A MODULAR SOLUTION FOR SCIENCE PLATFORM STABILISATION

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ABSTRACT

The paper describes a modular solution for science platform stabilisation. The solution was developed for project PoGOLite and is based on technology developed by DST CONTROL over the last 20 years. PoGOLite is a balloon-borne X-ray polarimeter with an energy range of 25–80 keV. To meet the scientific objectives, the platform must be capable of absolute angular positioning to within 0.1° or better. This requirement must be met without the support from star trackers.

The solution combines a distributed control system with intelligent bus nodes, a high speed bus for wide bandwidth servo loops, and a graphical design tool with an automatic code generator. All the bus nodes conform to a simple standardised bus interface and are equipped with powerful FPGAs providing enough computational power for advanced distributed signal processing. The presented modular solution is capable of meeting a wide range of scientific applications and budgets.

Key words: stratospheric balloons, X-rays, polarisation, modular, distributed, control, direct drive, inertial sensor, differential GPS.

1. INTRODUCTION

The Polarised X-ray Observer (PoGOLite) (Kamae et al. 2008; Kiss 2011; Pearce 2011) is a balloon-borne Compton-based polarimeter, with an energy range of 25–80 keV. The instrument is scheduled to be launched on its maiden flight in summer 2011 from the Esrange Space Center (SSC) in northern Sweden. The goal is to reach a float altitude of some 40 km and the ambition is to make a circumpolar flight, given that the treaty closed between Sweden and Russia is fulfilled by both parties.

The purpose of the project is to measure the polarisation of X-rays emitted from sources like the Crab nebula, the Crab pulsar and Cygnus X-1, a black-hole binary. To achieve the objectives of the project, the polarimeter must be pointed to the source to within 0.1° or better. Furthermore, the 0.1° accuracy must be achieved without the support from star trackers. The reason is that the star trackers available for the maiden flight are still experimental, and therefore cannot be fully relied upon.

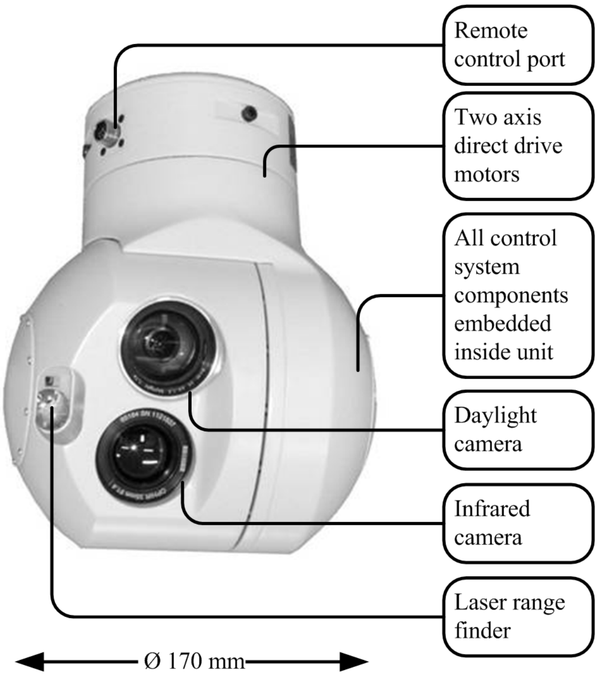

Figure 1. A member of the OTUS gyro stabilised micro gimbal family designed and produced by DST CONTROL. The OTUS gimbals deliver market leading stability for the given mass and volume. The mass of this particular unit is less than 2 kg.

To achieve these goals DST CONTROL was contracted to develop and deliver a purpose-built pointing system. DST CONTROL have a 20 year long track record of delivering high performance pointing systems for manned and unmanned aerial applications world-wide; see Figure1. To meet the challenging budget restrictions of PoGOLite it was necessary to develop a modular solution which could be cost efficiently tailored to a wide range of future scientific applications. This is the solution that will be presented in the present paper.

