistic approach of partnering the two teams proved to be highly successful and will be repeated in future research projects.

4. DESIGN OVERVIEW

The NASA Wireless Smart Plug (NWSP) system design can be seen in Figure 4 and consists of two main components. The first component is the NWSP module (shown in the area shaded grey) that acts as a power interface between the Deep Space Habitat (DSH) power grid and each device placed on the power grid. The purpose of the module is to allow remote control and monitoring of the power consumed by the end device. To this end, NASA requested a single module that could handle both the 28Vdc and 120Vdc power systems that might exist in the DSH and that would work with a single end device. The second component was a software interface that could run under Windows (shown in the light blue shaded area); could communicate with each NWSP module through an existing ISA 100.11a wireless infrastructure; and could provide remote control, monitoring and data logging for each module in the system.

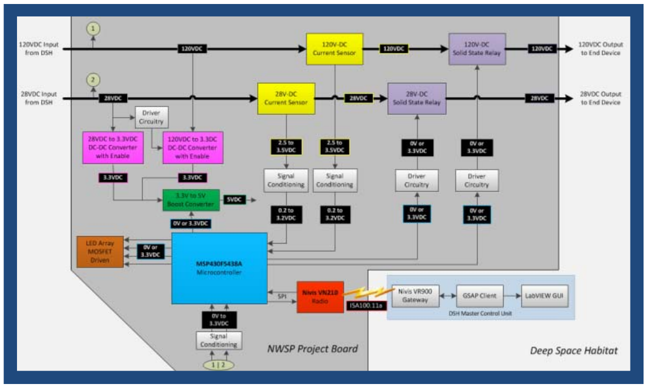


Figure 4. NWSP Functional Block Diagram.

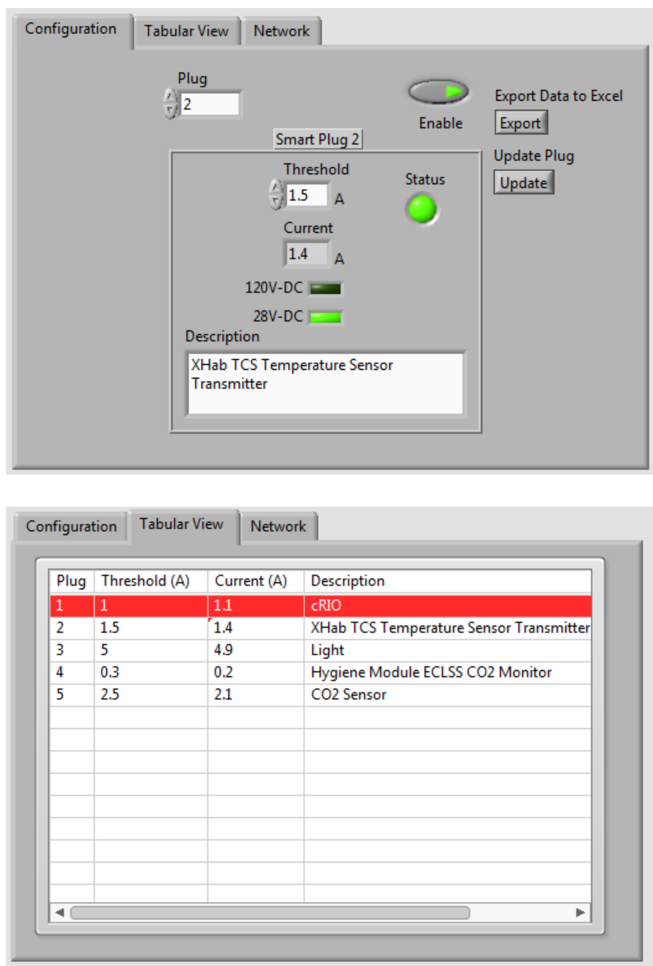
NWSP Module

As seen in the functional block diagram of Figure 4, the 120Vdc and 28Vdc power are connected to the input of the module. Both of these lines are then monitored for current flow through the use of hall-effect sensors and are independently controlled through solid state relays. The power lines are then made available at the output of the module where the end-device can be connected. The Texas A&M group specified six-pin screw-type input and output connectors for this proof-of-concept which were then adopted and supplied by the NASA DSH group. The connectors allow both 120Vdc and 28Vdc to be connected to the module simultaneously.

