SSC20-WP2-36

Methodologies for Development of a Modular Wiring Harness for Use in Small Satellite Constellations

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Abstract

With the rise of satellite constellations imminent, the University of Toronto Space Flight Laboratory (SFL) has prioritized creating repeatable, modular spacecraft bus designs that can be produced with lower effort, cost, and time. Streamlining for larger production quantities inspired the development of a new SFL bus. DEFIANT aims to satisfy the need for a spacecraft bus capable of supporting a wide variety of payloads all using almost identical structure, power architecture, computing systems and wiring harness. The wiring harness connects all electrical components within the structure and can pose significant challenges during assembly and integration if not considered during initial design. Using the principles of point-to-point harnessing coupled with an increased number of connectors and carefully selected connector location, the harness has been designed from the start to support constellation missions. Iterating through various degrees of fidelity in wiring routing provided practice for the engineering team to offer near constant feedback. With this work, the DEFIANT bus harness design is robust for various constellation missions at SFL and identifies a methodology for developing future modular harnesses for other spacecraft.

Background

The microspace approach prioritizes using existing components or subsystems instead of designing from scratch at almost every opportunity to reduces costs and development time. This coupled with extensive testing on components and assemblies proves the robustness of the strategy [1]. Unfortunately, wiring harness is often left until the end of the design phase, often resulting in complex, time-consuming and error prone designs that are discarded when a new mission is commences using the same bus. **Figure 1** illustrates the breakdown of a typical space mission where the harness would typically reside in the Systems level as it interacts at the component level and with the systems in place.

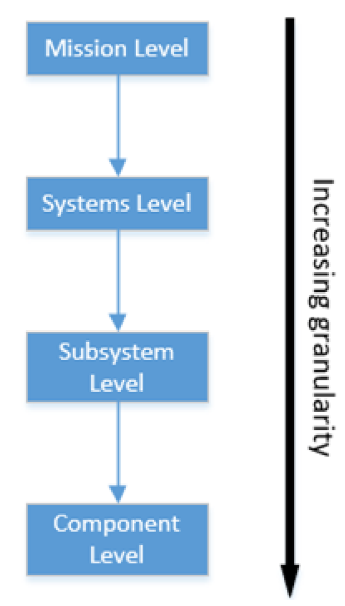

Figure 1: Space Mission Breakdown

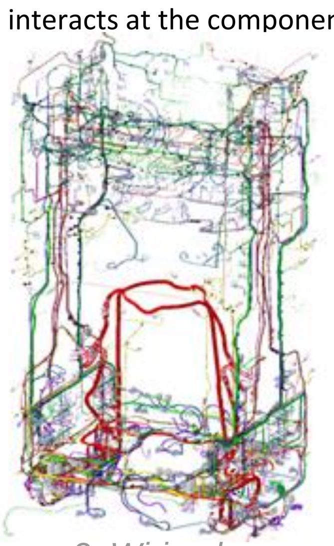
Figure 2: Wiring harness in large communications spacecraft

Figure 2 provides a model of a large communications satellite and the bundles diffusing throughout the structure. This structure has over 50,000 connections and 20km of wiring [7]. Large spacecraft also tend to prioritize redundancy with their subsystems as the missions are expensive, involve decades of work, and have long mission lifetimes, thereby reducing tolerance to perceived risks.

Figure 3 shows a small satellite harness with scale. The reduced complexity is due to the mass and volume constraints as well as the significantly lower number of parts in a microsatellite. The harness in a large satellite is made of several smaller harnesses combined, compared to what is typically a single harness for SFL spacecraft. This approach of one long harness is consistent with the initial designs for microspace as they were low cost, low complexity due to a limited number of components, and relatively easy to assemble.

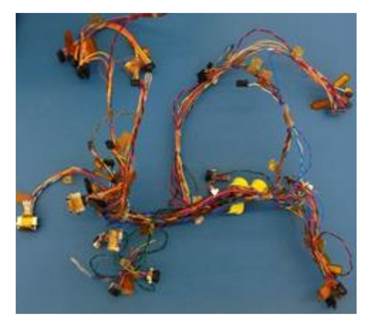
Figure 3: SFL NorSat-1 Harness with scale

DEFIANT Program

The DEFIANT bus is designed for constellation use and with this each subsystem is designed for high production quantities. Increasing the bus modularity and streamlining the development process through critical assessment contributes to the scalability of the design for future missions. The harness is a major component of that modularity due to its interaction with all subsystems. A sample of the DEFIANT bus external structure is in **Figure 4.**

The DEFIANT bus has more power generation, more payload volume and uses off-the-shelf separation systems as compared to smaller SFL satellites. DEFIANT is a size up from the NEMO bus, which uses an XPOD dispenser. DEFIANT is more mass efficient by virtue of not requiring a dispenser for launch vehicle attachment and separation [9]..

