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Research Article

Electrical Wiring Design and Development Studies of a Communication Satellite

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ABSTRACT

In this study, information about a harness subsystem, connects signals and electrical power with 25 km of wiring and 1100 connectors, which is designed and developed for the communication satellite consisting of communication module and service module is given. Harness 3 dimensional layout is developed in NX computer aided design software, providing key design features i.e., minimum bend radius, easy installation and stress relief. A variety of design solutions are implemented in order to achieve electromagnetic compatible electrical wiring interconnecting system. Possible electromagnetic interference sources such as wire-to-wire coupling, electromagnetic field-to-wire coupling and structural current-to-wire coupling are eliminated. The electrical interfaces are developed in three phases: avionics architecture, pin to pin and connectivity design. As intermediate connectors are implemented to harness to provide physical separation which support system level modular design approach, also safe/arm connectors and umbilical connectors are implemented to satisfy functional and operational needs. "On panel" and "in panel" type connector brackets are developed for plug and receptacle connector mating. Harness components are chosen based on thermal ambient conditions and wires are sized according to current derating requirements.

Keywords: *Electrical Interface Design, Electrical Wiring Harness Design, Satellite Technologies.*

Bir Haberleşme Uydusunun Elektriksel Kablolama Tasarım ve Geliştirme Çalışmaları

ÖZET

Bu çalışmada, haberleşme ve servis modülünden oluşan haberleşme uydusu için tasarlanıp geliştirilen, sinyal ve güç hatlarının bağlantısını sağlayan, 25 km uzunluğunda ve 1100 adet konnektöre sahip kablolama alt-sistemi ile ilgili bilgiler verilmiştir. 3-boyutlu kablolama rota tasarımı, minimum büküm yarı çapı, montaj kolaylığı ve konnektör çıkışlarında stressiz büküm gibi kritik tasarım çözümlerini sağlamak üzere NX bilgisayar destekli tasarım yazılımında gerçekleştirilmiştir. Elektromanyetik uyuma sahip bir elektriksel kablo bağlantı sistemi elde edebilmek için çeşitli tasarım çözümleri uygulanmıştır. Kablolar arası etkileşim, elektromanyetik alan-kablo etkileşimi ve yapı üzerindeki akım-kablo etkileşimi gibi elektromanyetik etkileşim sorunlarına karşı önlemler alınmıştır. Elektriksel arayüz tasarımı üç aşamada gerçekleştirilmiştir: aviyonik mimari, uçtan uca bağlantı ve bağlanabilirlik tasarımı. Sistem seviyesi modüler tasarımı desteklemek amacıyla kablolamayı fiziksel olarak ayıran arayüz konnektörleri kullanılmış olup, fonksiyonel ve operasyonel ihtiyaçları karşılamak üzere güvenli/ateşle konnektörü ve göbek-bağı konnektörü kullanılmıştır. Sabit ve hareketli konnektörlerin montajı için "panel üstü" ve "panel içi" tipte konnektör braketleri geliştirilmiştir. Kablolama malzemelerinin seçimi çevresel sıcaklık koşullarına göre gerçekleştirilmiş ve kablolar akım azaltım isterlerine göre boyutlandırılmıştır.

Anahtar Kelimeler: *Elektriksel Arayüz Tasarım, Elektriksel Kablolama Tasarım, Uydu Teknolojileri.*

I. INTRODUCTION

Harness Subsystem is also known as electrical wiring interconnect system (EWIS), an assembly of electrical cables, used to connect electronic components (avionics), control units, sensors and actuators. Cables and/or wires which transmit signals and electrical power are bundled together and fitted with electrical contacts that are inserted to electrical connectors (Trommnau et al., 2019). The size of harness and the multitude of the interconnection requirements of on-board avionics make EWIS a highly complex system (Zhul et al., 2017). Harness contains various components i.e., wires, connectors, backshells, contacts, cable ties, electromagnetic interference (EMI) braids to provide electrical interfaces during all mission phases of the spacecraft.

A harness subsystem, with 25 km of wiring and 1100 connectors, is designed and developed for the communication satellite. Mass of EWIS, which includes power cabling (25 %), data transfer cabling (55 %) and mechanical components and shielding (25 %), is generally about 10 % of the dry mass of a spacecraft (Amini et al., 2006). Thus, during the development, minimizing complexity followed as a natural approach, which is just as important as the minimization of mass and volume (Junge et al., 2014). In order to achieve these design goals, main requirements are selected from NASA-STD 8739.4A and IPC/WHMA-A-620E standards (IPC, 2022) (NASA, 2022).

