FlexCore: Low-Cost Attitude Determination and Control Enabling High-Performance Small Spacecraft

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ABSTRACT

One of the most important, yet complex, and expensive subsystems for virtually any spacecraft mission is the attitude determination and control subsystem (ADCS). Many payloads require precision ADCS to achieve the desired performance; however, such precision is typically cost-prohibitive for small spacecraft. To address this problem, Blue Canyon Technologies (BCT) has developed FlexCore, which is a highly-configurable ADCS that uses a core electronics box (based on the XACT cubesat ADCS), combined with any of the various reaction wheel sizes in the BCT product line. The FlexCore electronics and software stays the same, regardless of the spacecraft. The wide range of reaction wheel and torque rod sizes supports spacecraft sizes from large CubeSats to 100s of kilograms. The stellar-based attitude determination and control provides accuracy of 0.002 deg, RMS. Features of FlexCore include: multiple nano star trackers with integrated stray-light baffles; 3 or 4 low-jitter reaction wheels; 3 torque rods; GPS receiver; MEMS IMU; MEMS magnetometer; sun sensors; integrated processor and electronics; auto-generated flight software, including star identification, Kalman filter, momentum control, thruster control, and orbit propagation. The table-driven, auto-coded software is easily configured to support any mission, and is delivered to the user fully programmed.

INTRODUCTION

As the growth of the smallsat market continues, so does the desire for less expensive spacecraft. One of the most important, yet complex, and expensive subsystems for virtually any spacecraft mission is the attitude determination and control subsystem (ADCS). Many payloads require precision ADCS to achieve the desired performance; however, such precision is typically cost-prohibitive for small spacecraft. Leveraging much from their successful XACT cubesat ADCS, BCT has developed a very cost-effective, high-performance ADCS that can support ESPA-class spacecraft, and beyond.

CUBESAT POINTING SOLUTION

In 2011, Blue Canyon Technologies was awarded a contract by AFRL to solve the CubeSat pointing problem. After years of development, BCT created the fleXible ADCS CubeSat Technology (XACT), shown in Figure 1, which provides a reliable, high-performance design, compatible with a variety of CubeSat configurations. The BCT XACT architecture leverages a powerful processing core with BCT’s nano star tracker (NST) and reaction wheels to enable a new generation of highly-capable, miniaturized spacecraft. XACT enables CubeSats to point with much higher accuracy than any other available CubeSat attitude control system, and allows for a much larger number of mission possibilities. XACT is currently baselined in dozens of missions spanning LEO, GEO, Lunar, Mars, and deep space. XACT is currently flying on the University of Colorado MinXSS CubeSat, where preliminary on-orbit data shows control system errors less than 10 arc seconds on all three axes.

Figure 1: XACT Attitude Control Module for Cubesats
Features of XACT include:

- Nano Star Tracker for precise attitude determination (w/ integrated stray light baffle)
- Three micro-sized reaction wheels enabling precise 3-axis control
- Three torque rods
- MEMS IMU
- MEMS Magnetometer
- Sun sensors
- Hyper-integrated electronics board

Integrated Electronics

One of the many innovations with XACT is the collection of all electronics into a single highly-integrated processor board. Key features of the processor board are:

- FPGA with LEON soft-core processor
- SDRAM, DPRAM, FLASH memory
- Sensor/Actuator interfaces
  - Reaction wheel and torque rod drivers
  - A2D converters
  - SPI and I2C
  - GPSR data interface, and micro-second 1PPS timing
- Latching relay for image boot selection
- Volt regulators/converters

SMALL-SAT POINTING SOLUTION

Whereas the XACT avionics were primarily designed for CubeSats, their functionality is expandable to much larger spacecraft by simply utilizing one of BCT’s larger reaction wheel and torque rod sizes.

The first variation is XACT-Core, in which the internal micro wheels and torque rods are replaced with three or four larger external wheels and rods from BCT’s line of products. The first program to utilize this is the DARPA SeeMe spacecraft developed by Raytheon, shown in Figure 2. This system is typically utilized in spacecraft less than 50kg.

The second variation, and most capable, is FlexCore, in which multiple external NSTs (detached from the electronics core) are used, along with three or four wheels having momentum as high as 1.5 Nms (with larger currently in development). The external trackers can be placed as needed around the spacecraft for optimal pointing performance, and provide higher-precision pointing and redundancy. This system is baselined in multiple Air Force ESPA-class missions.