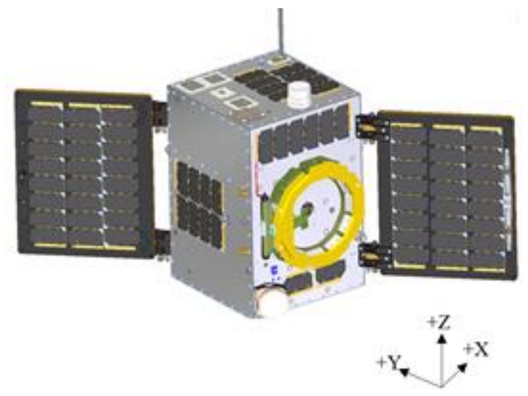

Figure 4: DEFIANT Bus Example

Table 1: DEFIANT bus characteristics

Mass	20-40kg (not including 5-10kg payload)
Volume	30cm x 30cm x 45cm (nominal)
Features	Deployable arrays mounted on long edges Off the shelf separation system
Payload	Variable masses and volumes (e.g. imaging, propulsion systems, radio)
Layout	3 trays internally, 6 external panels

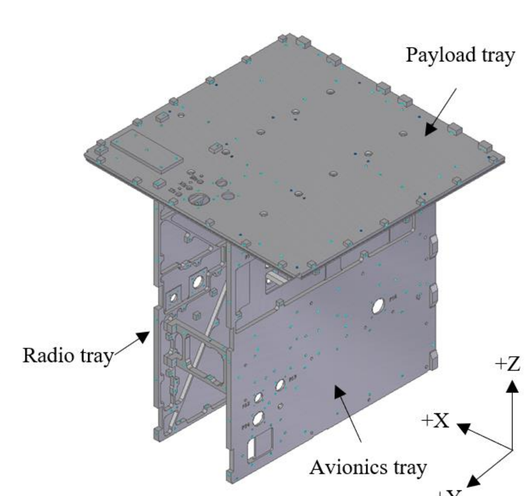

Figure 5: DEFIANT Bus Tray Example

The DEFIANT bus has been designed with the intention of modular capability by dividing the structure into three primary bays: payload (+Z), radio (+X) and avionics (-X). These divisions separate the components in each bay allowing the components to be built up on the outside surfaces of their respective trays on the benchtop before integration into the pi-shape in **Figure 5**.

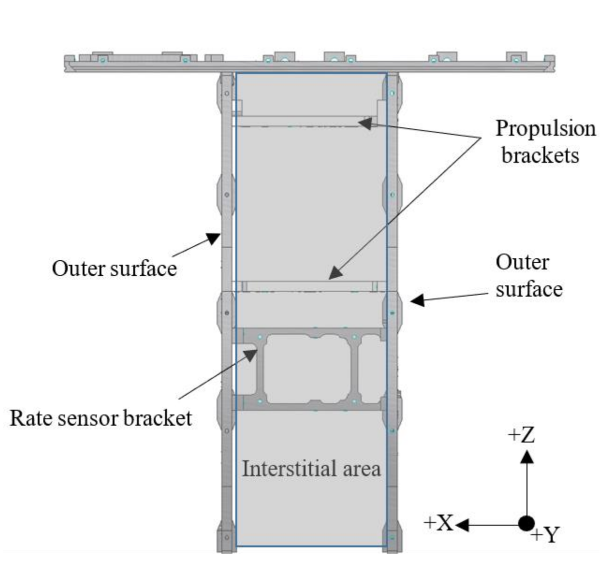

Figure 6: DEFIANT Bus Tray Example

As shown in **Figure 6**, there are three brackets that span the –X and +X trays: upper and lower propulsion system brackets and a bracket for the rate sensor. The interstitial bay is shown shaded between the two trays.

The bulkhead connector is defined as the connector that is panel-mounted to the tray structure. One side of the connector is mounted directly to the tray and the mating connector directly plugs into the tray. **Figure 7** below shows an example of a panel-mounted bulkhead with harnesses on each side.