The PoGOLite fully assembled gondola is shown in Figure 2. Solar panels are attached like a skirt at the bottom of the gondola. Two antennae booms on the top of the gondola carry two GPS antennae separated by 10

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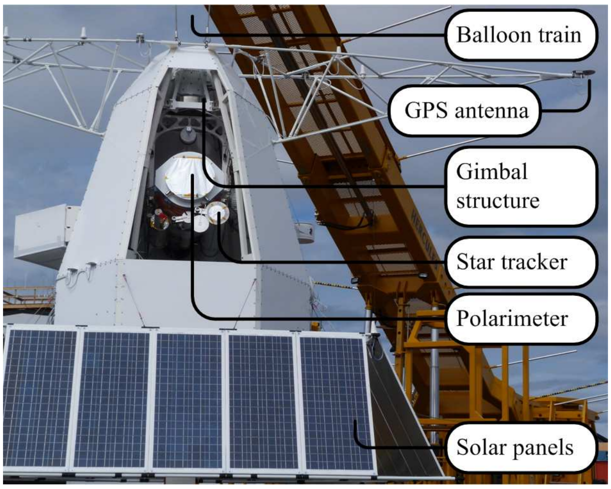

Figure 2. The fully assembled gondola hanging in the Hercules *launch vehicle (background) ready for lift-off. The inner gimbal structure can be seen inside the gondola through the front opening.*

m. These two antennae are used to measure the heading of the gondola at the required precision. The antennae booms also carry Iridium communication antennae and a standard magnetometer based heading sensor for backup. The polarimeter as well as two star trackers can be seen in the centre of the front opening of the gondola. The total take-off mass of the gondola is approximately 2 000 kg which is broken down into the following main contributing parts: polarimeter 700 kg, attitude control system including gimbal structure 300 kg, empty gondola including power supply, solar panels, communication transceivers and ballast 1 000 kg.

The stripped-down gimbal structure and its main control system components are exposed in Figure 3. The attitude control system design is classical in the sense that a flywheel is used to control the heading of the platform and a balloon train motor is used to eliminate the balloon train bearing friction and to dump flywheel momentum when needed. Both these motors are direct drive in the sense that the motor shafts are operating directly on the platform, the flywheel and the balloon train without the use of any gear-boxes.

The control system design is perhaps less classical in the sense that we also use a direct drive motor for the elevation axis. This enables us to potentially stabilise the platform in case the gondola starts to gyrate. It also enables us to stabilise vibrations that may be caused by turbulence and bearing stick-slip friction.

However, the most novel part of the Attitude Control System (ACS), is the highly modular design which allows us to modify the system to meet a wide variation of applications at a very low cost.

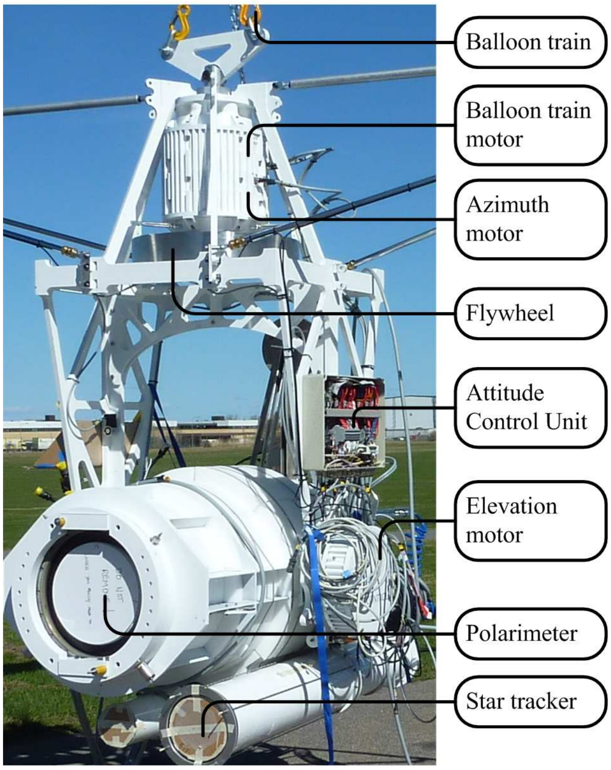

Figure 3. The stripped-down gimbal structure with its main control system components exposed.

