NEMO-HD: A HIGH PERFORMANCE MULTISPECTRAL EARTH OBSERVATION MICROSATELLITE ENABLED BY COTS COMPONENTS

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NEMO-HD is a high performance multispectral earth-observation microsatellite currently in development by the University of Toronto Institute for Aerospace Studies – Space Flight Laboratory (UTIAS – SFL) for the Slovenian Centre of Excellence for Space Sciences and Technologies (Space-SI). The NEMO-HD payload consists of two instruments: The primary instrument is capable of imaging in four spectral bands at a GSD of 2.8 m, and covers a swath width of 10 km. The secondary instrument produces images at a GSD of 40 m and a much wider field of view. In addition to still imaging, both primary and secondary instruments capture high definition video at 25 frames per second. The video is H.264 encoded and downlinked in real time. Commercial off-the-shelf electronic assemblies are used extensively throughout the payload to capture, store, and downlink the vast quantities of data generated, and to perform real-time video encoding. Their use has facilitated substantial reductions to development costs, and has allowed the demanding timelines of the NEMO-HD mission to be met. Furthermore, embracing of industry accepted protocols and open source software has drastically reduced the required software development efforts, and allowed the use of readily available tools for development, testing, and debugging. This paper discusses how the use of commercial off-the-shelf hardware and open source software has enabled the design and development of a high performance multi-spectral earth observation instrument. In addition, an overview of the NEMO-HD mission and spacecraft are also provided.

I. THE NEMO-HD MISSION

NEMO-HD (Nanosatellite for Earth Observation and Monitoring - High Definition) is a small spacecraft being designed and built by the University of Toronto Space Flight Laboratory (UTIAS-SFL). Weighing in at 65 kg, this spacecraft builds on the experience acquired during the design and construction of SFL's other optical remote sensing missions [1][2][3] to deliver a new level of performance in a very small package.

NEMO-HD is designed to provide moderate-to high-resolution Earth imagery in a number of bands, as shown in Table 1. In addition, NEMO-HD carries two high-definition video channels, each providing real-time video at 25 frames per second, as shown in Table 2. The video channels are co-boresighted with the still imagery channels. This allows for a unique real-time imaging mode, in which an operator views the real-time video feed and commands the spacecraft to image a target of interest.

Channel	BW (nm)	GSD (m)	Swath (km)
Pan	400 – 900	2.8	10
Blue	420 – 520	5.6	10
Green	535 – 607	5.6	10
Red	634 – 686	5.6	10
Near IR	750 – 960	5.6	10

Table 1: NEMO-HD still imagery observation bands

Channel	BW	GSD (m)	Swath (km)
Primary	RGB	2.8	5
Secondary	RGB	40	75

Table 2: NEMO-HD video channels

II. SPACECRAFT OVERVIEW

Spacecraft organization

NEMO-HD is a reasonably compact spacecraft with an octagonal planform. The spacecraft solid model is shown in Figure 1. As can be seen, the spacecraft is essentially designed around the payload. The payload optical bench, which comprises approximately one half of the spacecraft mass, is mounted to the bottom panel, which also carries the payload adapter fixture (PAF), used to connect the spacecraft to the launch vehicle. In this arrangement, the load path from the payload to the PAF is short, and the spacecraft strong back can be small.

The remainder of the spacecraft body consists of panels which are bolted together to form a monocoque structure. Spacecraft bus components, as well as some components of the payload electronics, are mounted in enclosures which are then bolted to the body panels. Six of the ten spacecraft body panels also carry solar cells on their exterior. On the outside of the spacecraft are the various apertures which are required for proper operation of the spacecraft: attitude sensors, antennas, and so forth.