The newly developed communication satellite has at least 15 years operational lifetime. It is designed for operation in the geostationary orbit. Spacecraft is based on fully electric propulsion, which will enable all solutions including satellite subsystem design, orbit rising, station acquisition, station keeping maneuvers and ground segment operations to be compatible with this technology.

In general, a satellite platform consists of a satellite bus and a payload. While payload is responsible for the mission aspect of the satellite, the bus controls the satellite and provides support to the payload (Reda et al., 2023). As expected, new developed satellite is formed by communication module (CM) containing payload operating in Ka-band and service module (SM) including flight avionics, i.e. power conditioning unit, power distribution unit, battery, on-board computer and reaction wheels. Four multi-feed array Ka-band reflectors are placed in the West and East panels of the satellite. Satellite platform includes following subsystems:

- Structure and Mechanism Subsystem,
- Thermal Control Subsystem,
- Attitude and Orbit Control Subsystem,
- Power Control Subsystem,
- Electrical Propulsion Subsystem,
- On Board Data Handling Subsystem,
- Payload,
- Telemetry Command and Ranging Subsystem,
- Harness Subsystem.

II. LAYOUT DESIGN

Harness layout design also called as routing mainly relies on human experience and engineering constrains (Zhao et al., 2021). The most important initial step of EWIS routing design is to establish the design space (Gwozdecky, 2020). A 3 dimensional (3D) computer aided design (CAD) model of bundles is created in Siemens NX CAD software to maintain space allocation while integrating following key design features:

- Minimum bend radius of wires,
- Stress on bundles during installation,
- Stress relief on connectors,

- Electromagnetic compatibility (EMC) restrictions.

Figure 1 shows the 3D CAD model of the EWIS.