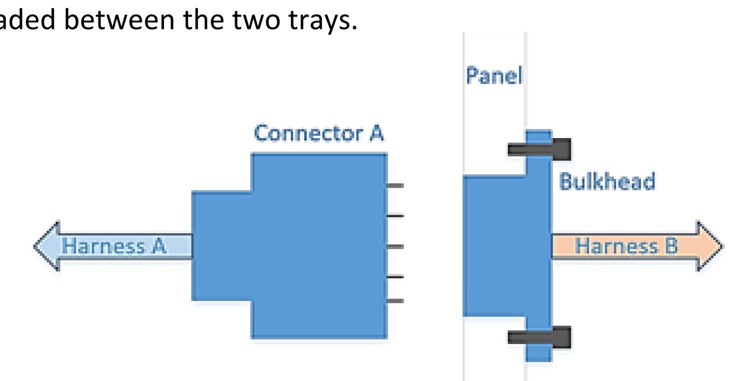

Figure 7: Bulkhead connector diagram

Harness Approach

From this perspective, there are three main areas that were considered for the DEFIANT harness design: connector bulkhead in structure, connector types, and harness routing. With this work done in advance of the flight builds, significant late-stage work is saved, and the design achieves the goal of modularity. **Figure 8** shows the typical process for the microspace approach in missions compared to what the SFL team recommended for harness development. To be able to develop the structure and harness at the same time, there are three major features that had to be defined that the author contributed, described in **Figure 9**.

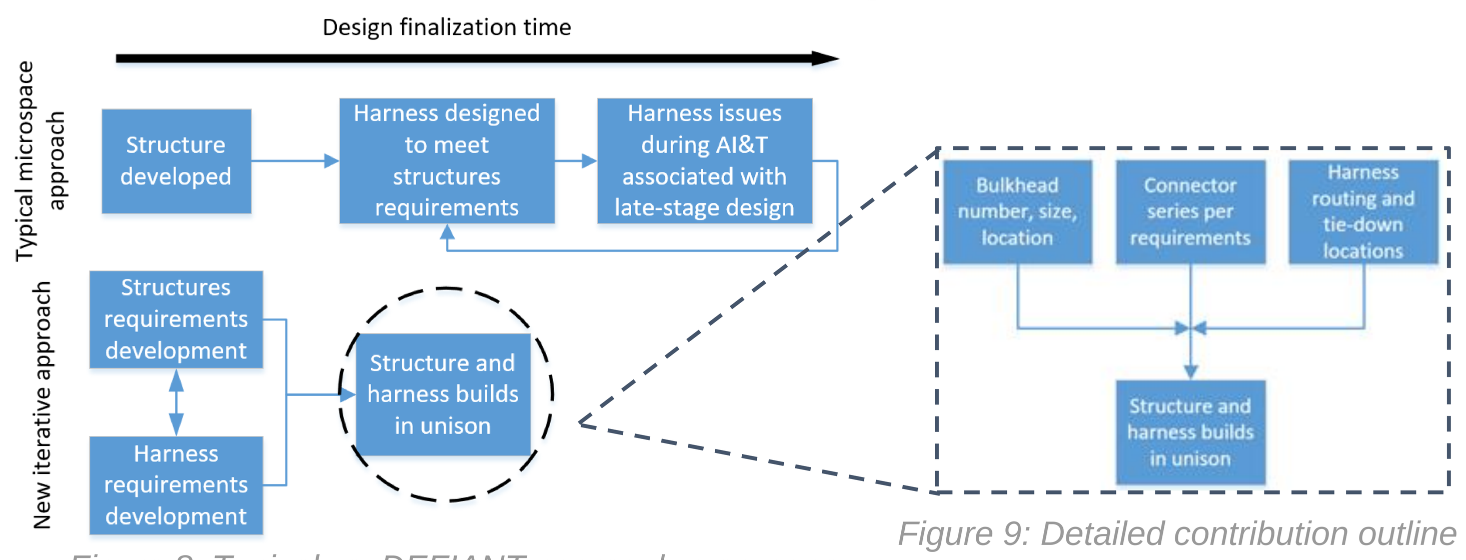

Figure 8: Typical vs. DEFIANT approach processes

Figure 9: Detailed contribution outline

It is vital to use this process to address the interstitial harness that spans between the –X and +X trays in the DEFIANT bus. This harness is particularly challenging due to the interconnectedness of the connections between the avionics and radio bays. In reducing the complexity on the outer side of each tray, the interstitial area becomes much more intertwined. The author's first step to design the harness was to determine which approach will guide decision-making. **Table 2** summarizes the advantages and disadvantages to each approach.