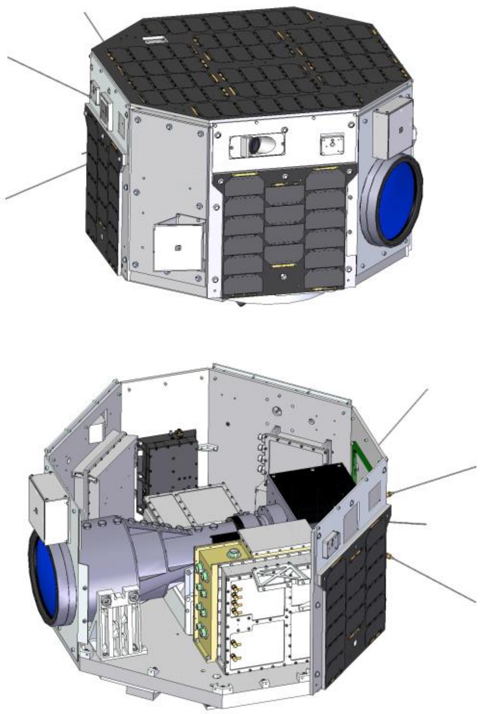

Figure 1: NEMO-HD spacecraft solid model

Figure 2 shows an overview of the NEMO-HD bus subsystems. At the centre of the bus is the power system; it is responsible for generating power, storing it, and distributing it as required to the remainder of the spacecraft. As described above, six faces of the spacecraft carry at least a few solar cells each. This arrangement ensures that the spacecraft is capable of generating power in all attitudes. It should be noted that not all attitudes provide enough power to run the full payload complement. However, the spacecraft has a "safe-hold" mode, in which power is distributed to the minimum set of bus components required to (re-)gain control of the spacecraft following LV kick-off or a loss of attitude control. The solar cell layout is designed such that the safe-hold mode is power positive in all attitudes and at all plausible thermal conditions. As such, NEMO-HD has no "point or die" constraints, even at the end of its design life.

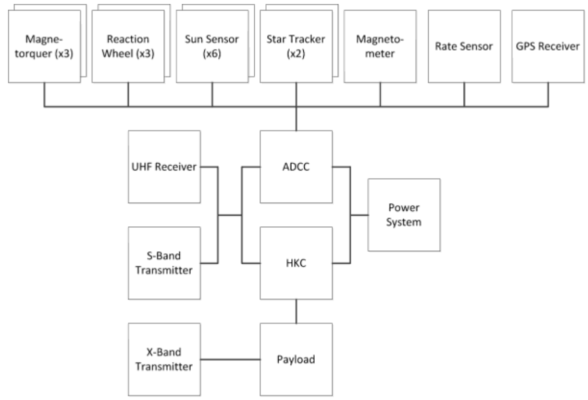

Figure 2: NEMO-HD bus architecture

Electrical power system

The NEMO-HD power system is based on SFL's Modular Power System, which is described in detail in [4]. For NEMO-HD, it is configured as a series-regulated, peak-power-tracking system. All of the solar array strings are connected in parallel (via blocking diodes) to a Solar Array/Battery Regulator (SABR) card. The SABR is a DC/DC converter which adjusts the voltage on solar cell strings so as to maximize the power delivered by the array. The power is then stored in a lithium-ion battery, which is attached in parallel across the spacecraft power bus. By monitoring the battery voltage, the SABR can determine the battery state of charge, and thus control the current required to keep the battery charged.

Bus electrical power is distributed to the remainder of the spacecraft via solid-state switch cards. These cards can be switched on or off either by ground command or by the housekeeping computer, and provide per-switch telemetry and over-current protection. The majority of the cards are configured to be in an "off" state when the spacecraft turns on after launch vehicle separation, with the remainder, powering key systems, defaulting to "on." This ensures that the spacecraft remains in a low-power state during kick-off or after a load-shed event, when available solar power is low.