To provide control, a TI MSP430 low-power microcontroller was specified. The microcontroller read the two current sensors by digitizing their analog output voltages using an internal 12-bit analog-to-digital converter. The analog signals were first conditioned to ensure that currents from 0 to 5A would effectively use the range of the converters. The microcontroller was interfaced to the solid-state relays through signal-conditioned digital output ports. In this way, the NWSP module could not only control whether the end-device was powered but could also read, record, and respond to the current drawn. Multiple LEDs were also interfaced to microcontroller outputs through driver circuitry. The LED indicators allow the user to determine whether the unit is powered, connected wirelessly to the DSH network, whether the module is currently providing power to the end-device, and whether an overcurrent condition exists.

To power the NWSP module's internal intelligence from either 28Vdc or 120Vdc, two DC-to-DC converters were used to deliver the required 3.3Vdc. In addition, a 3.3V to 5V step-up switching regulator was used to provide the 5V needed for the current sensors. The DC-to-DC converters were configured so that only one provided power at any time. Communications over the ISA 100.11a was accomplished using a VN210 wireless module from Nivis. In addition to limited technical support from the manufacturer, the students also had access to NASA engineers who had previous experience with the wireless module and gateway.

Finally, control and data aggregation of the NWSP modules was accomplished using two software packages. In order to log data and provide a user interface, the student team developed a server and GUI using LabVIEW as shown in Figure 5. The server allows the user to monitor the current measurements and control the on-off states of each NWSP module through the ISA 100.11a network. Because the API for the radios was not readily available, the student team had to use a second software package provided by Nivis (GSAP Client) to send control commands to the radios. This forced a situation where commands generated by the LabVIEW software had to be manually entered into the client software in order to control the radios.



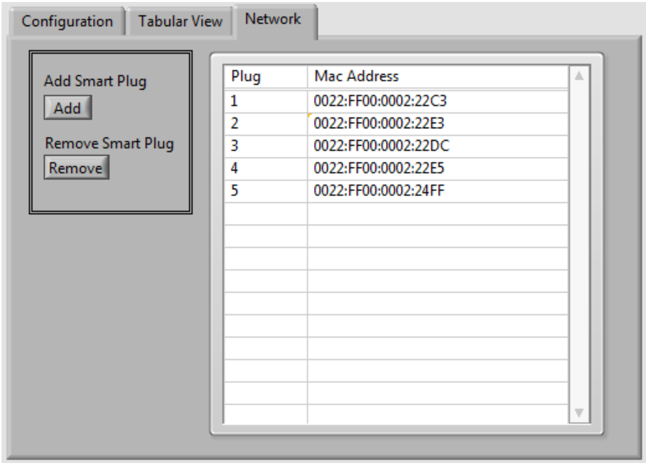


Figure 5- LabVIEW GUI Panels.

The hardware design for the NWSP was converted to schematics, board layouts and Gerber files using the EagleCAD environment. After procuring professionally manufactured PCBs, the Capstone team populated all the boards including the fine-pitch parts. Figure 6 contains a fully assembled NWSP Printed Circuit Board (PCB).

