A VERSATILE, SOFTWARE PROGRAMMABLE TELEMETRY SYSTEM FOR SATELLITE LAUNCH VEHICLES

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ABSTRACT

We describe the design and development of a baseband telemetry system for multistage launch vehicles. The system is organized as a three tier one with remote data acquisition and processing units and a centralized control unit. The front-end Data Acquisition Units (DAUs) feature software programmable amplification, offset, filtering and sensor excitation and thus are flexible to interface directly to a variety of sensors used in launch vehicles. The Data Processing Units (DPUs) gather data from DAUs through a serial link compatible to RS-485 standards and carry out a variety of data analysis and data compression functions on selected channels under software control. The central Telemetry Control Unit (TCU) receives this data through a transformer isolated link compatible to MIL-1553B standards and performs the functions of data delay, data storage, onboard computer data monitoring, PCM formatting and pre-modulation signal conditioning to achieve miniaturization. The configuration and features of this telemetry system make its integration simple without compromising on data integrity and reliability and suit the adoption of futuristic technologies and concepts such as smart sensor networks, adaptability, reconfiguration and vehicle health management.

Keywords: Software Programmable, Data Acquisition, Data Processing, Telemetry Control, Serial Multidrop Bus

INTRODUCTION

The major building blocks for a telemetry system are sensors in the physical domain; amplifiers, level shifters, filters, multiplexers and sample and hold circuits in the analog circuit domain; digitizer in the form of Analog-to-Digital Converter (ADC) in the mixed domain and Time Division Multiplexer (TDM) and formatter in the digital circuit domain. In a multistage launch vehicle these building blocks are conventionally organized as sensors distributed at different locations in various stages, signal conditioners for a number of channels in a stage in one unit located there, multiplexers and digitizers for these channels in one remote unit and a central unit that collects the data from various remote units to multiplex and format them into a serial PCM telemetry stream [1,2].

The feasibility of combining the signal conditioning and digitization functions using modern mixed signal ICs such as sigma-delta data converters is proposed here. Many of the parameters monitored for launch vehicle performance evaluation such as pressure and temperature are of low frequency nature and this has been the enabling factor for integrating these functions. A further look at the nature of telemetry data has revealed that a good number of them have a high static, dc content and are therefore amenable to data compression techniques. Status and health monitoring are typical examples of data in this category. The advancement of Very Large Scale Integration (VLSI) technology and the possibilities of functional integration and miniaturization that this offers have been another driving factor leading to the development of a new system. All the above factors contribute to rendering the system software programmable and thereby versatile to adapt to the measurement requirements of a variety of missions.

The system design is based on the concepts of remote data acquisition and processing, centralized control and formatting, integrated signal conditioning and digitization, digital serial half-duplex interface within a stage and a robust and reliable full-duplex link from lower stages to the upper one. Some of the previous publications [3] have dwelt upon a similar architecture but they do not adequately address how software programmability can be achieved and the advantages derived out of this. Further the merits of such a system topology such as its capability to support futuristic concepts like adaptive telemetry and technologies like smart sensor networks are not brought out there.

This work details the system architecture with the configuration of the constituent units and the interfaces between them. Specific emphasis is placed on aspects such as software reconfiguration and modular hardware organization. The performance aspects are discussed in the subsequent section taking a few typical measurements and processing cases as examples. The final section concludes the paper and gives a perspective on widening the scope of applying the system in conjunction with future avionics requirements and the technologies to be adopted for this.

DESIGN

System Configuration

The organization of the system is shown in figure 1. The Data Acquisition Unit (DAU) combines the signal conditioning and digitization functions and interfaces directly to the sensors. The serial link to the Data Processing Unit (DPU) is a simple, two-wire, digital one that is compatible to multidrop RS-485 standards. The DPU can carry out a variety of data analysis and processing functions such as data compression and limit checks under software control. The raw or processed data are then forwarded to a central Telemetry Control Unit (TCU) through a point-to-point link that follows an electrical interface and command-reply signaling scheme similar to MIL-STD-1553B bus used widely in avionics systems. The TCU gathers data from DPUs of various stages and does the time division multiplexing, PCM formatting and baseband premodulation signal generation. The configuration of individual units and their interfaces are further elaborated in the following sections.