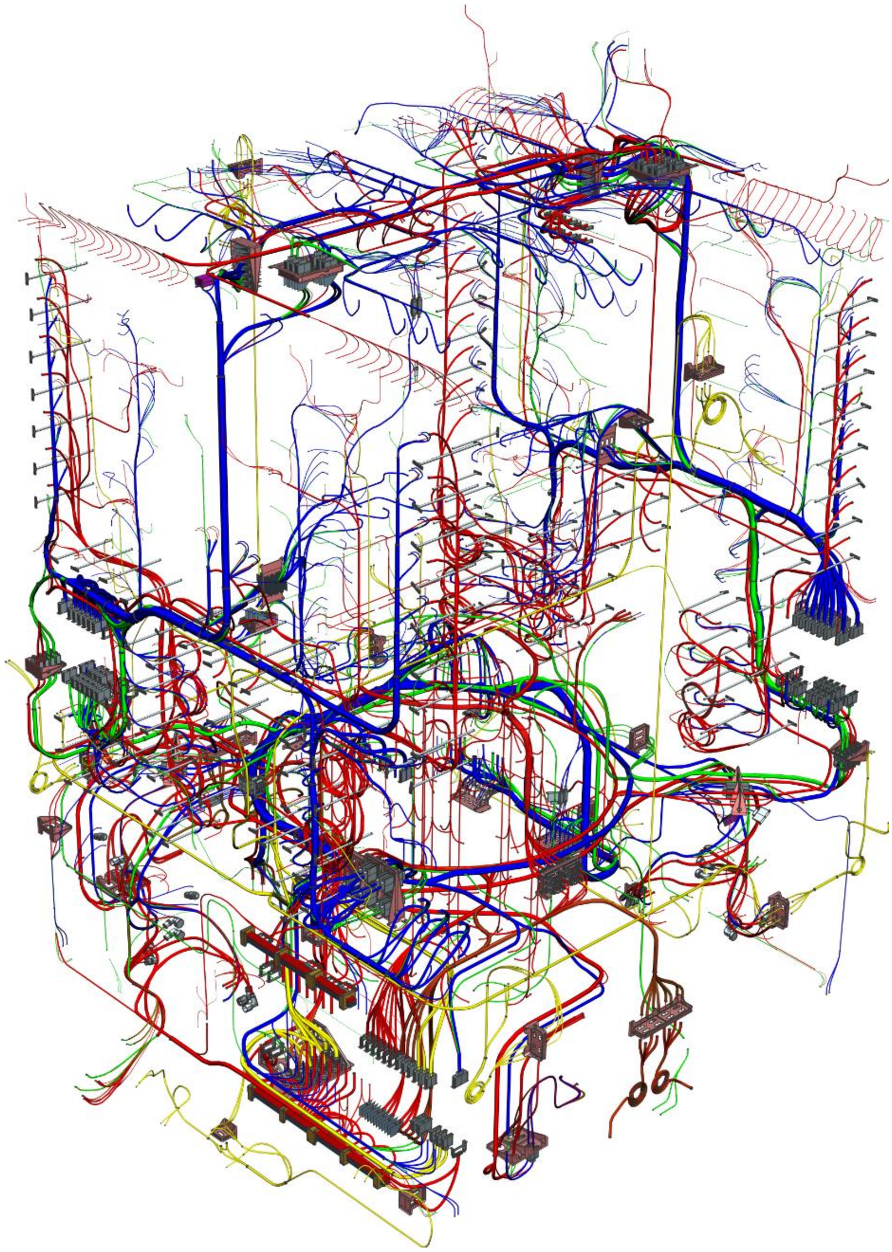

Figure 1. 3D CAD model of EWIS.

Due to absence of American wire gauge (AWG) 10 and smaller wires and coax cables inside wire bundles, the bend radius of bundles is limited to 3x (NASA, 2022). The automatic design features of NX CAD software are used during the development process to control bending of the bundles. In Figure 2, an example showing a proper bend radius practice of a cabled bundle is provided.

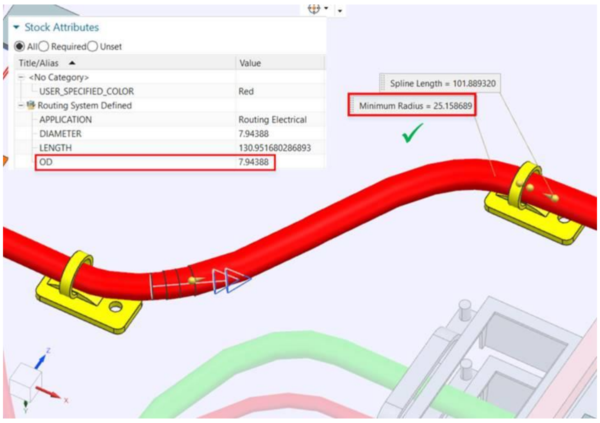

Figure 2. 3D CAD model of proper bend radius practice of a bundle.

In order to provide easy manufacturing, installation and integration in-line with modular design of the platform, harness is physically separated to CM and SM harnesses. Payload interface units, located on North and South CM panels, and intermediate connectors are used to connect CM harness to SM harness.

In contrast to traditional harness routing approach in SM, anti-earth deck is not used for harness routing and kept empty to maintain connector mating/de-mating operations during assembly, integration and test (AIT). As accessibility to connectors are analyzed in NX CAD software with a human model, no difficulty is foreseen for integration operations. Figure 3 shows the accessibility simulation performed in 3D CAD model.

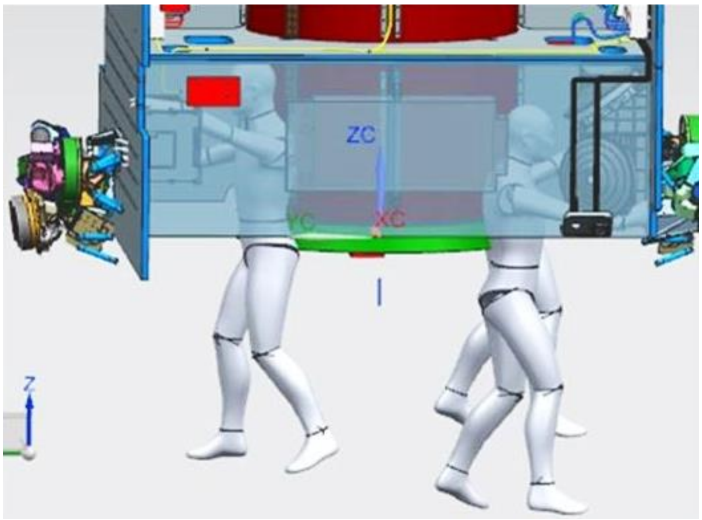

Figure 3. 3D CAD model of harness accessibility simulation.