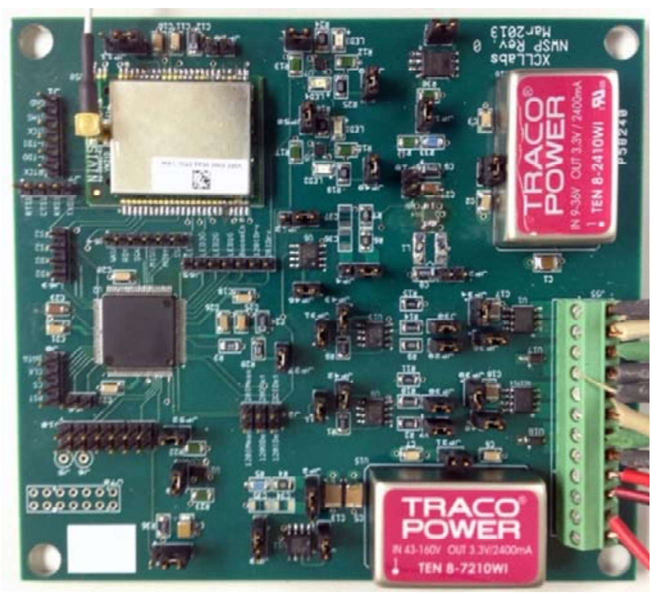


Figure 6. NWSP Populated Printed Circuit Board.

The enclosure for the final device was designed by the student group and prototyped using a 3D printing process. It should be noted that due to the rapid prototyping equipment available to the students in the Product Innovation Cellar, the team was able to turn both electronic and mechanical preliminary designs around in less than forty-eight hours. A picture of the final NWSP module can be seen in Figure 7.

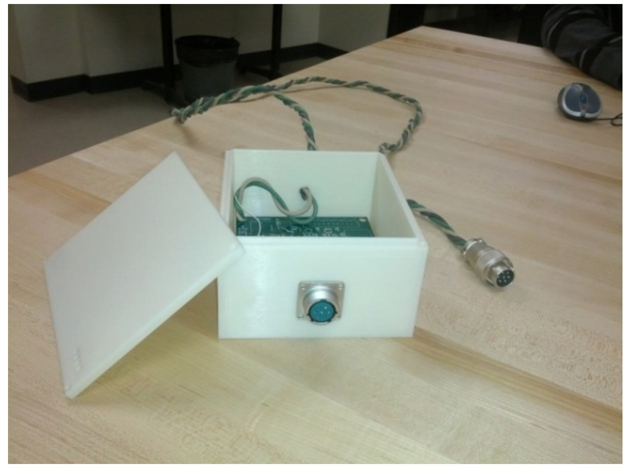


Figure 7 – NWSP Module.

The NWSP system design posed unique challenges for the student team. First, the students had never dealt with the problem of powering low voltage circuits from high (120VDC) voltages. Ultimately, they solved the problem through the use of a commercial-off-of-the-shelf DC–to-DC converter. Second, the intelligence of their module had to be powered from either 28VDC or 120VDC, depending on which was available. Their solution was to use the existence of 28VDC to power down the 120VDC DC-to-DC converter. Thus, the system always runs from 28VDC unless it is not available. Finally, while NASA required that the two power systems' grounds remain isolated from each other, the intelligence in the module had to be connected to both of the grounds. This problem was solved through a clever use of diodes to ensure that the two grounds remain isolated regardless of the module's power source.

5. SYSTEM TESTING

Lab Testing

The initial testing and validation of the smart plug system was done in the Product Innovation Cellar (PIC) and the Mobile Integrated Solutions Laboratory (MISL). To support system testing it was necessary to fabricate both adjustable loads and fixed power sources.

28VDC

The 28VDC source was simulated using a bench top DC power supply. For the load, a resistor bank was used. The bank consisted of five 30-ohm loads (three 10-ohm resistors in series) connected in parallel. Each load cold be connected or disconnected from the plug, allowing several different fixed loads to be configured to support test data collection. The adjustable load bank is shown in Figure 8.

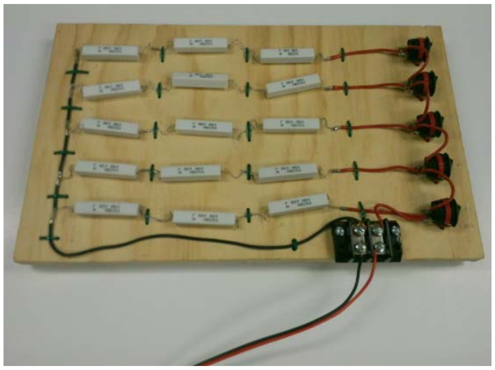


Figure 8. 28VDC Adjustable load.