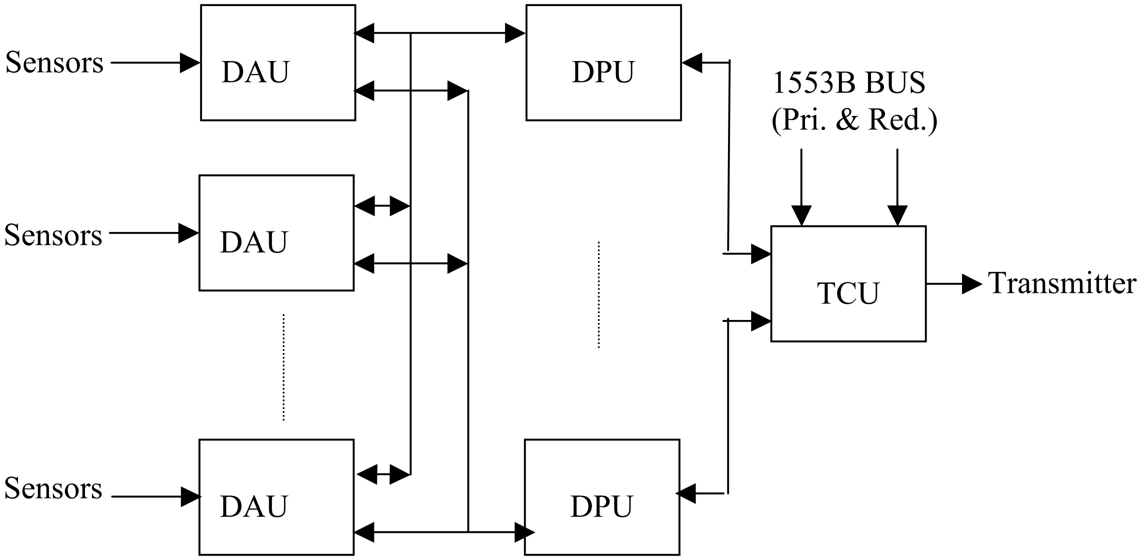

Figure 1 Telemetry System Configuration

Data Acquisition Unit (DAU)

This unit is designed to accept low-level voltage signals and hence interfaces directly to the sensors. The design has been described in detail in a previous publication [4] and is based on signal conditioning sigma-delta ADCs of AD77xx or ADS12xx families and modern integrated microcontroller devices such as PIC18F family. The gain of the front-end amplifier, the signal offset, the filter cut-off frequency that limits the signal bandwidth and the reference voltage that sets the fullscale input are all parameters that can be programmed by writing the control registers in the ADC. The magnitude of sensor excitation signal is another programmable parameter that makes it possible to use the same circuit to condition the output of a variety of sensors and is set by the on-chip current sources of the ADC. Further the system supports powerful calibration features that enables it to accommodate several variations of input signal range without tampering with the circuit hardware. The self-calibration routine corrects the offset and fullscale errors in the ADC chip. The system offset and gain calibration routines are used to correct and adjust the end-to-end signal ranges considering all board level nonidealities that may affect the channel zero and fullscale signal levels.

The block diagram of a group of 16 channels is shown in figure 2. The microcontroller device is a highly integrated one with onchip non-volatile memory for program storage, RAM for data buffering, timers for programmable delays and a variety of serial and parallel peripheral interface ports multiplexed into a compact package. The communication with ADCs is carried out over the Serial Peripheral Interface (SPI) port and that with the output RS-485 bus through the Universal Synchronous / Asynchronous Receiver / Transmitter (USART) interface. The RS-485 transceiver operates in half-duplex mode and has a variety of fault-tolerant features that makes it suitable for complex avionics network applications. The microcontroller polls the channels sequentially for data readiness, reads and buffers the ADC data and posts the data of the addressed channel to the output serial bus on receiving a command. The interrupt driven USART activity for servicing the

RS-485 serial bus is of sufficiently short timing so that two such links can be interfaced to the same unit for redundancy purposes.