2. ATTITUDE CONTROL SYSTEM

The control system of PoGOLite actually consists of two distinct sub-systems, namely the Attitude Control System (ACS) and the Payload Control System (PCS). At the heart of each control system there is a dedicated control unit. The Attitude Control Unit (ACU) is responsible for the pointing of the instrument, whereas the Payload Control Unit (PCU) is responsible for the operation of the instrument and the collection of the scientific data. The two control systems were developed independently of each other and can also be operated independently of each other if required. In normal operation, the two subsystems interact with each other via a single high speed serial connection, transferring signals in real-time at a rate of 100 Hz.

The PCS and the PCU are described in detail in Jackson (2011). The present paper will focus on the design of the ACS and the ACU only. In addition to the ACU, the ACS consists of the following key components as illustrated in Figure 4:

- Digital Direct Drive (DDD) actuators
- Inertial Measurement Unit (IMU)
- Magnetic Heading Sensor (MHS)

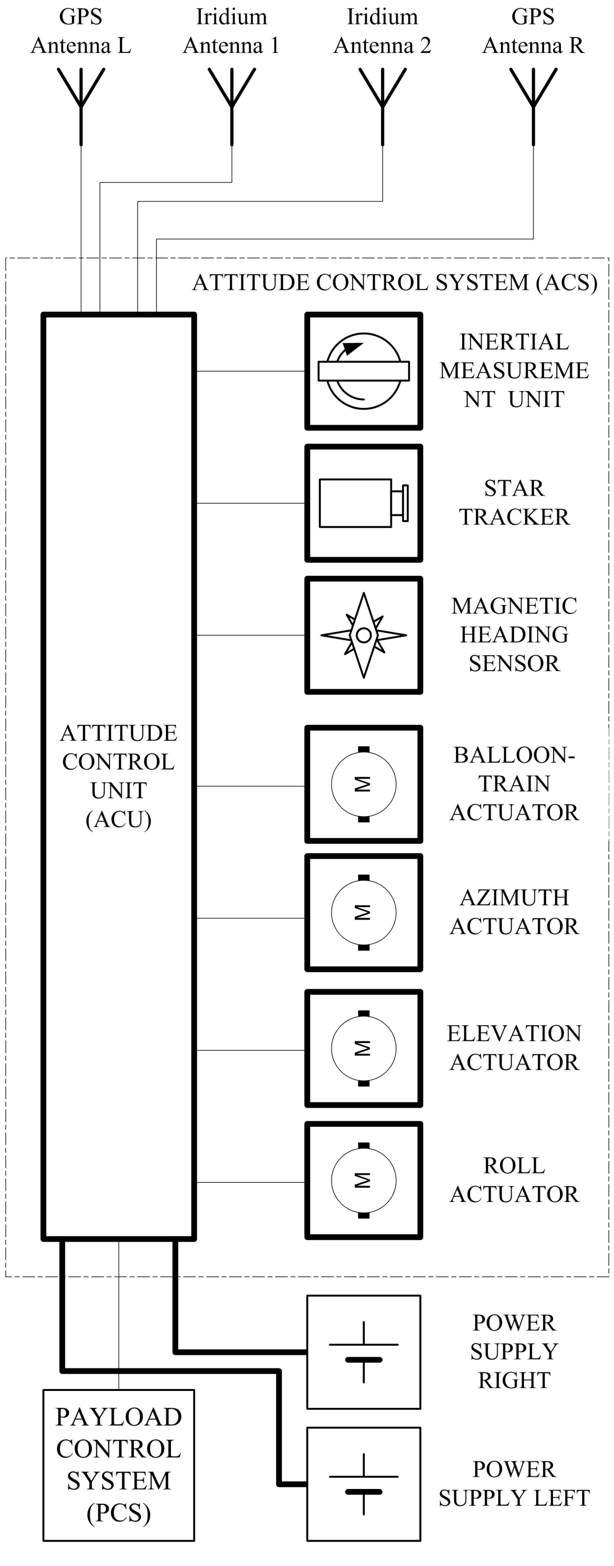

Figure 4. Simplified block diagram for the PoGOLite control system.