Satellite is subjected to mechanical loads during various stages of the launch, i.e., static loads, dynamic loads and mechanical shocks (Reda et al., 2023). Harness is designed to withstand the mechanical loads that occur during launch. Bundles are fixed to structural panels with aluminum tie-bases with a maximum distance of 150 mm between each installation point.

Stress relief is the portion formed of a conductor providing sufficient length to minimize stress between terminations (NASA, 2022). Provision is made during routing design in order to provide sufficient stress relief for wires entering connectors from bundles. Each bundle layout is organized with smooth bends and sufficient stress relief such as in Figure 4 (NASA, 2002). In Figure 5, an example is provided which shows a proper design practice of a 3D routing of stress relief on back of the connectors.

Figure 4. Proper practice of stress relief.

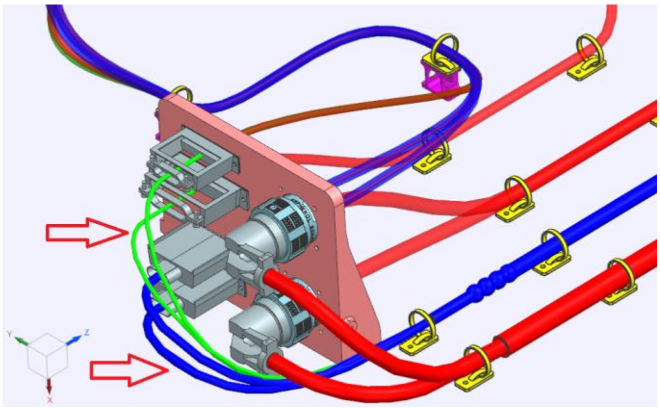

Figure 5. 3D CAD model of proper stress relief design practice of bundles.

Wires are bundled and routed respect to EMC categories of the electrical interfaces. In CAD model, different colors are used to clearly indicate EMC class of the bundles as defined in Table 1.

Table 1. Circuit type and colors used in CAD of the EMC categories.

EMC Category	Colors used in CAD model	Circuit Type
I	Red	Power Circuits
II	Blue	Digital Signals
III	Green	Analogue and Low Level Signals
IV	Yellow	Pyro Signals
V	Light Blue	RF Signals
VI	Pink	High Speed Signals

III. EMC DESIGN

EMC is one of the key design parameter for harness subsystem as EMI can be generated due to factors either created by satellite subsystems itself or generated by environmental factors such as launch vehicle or geostationary orbits electromagnetic environment. The possible EMI coupling sources can be wire-to-wire coupling, electromagnetic (EM) field-to-wire coupling and structural current-to-wire coupling (Dayashankara et al., 1997).

The reduction in wire-to-wire coupling can be achieved by proper choice of wires (shielded/unshielded) and by segregation of the wires according to EMC classes. Twisted cables are used for all power and signal circuits since inductive coupling is reduced by twisting the circuit with its return (Dayashankara et al., 1997). Based on electrical properties of the interfaces, bundles are categorized to different categories as listed in Table 1 (Air Force Space Command, 2009). Wires belonging to the same category are bundled together. Each bundle of different category is isolated from other bundles by maintaining a minimum separation of 30 mm distance (Air Force Space Command, 2009). In cases where this requirement is not practical due to insufficient free spacing, additional shielding is applied to prevent possible EM fields.

Based on the electrical properties of the interfaces, individually shielded cables or pre-woven overall shielding is used in EMI sensitive interfaces, as shielding reduces capacitive coupling (Dayashankara et al., 1997). As shielding provide metallic enclosure, the weak point of Faraday cage is the connection of shield to chassis ground at connectors. Different shield connection methods are outlined in a handbook of the European Space Agency. Handbook indicates that shielding connection at both ends of shields rejects external interference and improper pigtail connections creates weak point for shielding (ECSS, 2012). Thus, all shielding is connected to ground at both ends.