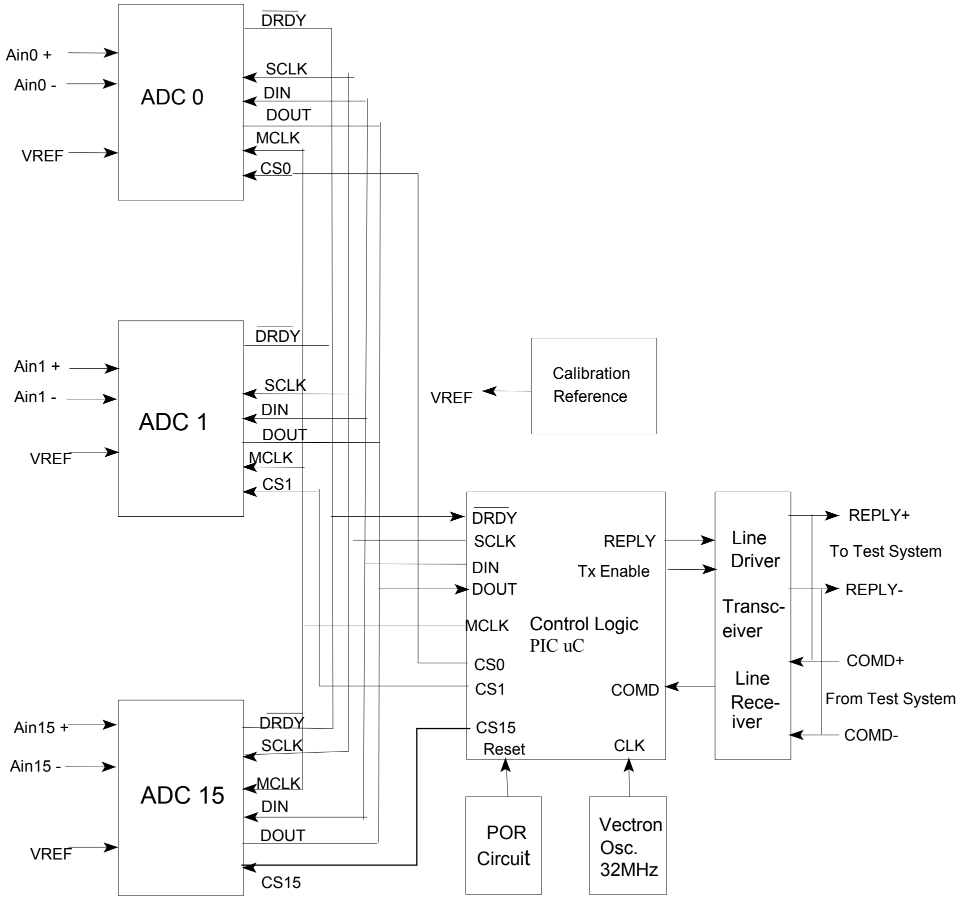

Figure 2 Block Diagram of a 16-channel Data Acquisition Unit (DAU)

In addition to the normal flight mode, the module also supports an offline programming mode, in which the ADCs of each channel can be configured according to the sensor and measurement requirements, calibration procedures can be done and the sensor excitation signal turned on and set according to the requirements of a channel. All these tasks are carried out by the program resident on a host computer through the same RS-485 interface in the same setup that is used to test the unit in flight mode. Thus the same module can be configured and used according to the requirements of different stages in different missions. The hardware realization features are use of low cost, low power surface mount devices so that only 500 mW power is consumed and 100 sq cm of board area occupied by the 16-channel circuitry. This leads to considerable advantages for telemetry applications in launch vehicles where weight and volume are at a premium.

Data Processing Unit (DPU)

This unit is designed to gather data from multiple DAUs in a remote locality such as a lower stage in a launch vehicle and communicate them to the central control unit positioned in the upper stage. It addresses the DAUs in a sequence determined by commands from the central unit and receives the data reply over the RS-485 serial bus. Further it is configured to acquire about 100 high level channels that do not need signal conditioning. Any of these channels can be configured for normal analog signals, bi-level event or digital status monitoring under software control. In addition it performs the important function of remote data processing also. Thus it can carry out loss-less data compression on analog channels by CCSDS recommended Rice algorithm, do limit checks on data and report events on status and bi-level channels. The channels and the salient parameters for processing are selected under program control from the information stored in the unit's nonvolatile memory. The above data processing and analysis capabilities lead to significant reduction in the overall telemetry bit rate as well as the signaling frequency in the interstage bus to enhance the noise margins under which the system operates.