120VDC Power Source

The 120 VDC supply was more difficult to achieve. To create the 120VDC source, several battery packs were cascaded to form a high voltage power source. In addition, a connector was added to simulate the DSH power system. The 120 VDC power source is shown in Figure 9. Light bulbs were used to simulate loads at the higher voltage.

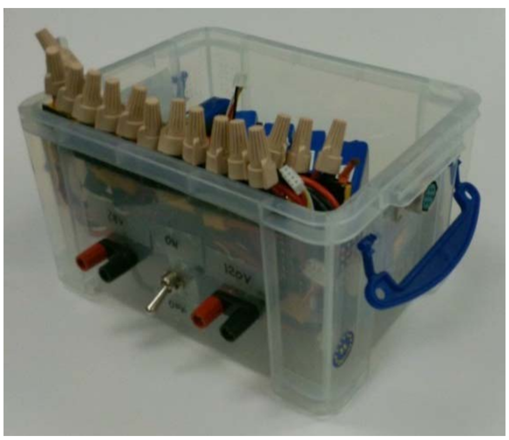


Figure 9. 120VDC Power Source.

Current Sensor Characterization

The current sensor that was signal conditioned provided a 0.2 to 3.2 V output that is proportional to the current being supplied to the load. To validate the hardware signal conditioning, several data points were taken and the accuracy of the conditioning was evaluated. A Current meter was used in series with the sensor and a Voltmeter was connected to the output of the signal conditioning circuitry. These results are depicted in Figures 10 and 11.

Figure 10 compares the digital output of the analog to digital converter of the microcontroller with a linear (ideal) change from the smallest to largest current measured. This graph indicates that the linearity of the current sensor is suitable for this application.

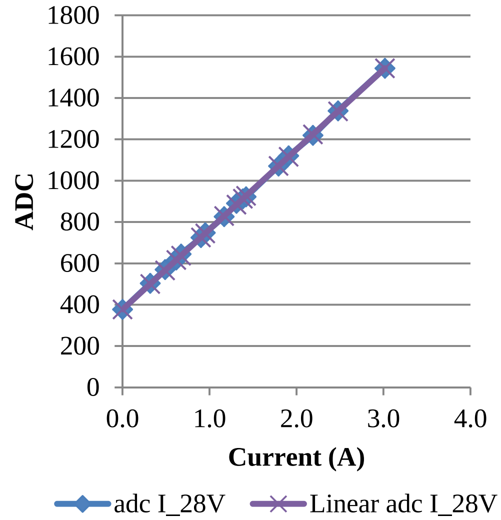


Figure 10. ADC Measurement vs. Ideal.

Figure 11 compares the voltmeter readings to the value determined from the conversion of the analog to digital output converted to a voltage reading. Based on these data which were similar across all smart plugs, a decision was made to offset the zero current value dynamically in software and then introduce a gain to provide the most accurate determination of actual current being supplied to the attached device for all levels of supplied current.

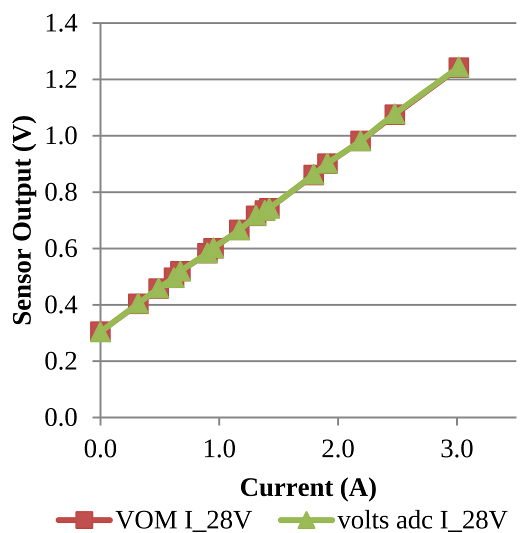


Figure 11. Sensor Output Results.