By Arthur T.Bradley and Richard J.Hare, the effectiveness of various shield termination techniques are evaluated under two different noise injection methods; transverse electromagnetic (TEM) at 3 MHz – 400 MHz and bulk current injection (BCI) at 50kHz – 400 MHz. The 5 samples which contain shielded cables are tested under TEM and BCI, which are shown in Figure 6. The results presented in Table 2 show that all type of 360 terminations provide nearly identical shielding properties except the pigtail method (Bradley and Hare, 2009). The EMI backshell method is employed for cable to shield termination within new developed harness, considering that backshells also provide mechanical endurance during connector mating/de-mating operations. Details of method used in EWIS are presented in Figure 7 (Bradley and Hare, 2009).

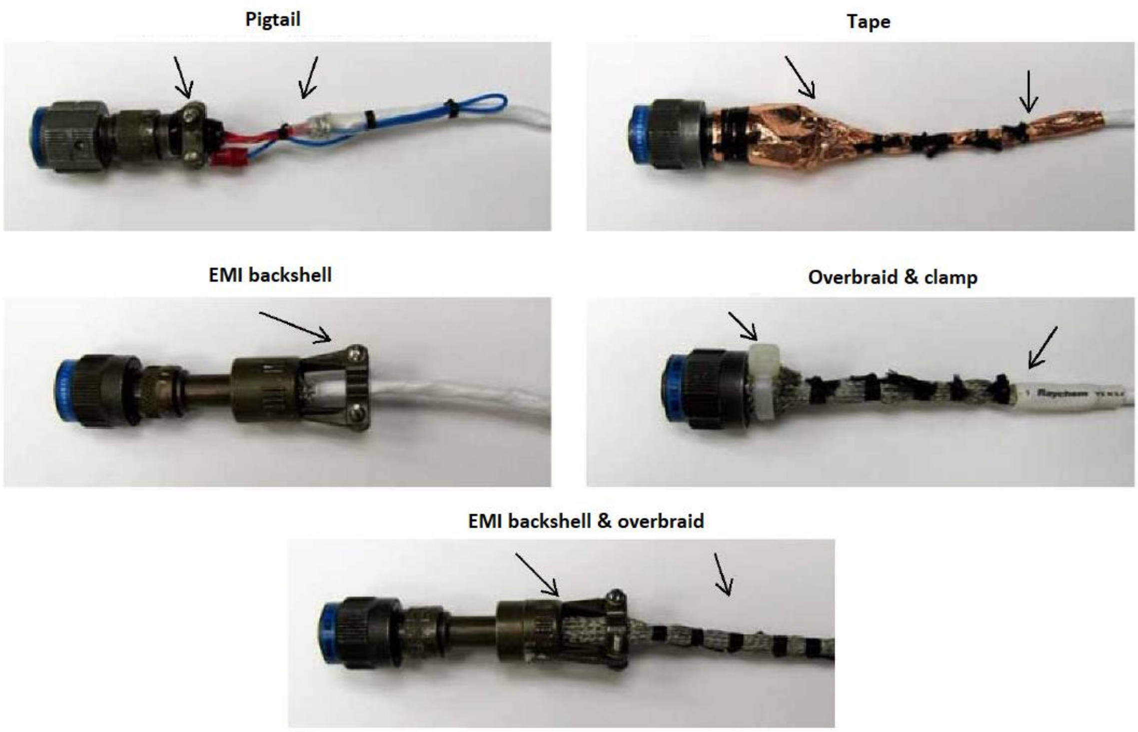

Figure 6. Tested different shield termination techniques.

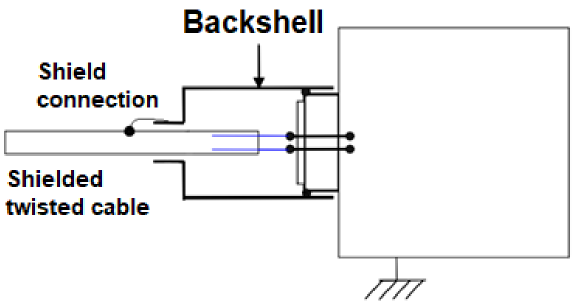

Figure 7. EMI Backshell shield termination technique.

Table 2. Test results of shield termination techniques.

Termination type	TEM (dB)	BCI (dB)
Pigtail	-7.10	1.26
EMI Backshell	-24.58	-17.68
EMI Backshell & overbraid	-25.31	-17.68
Overbraid & clamp	-24.47	-17.98
Tape	-24.24	-17.68

As Dayashankara and Hariharans (Dayashankara et al., 1997) EM field-to-wire coupling analysis shows, minimization of wire spacing or height above wires and ground plane leads to reduction of coupled voltage. Thus, all wires routed as close as possible to mechanical panels if no obstacle is present on the path.