The block diagram of the DPU is shown in figure 3 and it follows the configuration of a remote unit in a conventional telemetry system [2]. The only significant addition is a DSP microcontroller of ADSP21xx family that is used to perform the data compression and analysis functions. The control logic is implemented in FPGA. The digitized data is stored in RAM, which is read by the DSP for processing and the processed data is stored as packets in the RAM. The EEPROM is configured as the boot memory for the microcontroller as well as for storing the programmable parameters. It can be programmed from a host computer through the same link that is used for communicating with TCU. For an analog or processing channel digitization is performed 8 times in a sample period to enable application of averaging methods for removal of high frequency noise. Thus the unit enhances the quality of data without compromising on key requirements such as volume, weight or bandwidth.

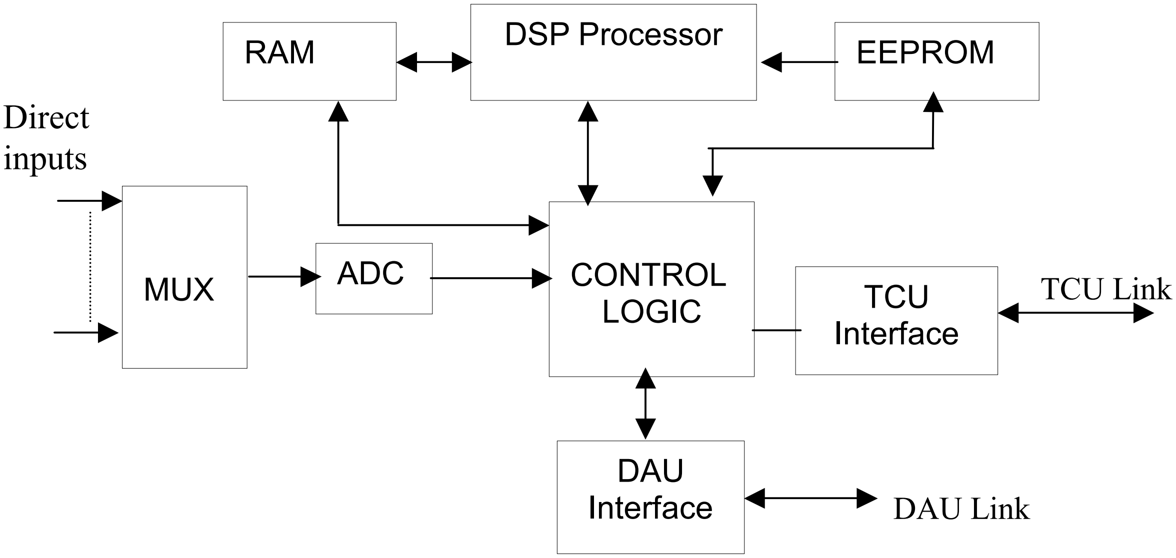

Figure 3 Block diagram of Data Processing Unit (DPU)

Telemetry Control Unit (TCU)

This unit gathers data from various remote DPUs located in lower and inter stages through a full duplex serial link. Its sequence of commanding the remote units and time division multiplexing the resultant replies is determined by a format stored in EEPROM. It also performs other major functions of monitoring a MIL-STD-1553 bus used for navigation, guidance and control of the vehicle, transmitting some of the data in delayed mode to account for data loss during events such as stage separation and storing and forwarding a few critical parameters to account for any non-visibility periods in a mission. The fact that the entire operation of the unit is controlled by a microprogram stored in EEPROM and the capability to compile and download this microcode under software control from a host computer through one of the DPU links enable easy reconfiguration of the unit according to various mission and test requirements. The major parameters such as telemetry bit rate, delay for critical data and data storage duration are also software programmable parameters stored in the non-volatile memory.

The functional block diagram of the unit is shown in figure 4. It features usage of state-of-the-art VLSI devices such as high gate count FPGAs, high-density memory chips and integrated interface ICs. It uses digital devices that are at least one generation ahead of what we have used in a controller for the earlier telemetry system [1]. The serial baseband digital signal is amplified, filtered for premodulation bandwidth limiting and transformed to low impedance using a driver before it is fed to the S-band transmitter. The analog signal processing circuits required to perform the above functions are packaged into Hybrid Micro Circuits (HMCs) to save board space. The fact that about 40,000 gates of digital logic, 200 Kbytes of static memory, 32 Kbytes of program memory, interface circuit for about 20 transformer-isolated links and analog circuitry of about hundred transistor complexity are all accommodated on a board area of 20 cm x 20 cm amply brings out the level of miniaturization achieved in this design. The whole unit weighs only about a kg and leads to significant payload advantages and harness simplicity by way of functional integration.