Although the sensor output was precise, it was not accurate enough to meet the ±3% of full scale specification. To increase the accuracy, a software calibration algorithm was developed. It consists of two parts: an offset and a gain. The output of the sensor is monitored while the smart plug is disabled. This voltage measurement becomes the zero current reference and is used to shift the output range to be 0V at 0 amps. After applying the offset, the sensor output is scaled using a gain. The gain adjusts the maximum value to be 3.3V at 10A. Figure 12 demonstrates the correction of the raw sensor output voltage to provide a linear transformation from 0 to 10A of supplied current. This algorithm provides the necessary dynamic calibration and gain correction to meet the required measurement specification.

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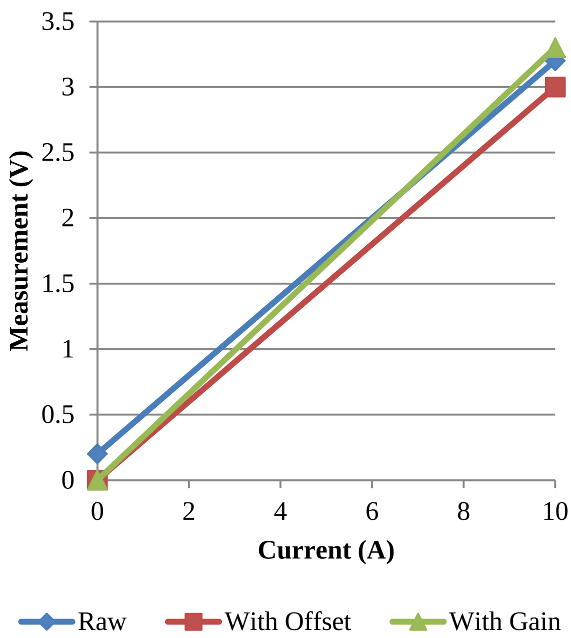

Figure 12. Sensor Output Correction Process.

Installation Phase.

The installation phase was fast tracked to ensure the NWSP system could be installed and accepted during early summer. This posed a problem because the DSH Nivis firmware update was not scheduled for the DSH until later in the summer. As a workaround, two gateways were used. One gateway supported the existing network running on the old firmware, and the other supported the Smart Plug network that operates on the new firmware. To accommodate the network changes, each smart plug was reprogrammed with a new IP address and associated (re-provisioned) with the new gateway. All NWSP radios were re-provisioned to the new gateway during the installation phase of the project.

Field Testing.

While preliminary system testing was done on the NWSP system within the MISL laboratory at Texas A&M University, complete functional testing was performed in the DSH facility at the NASA Johnson Space Center in Clear Lake, TX. The reasons for this were two-fold. First, full system testing required that the NWSP system be integrated into the DSH ISA 100.11a wireless network. Second, exhaustive functional testing required the use of specialized variable DC power supplies and programmable loads only available on-site at NASA.

To perform the field testing, three separate visits were made to the DSH facility in Summer 2012. The first visit focused on installing NWSP software on the DSH control computers and verifying interoperability between the NWSP system and the existing ISA 100.11a DSH network. Debugging was required to ensure that all of the NWSP modules were addressed correctly. Once these changes were made, testing demonstrated that NWSP modules were able to connect with and communicate over the DSH wireless network as expected. The second field testing visit was devoted to verify current switching capability and measurement accuracy. Figure 13 shows the testing setup used in the field. First, all five NWSP modules were powered and connected to the wireless infrastructure. Next, each module was tested sequentially by connecting them one at a time to the DSH power supplies and to a 0-5A programmable load (name, company). The current was then swept by programming the load from 0 to 5A in 0.5A steps at both 28V and 120V and the current readout was recorded for post-processing. In addition, each module was tested to verify the ability to wireless switch the circuit off and on.

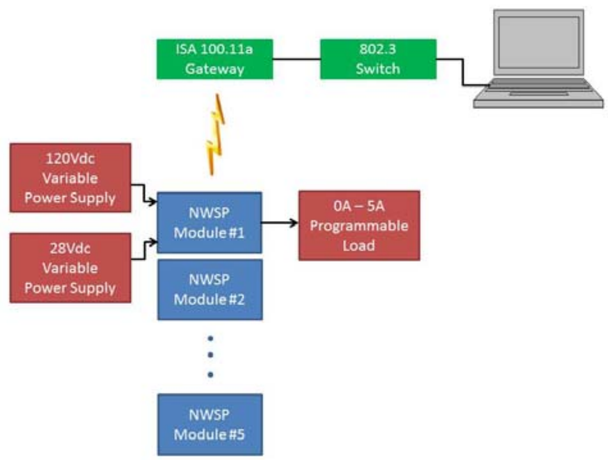

Figure 13 – NWSP Field Testing Setup.