Table 2: Harness approach criteria

Factors	One splitting harness	Multiple harnesses
Assembly	Assembled with many connections to move power and signal, limiting connectors to component-level	Assembled individually and connected with in-line or bulkhead connectors
Safe-to-Mate	Difficult and time-consuming due to high number of connections (e.g. double crimps or occasionally splices)	Simpler due to higher number of separate cables that can be tested individually
Debugging, Repair	Very difficult - requires taking apart major bundle to repair any harness	Easier as the harnesses can be disconnected and worked on individually
Connectors	Minimum required between source and destination components	More due to in-line and panel mount bulkhead connections
Mass and volume	Minimum mass and volume due to limited number of connectors	Higher mass, volume due to modularity
Routing	Can be tied at regular intervals as connectors spaced apart	Requires more tie-down locations to secure due to more harness, connectors

With the information above, the multiple harnesses approach was selected due to the benefit of modularity. DEFIANT requires a modular harness in order to build a modular structure overall. Objectives were defined to complete the harness design:

1. **Determine the type of connectors required for the DEFIANT bus**
2. **Perform a connector trade study to find the connector product lines to use**
3. **Determine the number of bulkheads on each tray and their locations**
4. **Draft first harness routing on 3D printed tray jigs**
5. **Select the appropriate harness manufacturing technique**

Connector Selection and Trade Study

Connector selection is vital for a new spacecraft bus as it drives a significant amount of time during assembly, integration and test. The type of connector in this case is driven by the need to use a bulkhead system, not in the case of other missions which are more mass and volume constrained. DEFIANT has assumed a larger harness mass to accommodate this design approach.

The types of connectors the DEFIANT program needed are Test Ports, Bulkheads (filtered and unfiltered), radio frequency connectors, and Mixed Power.

The next step was to assess which connectors would satisfy each condition. To achieve that, the author built a connector trade study comparing many previously used connector product lines and new connectors on the market. They were all compared on the following criteria:

1. **Cost (per standard number of units)**
2. **lead time**
3. **Availability of connector savers**
4. **volume (based on standard 9 pins)**
5. **filtering options**
6. **mounting options (e.g. jackposts, panel-mountable)**
7. **wiring type (e.g. pre-wired, solder cup, crimp)**
8. **shell material and plating**
9. **keying options**
10. **cycle life**
11. **tooling for install**
12. **vibration/shock ratings**
13. **temperature rating**
14. **space heritage.**

These extensive criteria in the previous section lead to the selection of the optimal connectors to enable DEFIANT to reach its goals through high cycle life, versatility, ease of installation and other factors.