- Star Tracker (STR)
- GPS antennae
- Iridium antennae

A corner stone in the design of the ACS is the combination of distributed control, intelligent bus nodes and - as a consequence - a standardised bus node interface. The advantages of this approach is that computation intensive code can be distributed over several computational nodes, power and heat is dissipated over a larger physical volume, the system is simple to reconfigure, and the system is robust against single point failures. A standardised bus node interface means that compliant actuator and sensor nodes can be added, removed or relocated without having to redesign the ACU hardware or software in any way. By providing a range of different sensor and actuator nodes, meeting a range of different performance needs, the solution is scalable and can be cost efficiently adapted to specific applications and requirements.

An important part of the standardised bus node interface is the *dBus* specification. The dBus is a simple serial bus designed for the sole purpose of efficiently transferring real-time signals between distributed control loops. The dBus does not comply with any widely known bus standard for the simple reason that we want the bus specification to be kept simple and free from compromises. Even though the dBus specification is proprietary, it is well documented (Hammarberg 2001) and may be used free of charge by anyone.

Another important part of the standardised bus node interface is the 18 to 36 Vdc power supply requirement. Every node part of the control system must be able to fully operate when powered by a power supply generating a minimum of 18 Vdc and a maximum of 36 Vdc. Hence all bus nodes can be directly connected to the power bus of most gondola power supplies equipped with standard low voltage solar panels.

The DDD:s and the IMU are both examples of complex bus nodes complying with this bus node specification. These components will be further described in the following sections.

The GPS antennae are used to feed the GPS differential receiver which is part of the ACU and will be discussed further in the next section.

The Iridium antennae are used to remote control and monitor the ACS when the PoGOLite system leaves the range of the SSC E-link. The remote control system will not be further discussed in this paper.

3. ATTITUDE CONTROL UNIT

Adopting the above described approach, the ACU becomes a very simple and basic device. Not only does the hardware of the ACU become simple. The software is also greatly simplified, which means that we can use a small power efficient micro processor and a small and simple real-time operating system. In fact, all our control systems delivered over the past 15 years, are based on the very same well tested software code. We will describe the compact ACU software architecture in the coming section.

Hence the ACU hardware consists of the following few components:

- Main Processing Unit (MPU)
- Power Distribution Units (PDU)
- Differential GPS (DGPS) receiver
- Ground communication hardware

The ground communication hardware further consists of sub-components such as Iridium modems, serial to Ethernet bridges and an Ethernet router. The focus of this paper is on the control system and therefore the ground communication hardware and software is outside the scope of this presentation.

The DGPS receiver is used to measure the attitude (heading) of the gondola with an accuracy of $0.05°$ or better. Hence the MHS sensor and the STR are only considered as "backup" sensors during the first few flights of the PoGOLite. In addition, the STR is intended to improve the pointing accuracy if available. To achieve an accuracy of $0.05°$ the GPS antennae are separated by some 10 m. The differential GPS receiver is using the phase difference between the carrier wave signals of the two antennae to determine a relative positioning of the two antennae to within a few mm accuracy. The DGPS receiver is calculating heading values at a fixed 20 Hz update rate.

The purpose of the PDU is to distribute power to the individual bus nodes and to protect the power supply against fatal hardware failures such as short circuits. The two PDU:s are identical and are connected to two independent power supplies to provide redundancy. Each PDU supply power to consumers via eight independent power channels. Each power channel consists of a relay switch, a current shunt for current monitoring, an auto resetting circuit protector and a slow fuse. The remote controlled relay switches are used to balance power over the two power supplies, switch between supplies in the event of a single power supply failure, generate a hard restart of a bus node or permanently isolate a bus node in case of a permanent node failure.

All PDU relay switches except one, are controlled by the MPU. The one switch which is *not* controlled by the MPU is supplying the power to the MPU itself. This particular relay is controlled by a simple hard wired watch-dog which is cycling the relay on and off at a slow fixed pace. The cycling can be stopped, and the relay kept on infinitely only if the watch-dog is receiving a permanent pulse train on its heart-beat input port. The heart beat signal is generated by the operating and control system implemented in the MPU and therefore ensures that power will remain on as long as the software is fully operating.