Command and data handling

The NEMO-HD bus command and data handling system consists of a housekeeping computer (HKC). The HKC is connected to the telemetry and command (T&C) subsystem (below), and is responsible for interpreting telecommands, and forwarding them to the rest of the bus using the spacecraft-wide CAN network; similarly, telemetry is gathered over CAN, and, after suitable formatting, is transmitted by the HKC via the T&C subsystem. The HKC is responsible for setting up and controlling all of the payload electronics: each of the cameras, as well as the associated data handling, storage, and downlink units, are connected to the HKC via point-to-point links. During an observation or downlink session, the HKC forwards configuration data to the payload, and provides synchronization signals to ensure that all operations are performed in the correct sequence.

The HKC can operate in a real-time mode (*i.e.*, while in contact with a control station), or in a "time-tagged" (or scheduled) mode. While in real-time mode, telecommands are received from the T&C subsystem, and are routed as required; responses are collected, and are downlinked immediately. Alternately, lists of time-tagged commands may be uplinked to the spacecraft, where they are stored in non-volatile memory. At the appropriate time, these commands are read out, and routed to their destinations; any responses are collected and stored for future downlink. At the same time, the HKC is capable of collecting whole-orbit telemetry, which can be downlinked when desired. Large non-volatile buffers are provided for both commands and telemetry, and so ground segment outages do not endanger the spacecraft.

Attitude determination and control

Attitude determination and control (ADCS) is performed by a set of sensors and actuators, with computation performed by an attitude determination and control computer (ADCC). During imaging and downlink, attitude is measured by a pair of star trackers mounted on the payload optical bench; two star trackers are used to ensure that an adequate unobstructed field of view is available in all required attitudes, and to reduce along-boresight roll error. Star tracker data is supplemented by a three-axis rate gyro assembly, which provides angular rates at a higher cadence than the star tracker. During times when fine pointing is not required, or when body rates are too high for the star trackers to provide a solution, sun sensors and a three-axis magnetometer provide data to the ADCC. Control authority is provided by a triad of reaction wheels, with desaturation being performed by magnetic torque coils. A summary of the ADCS performance can be found in Table 3.

Attitude determination	Pointing accuracy	Maximum slew rates
< 15", 1 σ	< 120", 2 σ	1.5 °/s

Table 3: ADCS performance

It is worth noting that the ADCC is physically identical to the HKC, with the functional difference defined by the software running on each computer, and the computers' connections to the remainder of the spacecraft subsystems. There are a number of cross-connections between the HKC, the ADCC, ADCS hardware, and the payload, allowing for graceful degradation in mission performance in the event of hardware failure.

Telemetry and command

Telemetry and command handling is provided via a command receiver, operating in the UHF ground-to-space band, and a telemetry transmitter operating in the space science segment of the S band. The receiver is connected to both the HKC and the ADCC, as well as to the power subsystem, providing hardware-decoded commands that can be used to reset the spacecraft in the event of a serious loss of control. The transmitter provides for a convolutional-coded downlink at data rates up to 1 Mb/s. Although the payload provides its own high-speed downlink (see below), the telemetry transmitter can, in the event of a payload transmitter failure, be pressed into service as a backup, due to the connections between the HKC and the payload computers. The T&C system provides full spherical coverage, and works at high body rates; as with the power subsystem, there are no "point-or-die" attitudes.

Thermal control

Thermal control of NEMO-HD is semi-passive: heaters are used to keep a number of components from freezing, but no active cooling is involved. Internal to the spacecraft, all heat is conducted through structure or through thermal straps, with no heat pipes or exotic devices used. Once the heat reaches the spacecraft's outer structure, it is rejected to space via radiation. The outer structure (that part of it which is not covered by solar cells) has its thermo-optical properties tuned via surface coatings. The large range in spacecraft power (the ratio of power between the high-power imaging and downlink operations, and the low-power safe-hold mode is upwards of 40) makes thermal control challenging. However, NEMO-HD is safe in all attitudes, keeping with the general approach taken by SFL on its missions.