As a result of this testing, it was found that the NWSP modules did not meet the current accuracy of the NASA specification of +/- 3% of full scale (.15A) at the high end of the measurement range. The modules were returned to MISL and the research team created a software calibration routine that used a slope and offset to correct for the error. In addition, a dynamic offset measurement routine was added to the software that automatically calculated the offset on power-up. Finally, a third field test visit was made to validate the changes and ensure that the modules would meet specifications. Once it was verified that the modules functioned and complied with all NASA specifications, the units were delivered for acceptance testing based on a test plan created by ESET faculty and students and approved by NASA engineers.

DSH Testbed

A key attribute of the DSH project is the Deep Space Habitat Testbed shown in Figure 14. The DSH Testbed serves as the proof of concept and early integration platform for deep space habitation subsystems and technologies in a vehicle-like context. Its purpose is to perform early integration and risk reduction of habitation systems while developing the capabilities needed for human exploration missions. The DSH Testbed also enables affordable development of DSH capability through partnerships and collaborations.

Figure 14. Deep Space Habitat Testbed.

Goals of the DSH Testbed include:

- Functioning as a habitat systems integrator and technology pull across many domains
- Developing and integrating software-based models of habitat systems with system-to-system interdependencies
- Enabling maturation of select habitat systems
- Integrating physical hardware where available
- Distributed testing to link to other facilities

The DSH Testbed provides a place to build the instance of the DSH vehicle, and as a result provide integration testing of habitat subsystems and technologies in a vehicle-like context. Some of these technologies include: wireless sensor nodes (WSNs), power, avionics, software, impact detection, communications, and crew systems (displays, tele-robotics workstation, and programmable lighting).

Testing in an incremental fashion, subsystems can be added on to the core architecture, modularly removed and replaced, and finally matured. Subsystems also do not have to be physically present in order to be included in the Testbed. The DSH Testbed is able to perform a combination of local and distributed connectivity to remote hardware and software to complete vehicle integration. Finally, subsystems can be of varying maturity levels, and even exist as simulations. The DSH Testbed is able to host subsystem models and simulations and include them in the integrated habitat vehicle.

Acceptance Testing

Acceptance testing was performed in the DSH Testbed according to the approved Acceptance Test Plan (Figure 15). The objective was to verify design and performance requirements levied by the DSH project. One smart plug was selected at random (Smart Plug #5), instrumented, and subjected to a total of nine acceptance tests.

Figure 15. Acceptance testing in progress.

Figure 16 contains a block diagram of the equipment configuration used in the testing conducted at the DSH.

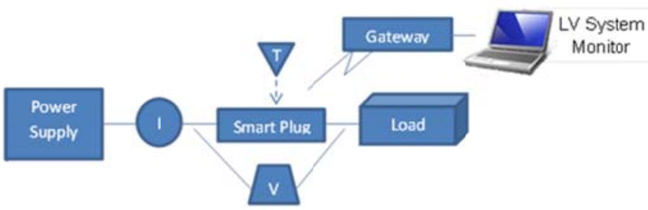

Figure 16. DSH testing configuration.

As shown in Figure 17, the smart plug was connected to a 28/120 VDC power supply as its source and a Kikusui PLZ-4W programmable load bank (PLB) as its load. Both the power supply and the load banks were powered by the DSH Testbed facility.

Figure 17. Acceptance testing configuration.

The NIVIS wireless gateway was installed in the DSH Ethernet network with a vehicle IP address, as was the LabVIEW System monitor computer. The NIVIS wireless gateway used for the design and test of the NASA Wireless Smart Plugs is an upgraded version of the model gateway already used in the DSH vehicle to monitor environmental instrumentation.