A structural current caused by electrostatic discharge (ESD) may couple energy through cables exposed to space environment and entering into the interior of the satellite (Dayashankara et al., 1997). In order to avoid ESD risks, all wires routed outside of the satellite are protected with overall braid. When these bundles enter into the satellite, overall braid is connected to chassis ground.

IV. Electrical Interface Design

The electrical interfaces are developed in three phases: avionics architecture, pin to pin and connectivity design. Figure 8 shows electrical interface design flow chart followed during the EWIS design and development.

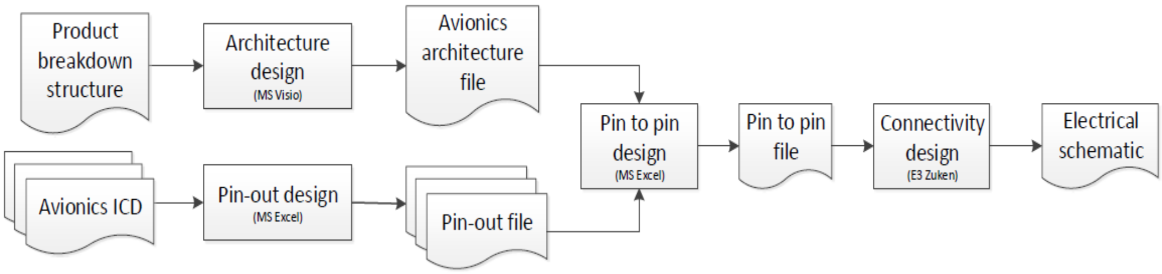

Figure 8. Electrical interface design flow chart.

As the type and number of avionics for each subsystem in product breakdown structure (PBS) are defined, an architecture design is done to create an avionics architecture file which defines electrical interfaces at very high level to show connection philosophy of the satellite. In the meantime, each avionics interface control document (ICD) is examined to perform the pin-out design. With this study, cable type, bundle category and definition of each electrical interface is defined in pin-out file including EMC category and cable type features. Table 3 lists the main electrical interfaces used in the satellite.

Table 3. Some of main electrical interfaces.

Signal Type	Description	EMC Category	Cable Type
PWR	Power	I	Twisted pair
BDM	Bi-level discrete status and telemetry monitoring	II	Twisted pair
HPC	High power pulse	II	Twisted shielded pair
1553	1553 Bus	II	Twisted shielded balanced pair
ASM	Analogue signal monitor	III	Twisted pair
TSM	Temperature sensor	III	Twisted pair
PYR	Pyrotechnic signals	IV	Twisted double shielded pair
RF	Radio frequency	V	Coax
SPW	Spacewire network	VI	Spacewire

With the study combining avionics architecture file and pin out files, pin to pin design is done and a complete pin to pin file that includes approximately 15000-line data with the following information is created:

- Signal – Name, type, description,
- Origin – Unit signal, subsystem, unit, module, in/out, from connector, from contact, connector type,
- Cable – AWG, shield, twist,
- Destination – Unit signal, subsystem, unit, module, in/out, from connector, from contact, connector type.

While this file contains all information regarding connection of the electrical interfaces, details belongs to manufacturability, i.e. harness definition, cable definition, connector definition are missing. Therefore, in order to define all connection details in schematics, connectivity design is shaped in E3 Zuken software. An example connectivity schematic is shown in Figure 9.