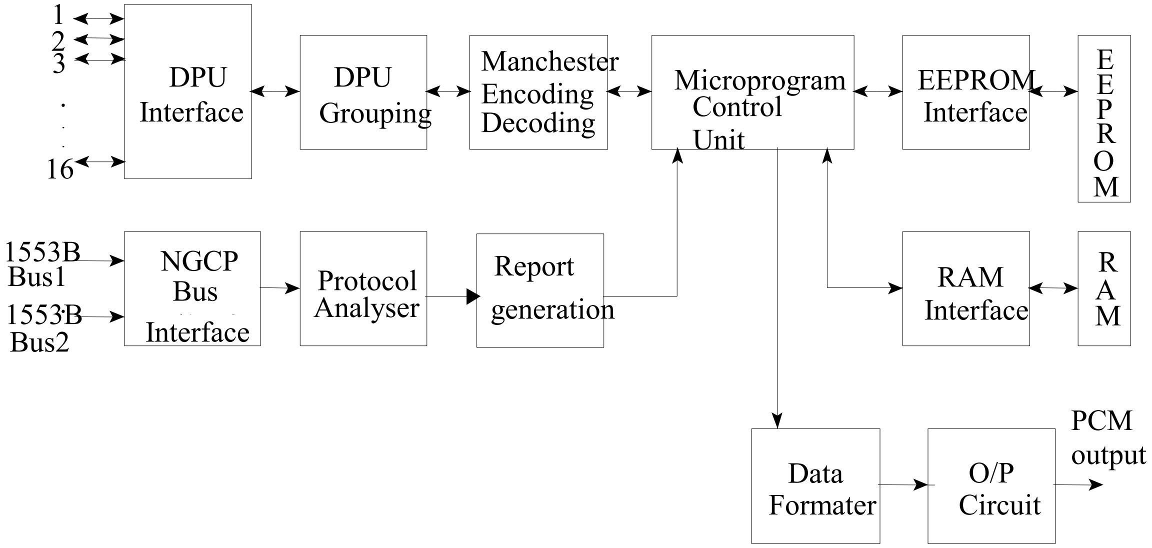

Figure 4 Block diagram of Telemetry Control Unit (TCU)

Interfaces and Timing

The entire system is arranged in a three-level hierarchy with two interfaces - one between the DAUs and DPU within a stage and the other between the DPUs of various stages and TCU.

The intra-stage RS-485 interface is a multidrop one and supports half duplex communication over a single pair of Twisted Shielded Pair (TSP) cables. The command-reply protocol on this link follows the addressable, asynchronous serial link standards with start, stop and mode bits. The signaling speed is 2 Mbps to support a throughput rate of one sample every 32 microseconds with sufficient timing margins. One link supports 128 nodes according to the receiver load and 256 channels consequent to the 8-bit addressing scheme. Thus 16 units of 16-channel DAU circuit can be accommodated on one link. In a future scenario where smart sensors with each having its own serial interface are used the number of nodes will still suffice especially with transceivers of higher input resistance. Similarly, the transceiver devices used can support operation up to 10 Mbps, which can enhance the link throughput for any high data rate applications. Fault protection and fail-safe features are ensured by transceiver device choice and design so as not to compromise on the much-needed reliability required in avionics applications in spite of the simplicity achieved in the stage harnessing and integration.

The inter-stage link is a point-to-point one in star configuration and supports full duplex communication between DPUs and TCU over two pairs of TSP cables. The command and reply words here are similar to those in MIL-STD-1553B bus with three sync, sixteen data and one parity bits. The signaling frequency is 1 Mbps to support a typical throughput of 250Kbps on one link. Four such links can thus sustain a total telemetry bit rate of 1 Mbps, which is sufficient for most of the launch vehicle applications. We are planning TCUs with 8 links and 2 Mbps also for future applications. This inter-stage link makes use of a more elaborate interface circuit consisting of line driver / receiver ICs and isolation pulse transformers for robust performance in hostile, noisy and high common mode environment typical of complex multistage launch vehicles.