The in-house designed MPU is based on a simple low performance "Pentium" type micro controller. Thanks to the adopted distributed approach, the demands on the MPU is very low even though the control loops of the control system is running at frequencies as high as 50 kHz. The main purpose of the MPU is to act as a supervisor and as an interface between the control system and the ground control station. It is doing so by maintaining a database of all real-time signals and scheduling the distribution of all signal values to/from all nodes.

Since the demands on the MPU are fairly low, it is running at a clock frequency as low as 100 MHz. It has a DRAM and a Flash disc as small as 64 MBytes each. This turns out to be more than adequate to implement a control system of PoGOLite type. In the PoGOLite system there are control loops running at five different frequencies (20 Hz, 100 Hz, 1 kHz, 10 kHz and 50 kHz). The operator has access to some 200 signals for diagnosis and monitoring and still the CPU load is as low as 20% and the DRAM and Flash disc usage is less than 1 MByte (out of available 64 MBytes).

4. DIGITAL DIRECT DRIVE ACTUATORS

There are four different actuators in the PoGOLite gondola. Three of these - namely the balloon train, the azimuth and the elevation actuators - are based on the novel Digital Direct Drive (DDD) technology. The fourth actuator - namely the roll actuator - is based on a classical geared motor and will therefore not be discussed any further.

We refer to the DDD actuators as *digital* since the electrical interface consists of nothing else but one dBus and one power bus connection. There is yet another optional port available for the safe disabling of all actuators upon the opening of a simple emergency stop circuit.

This very simple interface is made possible by fully integrating the power amplifiers and servo controllers with the motor itself. In fact we employ a novel approach, developed over the last decade, to tightly integrate the power amplifier with the armature windings; see Figure 5. The advantages of employing such an approach are that heat is better distributed, and that EMC levels becomes exceptionally low.

Each DDD actuator also have a powerful servo loop controller tightly integrated with the armature. The servo loop controller is based on a powerful FPGA (Field-Programmable gate Array) capable of running several control loops in true parallel at high frequencies. In the PoGOLite project the motor controller FPGAs are executing control loops at four different frequencies (100

Figure 5. The corner stone of the Digital Direct Drive concept; tight integration of the drive stage with the motor armature on a single hybrid substrate.

Hz, 1 kHz, 10 kHz and 50 kHz). These three frequencies correspond to three different control loops closed by the same localised FPGA. These four loops correspond to the low-level switching of the drive stage, the commutation of the stator, current control, speed control and position control.

The interesting feature of the distributed approach is that each individual motor is capable of handling its own control even though not all required sensors are locally available. Again this is made possible through the dBus. As an example, when the PoGOLite is pointed to a star, it is required for the motors to have access to the IMU gyro rate signals at a 1 kHz pace in order to close the speed loop. This is made possible through the dBus and a simple configuration file specifying which signals shall be available to which motors. Hence it is very simple to add new motors or sensors to the control system without having to change any software or hardware.

The DDD actuator concept was originally developed sa few years ago for our *OTUS* range of gyro stabilised micro gimbal products (Figure 1). Hence the motors used in the PoGOLite system is essentially a scaled-up version of this original OTUS motor. Since then, yet another motor size was developed so that we now can offer three different sizes, capable of delivering 0.25 (0.50) Nm, 2.5 (5.0) Nm and 25 (50) Nm respectively. The values in parenthesis represent peak performance limits.

5. INERTIAL MEASUREMENT UNIT

In analogy with the DDD actuators, the digital IMU is a fully integrated device in which sensor elements are tightly integrated with FPGA based computational hardware. Like in the DDD actuator, not all sensors required for all the calculations are available locally. For instance, when the differential GPS is fully operational, the IMU uses the GPS based heading values to compute gyro bias values and absolute angles with respect to the inertial system. Also, the IMU automatically switches over to use the MHS signals when they are the only ones available for estimating the heading (which happens when using the system indoor or when the GPS fails due to obstructions on ground). This is again made possible thanks to the dBus.