III. THE NEMO-HD PAYLOAD

The NEMO-HD payload consists of two optical instruments. The primary instrument is subdivided into five discrete channels. These are the High Resolution Spectral - Panchromatic channel (HRS-PAN), four High Resolution Spectral - Multispectral channels (HRS-MS1 through HRS-MS4), and the High Resolution – High Definition video streaming channel (HR-HD). The secondary instrument contains the Low Resolution – High Definition (LR-HD) channel for video streaming and still imaging.

Through the application of pan-sharpening, the primary payload will produce still imagery in four spectral bands with a ground-sample-distance (GSD) of 2.8 m and a ground swath width of over 10 km. The signal-to-noise ratio (SNR) is expected to exceed 75 in each spectral band.

In addition to still imagery, the primary and secondary instruments also generate an RGB video stream with a GSD of 2.8 m and 40 m respectively. The produced video streams have a resolution of 1920 by 1080 pixels and a frame rate of 25 frames per second. The streams are encoded with the H.264 codec and relayed to the ground in real time or, optionally, recorded on-board for later downlink.

Payload electronics

One of the main challenges associated with the NEMO-HD project is its very aggressive schedule: about two years were allocated from the time of contract signing to the delivery of flight accepted hardware. SFL has extensive experience in delivery of spacecraft on accelerated schedules, with some having been successfully completed on even shorter timelines. However, the development of an instrument such as the one described above would be unprecedented.

To meet such a short timeline, a decision was made at the very early stages of the project to utilize commercial off-the-shelf (COTS) hardware, as well as open source software to the maximum extent possible, in a way that would not compromise the mission requirements. Doing so can immensely reduce the non-recurring engineering efforts. However, their use introduces a number of other issues that are not present with hardware custom designed and built for space applications.

To overcome the issues commonly encountered when using COTS electronic assemblies in spacecraft, SFL has developed a proprietary process that is used to identify and evaluate shortcomings in the mechanical, thermal, and electronics aspects of the assembly, and to perform the necessary modifications. Thus, a strict qualification process is undergone by every COTS assembly. In addition to numerous other tests, radiation testing is done to check the unit's susceptibility to single-event upsets and latch-ups, as well as tolerance to total ionization doze. Additionally, each solder joint on COTS assemblies, as well as SFL designed hardware, is visually inspected and reworked as necessary by skilled technicians to meet industry quality standards.

A high level architecture diagram of the NEMO-HD payload electronics is shown in Figure 3. As can be seen, the payload consists of seven independent channels, of which five are used for still imaging and two are dedicated for streaming video. The subsections below focus on each of the payload components individually.

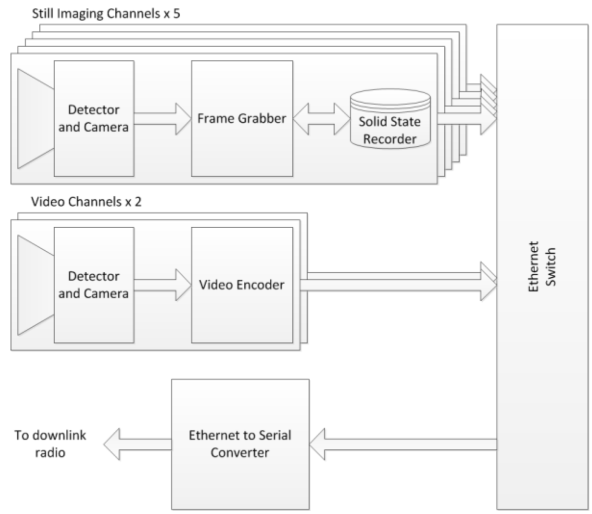

Figure 3: NEMO-HD payload architecture

Detectors and cameras

As the NEMO-HD mission's primary objective is earth observation, the electronics design naturally revolved around the imaging detector. To stay within the objective of utilizing COTS assemblies, the selection of detectors had to be limited to those utilized by COTS camera units, which had a limitation on the available selection. The pixel pitch, resolution, frame rate, and chroma were all considerations that had to be taken into account in order to find a detector suitable for this instrument.