PERFORMANCE CHARACTERISTICS

Acquisition

The dc characteristics such as accuracy and resolution of the system primarily depend on the performance of DAU [4]. There is a trade-off between channel parameters such as gain and bandwidth and these performance metrics as is expected of any system based on sigma-delta ADCs. At the lowest gain and bandwidth, we could get resolutions exceeding 16 Effective Number of Bits (ENOB) and accuracies better than 0.01%. Even at the highest gain and bandwidth settings of 128 and 100 Hz respectively, the number of noise-free bits was maintained at about 10 and accuracy better than 0.1%, which is clearly superior when compared to conventional telemetry systems based on mux-successive approximation ADC architecture. The dynamic characteristics of the system were also evaluated by injecting ac input signals. Sinusoidal signals of amplitude as low as 1 mV could be reconstructed at the system output and this further establishes its capability to resolve inputs well into the microvolt range even in the presence of noise.

We have conducted exhaustive end-to-end tests on the system interfacing a variety of sensors. Figure 5 shows the results of one such test with a piezo-resistive bridge type pressure transducer.

The upper curve with triangles indicates the uncalibrated output and the lower line with circles after a system calibration procedure with 0 and 100 bar being the offset and fullscale inputs. The linearity of the system as well as its ability to nullify system errors through calibration are evident from this example. The sensor excitation scheme was also tested by interfacing Resistance Temperature Detector (RTD) device and accommodating various input temperature ranges through configuration and calibration.

Processing

The results of applying the Rice compression algorithm on some of the channels are shown in table 1. We have achieved compression ratios better than 10 for a majority of channels. Even in the case of dynamic parameters such as acceleration, the figure is above 5. This has led to reduction in telemetry bit rate by as much as half without any loss of information. We have also developed decompression algorithms that can run on telemetry data processing computer in real time so that uncompressed, raw data can be displayed during flight with minimal latency.

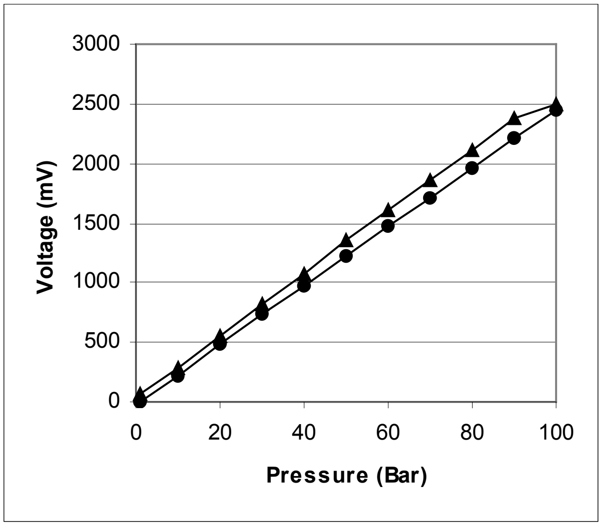

Figure 5 Results of Pressure Transducer Test

Parameter	Sampling rate (Hz)	Compression Ratio (%)
Wall Temp.	122	93.42
Gas Pressure	122	91.38
Gymbal Acceleration	122	86.67
Injection Pressure	244	94.29
Position Feedback	488	98.44

Table 1 Results of Data Compression Analysis

CONCLUSION

The architecture and block level design details of a new generation telemetry system has been described in this paper. The system is based on remote data acquisition and processing and central control for formatting, storage etc. The remote units are interconnected through a multidrop serial bus for harnessing simplicity. The stage-to-stage link is a full duplex serial bus that follows the conventional, more rigorous interface standards for robust operation. The system has been tested exhaustively for various measurement requirements and its performance characterized for key parameters such as accuracy, resolution, compression factor etc.

The design concepts employed in the design of this telemetry system such as a simple serial link for intra-stage network between DAUs and DPUs and more robust inter-stage link between

DPUs and TCU makes the system simple to integrate without compromising on aspects such as data integrity and reliability. Features such as software programmability and use of multidrop bus topology and modern VLSI ICs renders the configuration suitable for adoption of technologies such as smart sensor networks and futuristic aerospace concepts such as adaptability, reconfiguration and vehicle health management [5,6] that are especially relevant in the context of Two/Single Stage To Orbit (T/S STO) missions.

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