Under a wide tolerance of input voltages, the smart plug was configured to provide and measure a constant current to the PLB and also to representative "real world" inductive loads. The result of acceptance testing was a "Pass" for all eight tests, as the smart plug was able to measure its supplied current within +/- 3 % of full scale for all power and load configurations.

Endurance Testing

Figure 18 depicts the ninth and final acceptance test configuration for endurance testing. All smart plugs were connected to DC loads and run continuously for 168 consecutive hours. The smart plugs supplied 1A of current to each load for the duration of the test. Each smart plug held its output steady for the entire 168 consecutive hours with no drift. The touch temperature of each box also remained steady, which was a potential concern.

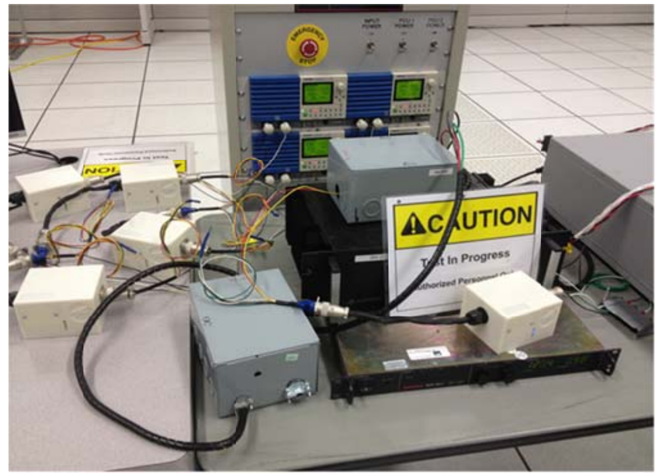

Figure 18. Endurance testing in progress.

6. LESSONS LEARNED

Throughout the process, several lessons learned were gathered from all aspects and partners in the project. These lessons are bulletized below.

- Conduct meetings/discussions in initial phases to make sure all the requirements from various stakeholders are included and everyone is on the same page.
- Project success was enhanced by having a technical POC and DSH POC regularly involved, which helped to get the information the students needed and focus the work.
- Voltage measurements should be present in addition to indication – Voltage was "detected" by the smart plug and even identified as 120 or 28, but its exact value was not measured and displayed. This was not a project requirement, but should be a relatively simple and essential addition.
- LABVIEW should be the front end for commanding the NWSP - Using LabVIEW as the intermediary to the NIVIS native software was a good first step in a path to DSH core software architecture, but it could be expanded. The LabVIEW GUI should be the front end for both telemetry viewing and sending commands, as is commonly done with other DSH subsystems. That would leave the NWSP only one step away from fully integrating with the DSH core software, and that could allow for more intelligent and autonomous control of the NSWP and the DSH vehicle in general.
- Be prepared for difficulties when implementing new communication protocols where there is limited vendors and technical support.

- Project transfer from Capstone team to MISL team could have been improved by additional interaction of the teams during design/implementation.
- Integration of two disparate power sources with isolated grounding presented unique technical challenge.
- Need to maintain balance between customer needs and ability to include technical features, which is important to overall project success.

7. FUTURE WORK/ RECOMMENDATIONS

This project was a first step at developing wireless DC current sensors with command capability. From the lessons learned and the testing completed, there are several recommendations for enhancing the design of the prototype and expanding this type of partnership in the future. This future work and the recommendations are discussed below.

- Full integration with the avionics/software of the DSH
- Upgrade to metal enclosures instead of plastic for EMI issues
- Fully integrate command and control capability into the master program
- Upgrade DSH mesh network and have both sets of instrumentation running on the same network to see how it all works together
- Need to further investigate the high temperatures of the units at higher amperage
- Long-term development partnership between NASA and academia needs to be develop for continuity of major development activities
- On-campus student internships should be integrated into major development projects such as the NWSP

8. SUMMARY

In summary, the NASA Wireless Smart Plugs were designed, built, and tested per the Deep Space Habitat vehicle architecture. Using the NIVIS wireless gateway, ethernet, and LabVIEW software, these innovative devices will prove immediately useful as part of the DSH vehicle instrumentation suite.

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