When suitable detectors were selected, the next step was to identify COTS camera modules which used those detectors. A camera module would typically include the detector itself, along with the readout electronics, control firmware, and a high speed output for interfacing with a frame grabber. Due to the high frame rates at which the cameras were required to operate, a significant challenge in this area was identifying camera modules capable of supporting the high data throughput. After a survey of hardware available on the market, cameras using Gigabit Ethernet were selected.

Frame grabber

With the detectors selected and camera modules identified, suitable frame grabbers were required next. During imaging, the purpose of the frame grabber is to interface with the camera module to capture raw image data and store it into non-volatile memory. During a pass over the ground station, the frame grabber would read the image data from non-volatile storage and send it to the high-speed payload downlink transmitter. To meet these functional requirements, a frame grabber would require having a correct interface to the camera module as well as the downlink subsystem, have sufficient on-board non-volatile storage, and also contain sufficient computational capacity to receive and store the high-speed raw image data. After conducting an extensive trade study of different technologies, industrial grade embedded computers were selected for this application. As will be described further, each frame grabber module is connected to the high-speed downlink subsystem via Ethernet.

Next, consideration was given to the storage requirement. This challenge was two-fold: firstly, sufficient capacity was required to store the vast quantities of data generated while imaging. Secondly, high read and write speeds were necessary to maximize the capabilities of the spacecraft. Solid state flash drives with a SATA interface were selected due to their ability to meet the above requirements. In total, the NEMO-HD payload is capable of storing hundreds of gigabytes of raw image data, giving the flexibility of increased imaging times before downlinking of data is necessary.

Video encoder

In addition to still imaging, the NEMO-HD payload is required to capture high definition (1920 x 1080 pixels), 25 frames per second video streams from the primary and secondary instruments, which are to be encoded through the H.264 codec and streamed to the ground in real time or recorded for later downlink. COTS digital signal processors (DSPs) with integrated video processing subsystems were applied to implement this functionality. As with the frame grabber, each video encoder module also ties to the high-speed downlink subsystem via Ethernet.

High speed downlink subsystem

The NEMO-HD spacecraft contains two downlink paths. The primary S-band transmitter is slower, and is used for telemetry and commands. The secondary and faster X-band transmitter operates at 50 megabits per second, and is used for downlinking payload data such as still images and real-time video streams. Ethernet was selected for interconnecting each of the payload channels to the high-speed downlink radio for a number of reasons. Primarily, it naturally lends itself for use in point-to-multi-point network topologies, such as the one described here. Secondly, Ethernet was readily available on the components interfacing with the downlink subsystem, namely the five frame grabbers, and two video encoding units. Additionally, open source software and higher level protocols leveraging Ethernet were also readily available. Electrically, Ethernet has many favourable properties, such as galvanic isolation through transformer coupling, and high noise immunity over long harness lengths. 100 Megabit Ethernet is capable of supporting the 50 Mbps downlink stream, while maintaining sufficient margin for inter-unit communications. Aside from the downlink transmitter itself, the high-speed downlink subsystem performs two important roles: multiplexing seven individual data streams into one, and interfacing the resultant output to the radio transmitter by applying the required data encoding and performing conversion of physical layers. To meet these needs, SFL has developed two custom solutions. The first is an implementation of an eight-port Ethernet switch, seven of which connect to the payload components, and the eighth connects to the downlink radio. The second applies a special coding scheme to the Ethernet packets and transmits them over synchronous low-voltage differential signaling (LVDS) to the downlink transmitter. Having developed these key components, the flexibility of Ethernet can now be easily leveraged in future SFL spacecraft.