The in-house designed IMU is based on a micro-mechanical sensor elements designed by the IMEGO institute in Sweden. The performance of these sensor elements is unique in the sense that it meets or exceeds the performance of fibre optic gyros.

6. CONTROL SYSTEM SOFTWARE

By employing the presented distributed approach, the software of the control system becomes very simple. Furthermore, some 15 years ago, we succeeded to design a software which is invariant with respect to the system hardware architecture. All the application specific adaptations are described by four distinct group of configuration files that are parsed by the control system upon start of the system. The following is a summary of these four configuration files and their purposes:

1. A parameter file, containing all the control loop tuning values.
2. An XML based hardware configuration file describing the control system nodes and the transfer of signals between these nodes.
3. A control loop implementation file specifying the computations to be performed on the signals specified above.
4. A set (possibly empty) of hardware specific device drivers for sensors and actuators not compatible with the dBus specification.

All control loops are associated with a large number of parameters. For the PoGOLite project there are a few hundred parameters associated with all the 25 or so control loops. By collecting all parameters into one single file it is rather simple to tune all the different control loops. All control loop parameter values can also be altered in run-time. The purpose of the parameter file is to make sure a well defined parameter setting is established after cold start.

In a control system the size of PoGOLite there are a few hundred control signals available at different rates. All these signals are sampled at different rates and are generated and consumed by different parts of the system. All signals are at all times available for remote monitoring by the operator, but at the lowest possible update rate and hence not necessarily in real-time. In order to keep the dBus simple and the traffic deterministic, all the signals transferred over dBus must be specified in one single *connection* file. The dBus specification follows a very basic *single master - multiple slaves* approach in order for the traffic to be analysed and the timing to be verified before run-time.

The control loop configuration file is probably the most advanced of the four configuration files. Roughly speaking the file should contain a sequence of mathematical operations on signals. More specifically there should be one such sequence of operations for each sampling frequency implemented by the control systems. The operating system will then automatically execute these sequences according to a rate-monotonic scheduling mechanism. There are a number of rules that must also be followed when designing the file. An example of such a rule is that *LOOP* constructs are not allowed and that *IF* cluses are not allowed to bypass any calculations. By following simple rules like these we can rest assured that the resulting computational load will be fixed and not vary over time.

To ensure that these rules are automatically followed we recommend using modern graphical control system design tools. We currently support Simulink, which is part of MATLAB (Mathworks 2011), and SystemBuild, which is part of MATRIXx (Instruments 2011). By using one of these two tools the control loop specification file can be fully automatically generated from the graphical model.

Apart from parsing the above four configuration files, the very simple operating system of the MPU is providing the following functions:

- Initialisation of all bus nodes.
- Scheduling of the dBus transactions.
- Scheduling of the control loop computations.
- Automatic real-time logging of arbitrary signals.
- Remote viewing of arbitrary signals in non-real-time.
- Remote modification of control loop parameters.
- Detection and reporting of faults in bus nodes and the dBus communication.
- Low-level debugging of FPGA:s of individual bus nodes.
- Update of firmware of individual bus nodes.

In order to simplify the use of these advanced services of the operating system, we also provide a standard PC hosted remote control software referred to as *dScope*. In addition to providing a user friendly interface to the above services, the dScope software also provides functions for analysing the performance of control loops and exporting logged signals to MATLAB or MATRIXx.

7. CONCLUSIONS

We have presented a modular solution for cost efficient stabilisation of a wide range of scientific applications. The solution is based on the following key concepts:

- Distribution of control loops over any number of computational nodes.
- Use of a simple high speed bus for efficient signal transfer between nodes.
- Digital Direct Drive actuators in which the motor armature is tightly integrated with drive electronics and FPGA based signal processors.
- Intelligent sensor nodes in which sensor elements are tightly integrated with FPGA based signal processors.
- Simple configurable real-time operating system focused on closed loop control and nothing else.
- Standardised PC based remote control and debugging tool.
- Graphical control loop design tools and fully automatic code generation.

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