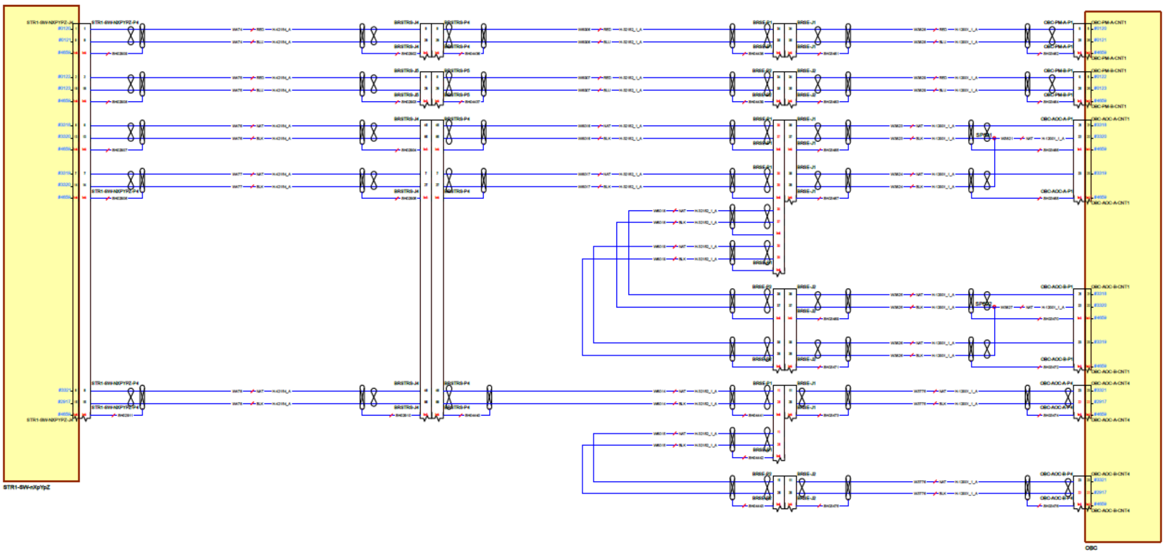

Figure 9. Example connectivity schematic from E3 Zuken software.

A. *Intermediate Connectors*

The intermediate connectors are implemented to harness to provide physical separation which support system level modular design approach. The "on panel" and "in panel" type interface brackets shown in Figure 10 are designed to provide mating plane for plug and receptacle type connectors. Functionally, following 5 different type interface connectors are used in the satellite:

- SM-CM Interface Connectors:
  Physically separates SM and CM harnesses. After the integration of the CM to SM, electrical interfaces are finalized via SM-CM interface connector.
- CM-Earth Panel Interface Connectors:
  Physically separates harnesses on Earth Panel. After the integration of Earth Panel, electrical interfaces are finalized via CM-Earth Panel interface connectors.
- Battery Interface Connectors:
  Provides physical separation and test functions for battery electrical interfaces. After the integration of North and West SM panels, where batteries are located, electrical interfaces are finalized via battery separation connectors.
- Thermal Interface Connectors:
  Provides physical separation of thermal components (heaters and thermistors) from main harness. After the integration of dedicated panel, electrical interfaces are finalized via thermal interface connectors.

- Test Connectors:
  Provide test interfaces for on-board computer and electrical propulsion subsystem. After the integration of all satellite panels, test activities are carried out via these connectors located on the exterior surface of the satellite.

(a) (b)

Figure 10. a) “on panel” type interface connector bracket, b) “in panel” type interface connector bracket.

B. Safe/Arm Connectors

The new developed satellite includes the electro-explosive devices (EEDs) used in solar panels, payload reflectors and electrical thrusters. According to the requirements defined in ECSS-E-ST-33-11C, the electrical interfaces of these devices are designed to prevent any unwanted firing during AIT operations (ECSS, 2017). Firing signals between driver unit and EEDs are physically separated by connectors which provide safe/arm functions. For connector mating, an interface bracket of “in panel” type is used.

- Arm Receptacle:
  Physically separates and isolates EED electrical interfaces. It is located on the exterior surface of the satellite.
- Arm Plug:
  Electrically connects driver and EED circuits when connected to arm receptacle. It is installed only just prior to launch operations of the satellite.
- Safe Plug:
  When connected to arm receptacle, grounds driver and EED circuits. It is installed during AIT operations and replaced by the arm plug just prior to the launch.
- Test Plug:
  When connected to arm receptacle, provides electrical connection between electrical ground support equipment and firing circuits. It is installed and used during the tests of EEDs.

C. Umbilical Connectors

Harness provides electrical interfaces between spacecraft and the launch vehicle via redundant umbilical connectors located on the anti-earth deck of the satellite. Umbilical connectors are equipped with ESCC 3401/008 push-pull type circular receptacles to provide high reliable disconnection during satellite separation.