Payload software, protocols, and data formats

In addition to the significant savings in development time and costs obtained through the use of COTS electronics components and assemblies, further savings were realized by employing standardized protocols and file formats, and through the use of open source software. Utilizing standardized protocols wherever they are applicable has a number of advantages. Firstly, these protocols were designed and improved upon by industry consortiums, often over the span of years, ensuring optimality for their intended purpose. Secondly, reference implementations and libraries were often available either through the open source community, or for purchase. Using such implementations can save a great deal of time in development and debugging, and they are equally applicable for use on the spacecraft and in ground segment software. Even where further optimizations to the available code were desired, a reference implementation could be used for proof of concept, and to verify compliance. Standardized file formats and codecs share many of the benefits described above. The following sections provide examples of a small subset of standardized protocols, codecs, and open source software as used on the NEMO-HD payload.

Bootloader and operating system

Perhaps two of the most complex software components required for each of the frame grabber and video encoder modules are the bootloader and the operating system.

The bootloader used on NEMO-HD frame grabbers and video encoders is based on an open source project. This bootloader is primarily intended for use on embedded systems, and is well suited for booting the Linux operating system. A port of the bootloader for the platforms used on NEMO-HD was provided by the platform manufacturers. The port includes all of the necessary peripheral device drivers, and processor core configurations. The functionality necessary to load new operating system images and store them into non-volatile memory, as well as to select which image to boot is also present. Additional work was conducted by SFL to improve upon the existing code base in order to add reliability and protection features, and to qualify this bootloader for use in spacecraft.

While developing custom operating systems is at times appropriate (such as in the case of SFL's custom-designed HKC and ADCC), matching the capabilities of mature open source products such as Linux is difficult, especially for very complex processors like the ones used in the NEMO-HD payload. One additional advantage of using the Linux operating system is the plethora of open source software and development tools that are available for it. A port of the Linux operating system, including all device drivers, source code, and development tool chain were provided by the platform manufacturer.

GigE Vision

Building on top of lower level Ethernet protocols, the Gigabit Ethernet Vision (GigE Vision) protocol [4] is used to manage raw image data streams between camera modules and frame grabbers. Designed specifically for gigabit-per-second or faster Ethernet links, this protocol is often used where large volumes of data are present. To facilitate this, minimal overhead is added to the raw image data. GigE Vision implements the functionality necessary to detect and re-request missing packets in the data stream, guaranteeing reliable acquisition of all image frames.

RTSP and H.264

The Real Time Streaming Protocol (RTSP) [6] and H.264 video compression codec [7] are used in conjunction to encode and transmit live video streams from the primary and secondary video channels on NEMO-HD to the ground station.

H.264, also known as MPEG-4 Part 10, is a video compression standard commonly used for high definition video streams. This codec provides much higher compression rates for similar video quality when compared to other standards, while requiring less computation than competing codecs. Since one of the main applications of this standard is video streaming over the Internet, it is well suited for an environment that may introduce variable latency as well as occasional connection dropouts. This makes it ideal for use over a radio link which possesses similar qualities. The use of RTSP, which is a network based stream control protocol, significantly simplifies transferring of video over the Ethernet high-speed downlink subsystem.

IV. SUMMARY

NEMO-HD is a high performance, multispectral, earth imaging microsatellite currently in development by the University of Toronto Space Flight Laboratory. Through the extensive use of COTS electronic assemblies, open source software, and an innovative design approach, this project is on track to deliver an integrated spacecraft in a very short time span. The use of COTS electronic assemblies has drastically cut down on electronics design and test time, though an extensive modification and qualification process was developed in order to upgrade these assemblies for space applications. Employing open source bootloaders and operating systems has arguably removed the necessity of developing some of the most complex software components of the payload, while the selection of standardized protocols and file formats has ensured the availability of open source libraries and programs to implement much of the required functionality. Overall, the approach described herein has allowed the development of a high performance Earth observation spacecraft at a timeline that would have otherwise not been possible.

V. REFERENCES

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