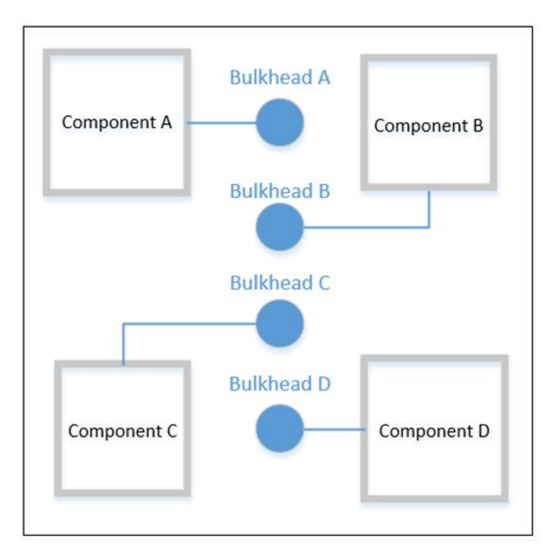

Figure 10: Bulkhead connectors and components A-D on front side of tray

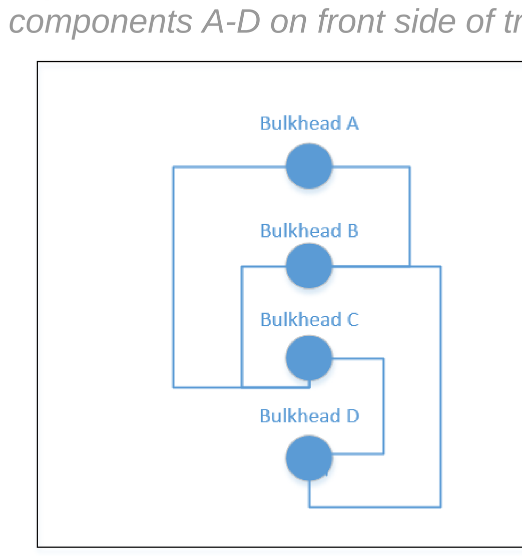

Figure 11: Bulkhead connectors and components A-D on back side of tray

Methodologies

With the understanding of what approach is selected, the kinds of connectors required, and the choices are made on the suppliers, the next steps are to both confirm the full design of the harness and begin routing. As described in Section 2, this means working with the subsystem engineering teams to confirm the harness will achieve functionality from a design point of view to connect and power all components.

With the design confirmed, this allowed the harness signals and destinations and gauges of wire to stay consistent, but the mechanical accommodations were able to be altered to best suit the platform. Specifically, the author made the following assumptions and are provided in **Table 3**, below:

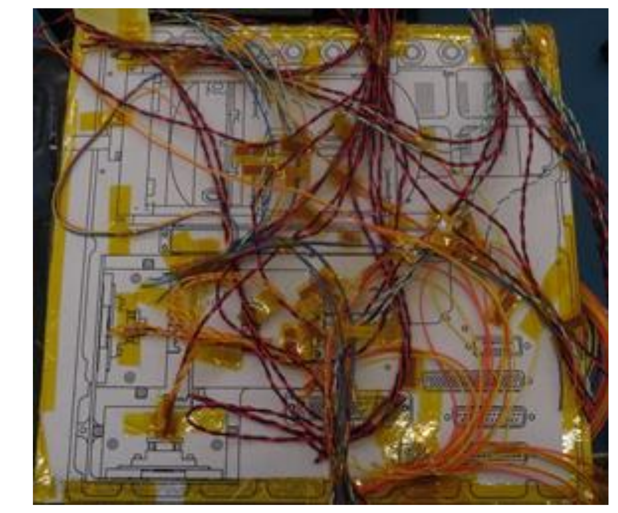
Figure 12: First attempt of cardboard routing to determine bulkhead locations

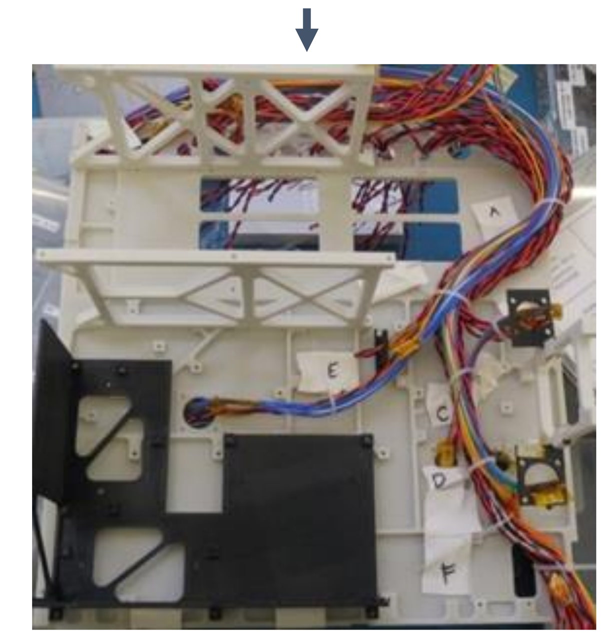
Figure 13: Author built first interstitial harness on 3D printed jig


Figure 14: Technician terminated interstitial harness

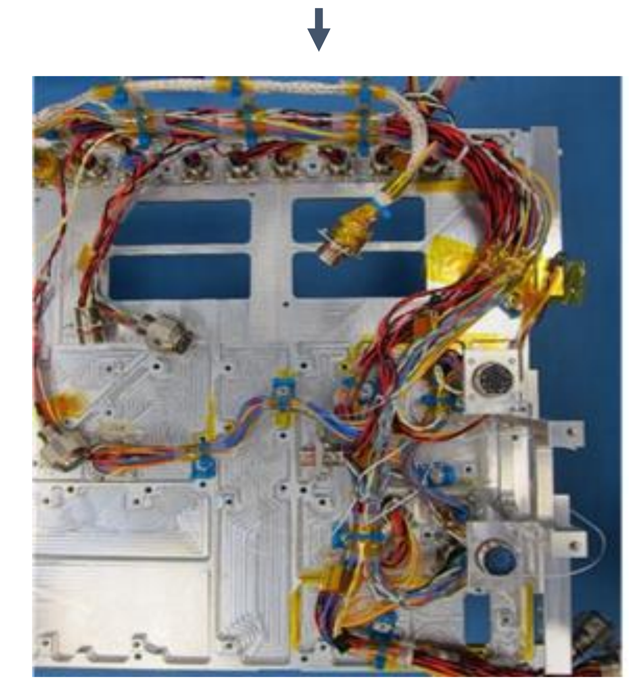
Figure 15: Final flight build interstitial harness mounted on flight structure