V. THERMAL DESIGN

Thermal design of EWIS is based on two major design criteria i.e., component selection and current derating of the wires. Thermal control subsystem (TCS) comprises active and passive control elements to maintain the satellite components and structures including harness within a controlled temperature range (Sozbir et al., 2008). Satellite TCS assures a temperature limit from -30° C minimum to 45° C maximum inside the satellite. The thermal properties of each harness component, main ones defined below, are easily meeting ambient temperature limits.

- Connectors : -55° C /+120° C
- Backshell : -55° C /+120° C

- Wires/cables : -200° C /+200° C

Bundles routed outside the satellite are protected by multilayer insulation heat shield and wrapped with Kapton tape as an additional thermal protection layer.

ESCC No.3901/025 and ESCC No.3901/019 type wires are used in the satellite for power and signal wiring (ESCC, 2012) (ESCC, 2013). According to European Space Components Coordination (ESCC), allowable rated maximum current values (I_{max}) for different gauge wires are listed in Table 4.

Table 4. Maximum current rating for different wire gauges.

I_{max} (A)	Wire Gauge
1,5	28
2,5	26
3,5	24
5	22
7,5	20
13	16

Maximum allowable current for each wire is derated according to ESCC standards to prevent exceeding wire temperature limits due to resistive heat dissipation within the wires or wire bundles (Rickman and Iannello, 2016). As the wires of type ESCC No.3901/025 and ESCC No.3901/019 are used in design, derating rules defined in these specifications are applied. Maximum current for each wire used in a bundle is calculated with Eq.1 or Eq.2 (ESCC, 2012) (ESCC, 2013).

$$I_{B\max} = I_{\max}\, x\, \frac{29-n}{28}\ (for\ 1 < n < 15) \quad (1)$$

$$I_{B\max} = \frac{I_{\max}}{2}\ (for\ n > 15) \quad (2)$$

The current flowing through the wires in a vacuum environment, according to ESCC specifications, generates a temperature rise (T_{rise}) of approximately 50 °C above ambient temperature (ESCC, 2012).

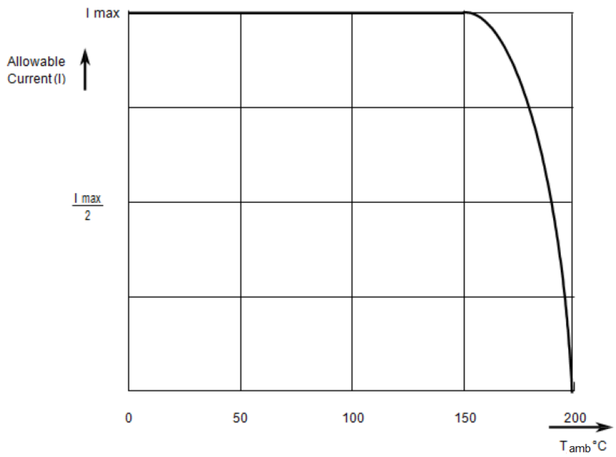

Figure 11. Allowable current versus temperature.

The corresponding graph given in Figure 11 shows that at ambient temperatures (T_{amb}) higher than 150 °C allowable maximum current ($I_{\max}$) shall be reduced.

$$T_{wire} = T_{amb} + T_{rise} \quad (3)$$

Since total temperature (continuous operating temperature) of the wire calculated by Eq.3 in the satellite is below 150° C, no additional precaution taken to reduce allowable current ($I_{\max}$).

Although bundle derating is performed according to the detailed specifications of the ESCC, the difference in derating rules is significant between the agencies i.e., National Aeronautics and Space Administration, Japan Aerospace Exploration Agency and European Space Agency because specifications are based on their own analyzes or test results. The ESCC standards are conservative in comparison to other international standards (Van Benthem et al., 2015). Therefore, an optimization for derating calculations is considered as a future study in the project which could lead to save a significant mass of both the harness and connectors and facilitate spacecraft integration with smaller diameters and lower bend radius wiring (Van Benthem et al., 2015).

VI. CONCLUSIONS

Harness design is one of the most challenging phase of the satellite development due to the high complexity of EWIS with mass and volume optimization requirements. This article attempted to present a general view of harness design practices followed during a telecommunication satellite project answering both functional and operational needs. Based on the experience gained during the project, layout, EMC, electrical interface and thermal design of EWIS are explained.

Presently, project has completed its critical design review milestone. Future studies i.e., production drawings, bill of materials and integration procedures are not a part of the paper.

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