Table 3: Design space definition

Characteristic	Status
Signal name, source and destinations	Pre-determined
Splice number	Pre-determined
Splice location	Adjustable
Wire gauge, colour and material	Pre-determined
Wire length	Adjustable
Wire route	Adjustable
Bulkhead locations and size	Adjustable
Number and location of in-line connectors	Adjustable
Tie-down locations and type	Adjustable

These criteria were important to understand in order to recognize the boundaries of the design space. This approach to simplify the builds as determined at the start of the DEFIANT bus development process requires however that the outer side of the avionics and radio trays are simplified in terms of harness assembly.

Once the engineering team understands the design space, these are the steps that guide the build for the DEFIANT platform:

1. **Mount trays onto GSE so to lay with X-axis towards the table**
2. **Mount harness on inside of selected X tray per Figure 11**
3. **Flip tray and GSE to mount components to outside of X tray (Figure 10)**
4. **Plug in bulkhead connector to outside of tray for each component**

The processes for iterating on the harness development for the interstitial bay is summarized in **Table 4** and **Figures 12-15.**

Table 4: DEFIANT interstitial harness build process

Step	Process and Goals
Cardboard laydown	The author printed off two-dimensional cardboard to-scale copies of the tray and panel structure, mount them to cardboard, build up mock components and begin preliminary routing to determine the number, location and size of bulkhead connectors (shown in **Figure 12**). This exercise was helpful in the preliminary stages of structural design but is not true enough to the structure to be useful for the iterations of detailed design.
3D printed routing	**Figure 13** shows the first attempt at routing the interstitial area harness in two dimensions. To do so, the author cut out pieces of wire specified to the draft schematic and attempted to lay them on the cardboard in groupings to identify certain routing trends which would allow specific signals to pass through the same bulkhead.
3D printed tray schematics	The interstitial harness would be extremely difficult to manufacture with a traditional schematic for issues with repeatability. Specifically, the harness must be assembled in the correct order or else it is possible it will not reach to all the bulkhead locations without straining the wires. **Figure 14** is the harness after technicians build the harness through the advanced jig method and schematic details.
Flight builds and assembly	Harnesses built on the 3D printed jig are mounted to the flight structure in the cleanroom. All minutia for routing and tie downs are determined.

Figure 14 is an **image** of the completed harness where technicians have followed the detailed schematics and built the harness on the jig. Simultaneously, technicians were building the other approximately 45 harness stubs designed for this example spacecraft with notable consistency. Once the harnesses are built, the first step is the safe-to-mate test to ensure continuity and ensure the contacts are properly seated in the connectors. The author was responsible for the majority of STM for these flight and non-flight harnesses, including GSE and dirty sat.

Figure 15 is the interstitial harness mounted in the flight structure with all the components in place.

Results and Conclusion

The author assembled a significant proportion of these DEFIANT spacecraft and was responsible for assembly and routing for builds of all major subsystems. The principles outlined in this poster enabled the development of a highly modular, adjustable, easy to assemble and rework wiring harness that can accommodate many different payloads and components. Recognizing the new DEFIANT bus has the capability to support many new missions, the author used the methodology of iteration and non-recurring engineering to find the right connectors, the right locations, and the ideal routing.

The author worked from trade studies about connectors to cardboard routing and to 3D printing harness assembling jigs, the result is a modular wiring harness that is easy to assemble, disassemble, repair and troubleshoot.

The focus on a specific harness, the interstitial bay harness, enables a clear understanding of the reasoning behind each type of prototyping performed as part of the development phase, enabling the flight harnesses to be as repeatable and optimized as possible. This harness is robust, reliable and forward-thinking – features all spacecraft and engineering teams must have to ensure success in the future of constellation missions.