Figure 3 shows an example of FlexCore flight hardware.

Figure 2: XACT-Core ADCS Hardware

Figure 3: FlexCore ADCS Hardware

Figure 4 contains a series of block diagrams that illustrate the similarities and differences of the XACT, XACT-Core, and FlexCore products.
For each of the systems, the flight software supports closed-loop simulation during system integration and test, providing a test-like-you-fly environment. Interfaces to an optional propulsion subsystem are accommodated and propulsion software has been implemented.

**Nano Star Tracker**

The key component for achieving precision attitude determination is the nano star tracker, shown in Figure 5.

**Figure 5: Nano Star Tracker (NST)**

Features of the star tracker include:

- Star-light in -> attitude quaternion out, at 5Hz
- Lost-in-space initial attitude solution within 4 seconds.
- Tracks stars down to 7.5 magnitude
- Can process up to 64 stars at once
- On-board star catalog >23,000 entries
- Integrated high-performance stray-light baffle
- Supports photo/video mode with full image or region of interest (ROI)

One of the most important (and most difficult) steps in star tracker operation is determining which stars the tracker is looking at. Without that, it has no way of knowing how it is oriented in space. The NST star ID algorithm is robust and efficient, and employs the following features:

- Efficient database structure and search algorithm to achieve Lost-in-Space star ID in <4 seconds
- Completely insensitive to absolute star magnitude knowledge
- Very insensitive to relative star magnitude knowledge
- Simulations with high relative magnitude errors, high centroid errors, and an unknown bright object in the FOV show >99.5% success rate
- Has demonstrated successful star ID with detector 80% saturated with ambient stray light
The NST can perform star ID at rotation rates of at least 1 deg/s.

**Stray Light Baffle**

It is very important for a star tracker to have a stray light baffle. Without one, the tracker will almost certainly be blinded by reflections of the sun anytime it is in the same hemisphere of the tracker boresight. The NST tracker baffle was made an integral part of the overall tracker design from the very beginning, rather than an afterthought. The baffle delivers excellent sun rejection. BCT conducted performance testing of the NST baffle in a Heliostat chamber at the University of Colorado LASP. This test was used as an evaluation of the baffle design to verify its light extinguishing characteristics. Figure 6 shows the baffle performance. The value 10 to the minus 10 was determined to be the sun extinction level at which dim stars can be tracked, and occurs at an angle of 45 deg from the tracker boresight. At around 25 deg off boresight, the extinction level rises sharply, which corresponds to the angle at which the bright earth might cause problems. Overall, the performance matched analytical models very well. One should note the slope of the extinction curve between 45 deg and 25 deg -- it is relatively shallow. As a result, it is very likely that the tracker can get closer than 45 deg to the sun, and still track a reasonable number of brighter stars. The tracker employs a series of background corrections to compensate for high background, among other things. The tracker has demonstrated the ability to operate with the detector 80% saturated with ambient stray light.

**NST Tracker Performance**

After successful star ID, the tracker transitions to Track mode, using all available stars. A number of quality checks are performed on each star to determine if it should be included in the attitude solution. During this mode the attitude solution has its full accuracy.

Night sky tests were conducted, using a high-precision telescope gimbal, where the tracker was slewed at various rotation rates (up to 1.5 deg/s) to determine its performance (i.e. attitude error vs. rate). The gimbal motion is accurate to a couple of arc-seconds, so its contribution is considered small enough to ignore. Attitude data was collected from the tracker during the slews. The data was post-processed to remove the mean motion of the gimbal from the tracker attitude. The resulting error is the star tracker attitude knowledge error. Due to gimbal drive limitations, higher rotation rates could not be collected. Analysis and simulation shows the tracker should be able to track up to at least 2 deg/s.

Figure 7 shows the RMS star tracker pointing error as a function of slew rate. The cross-axis errors are very low over the entire range. The roll axis (or about boresight) is larger than the cross-axis by a factor of about 12, which is to be expected, given the tracker FOV of 10x12 deg. If two trackers are used, all three spacecraft axes will exhibit the cross-axis performance. For a spacecraft performing earth imaging of a target directly below, the maximum slew rate might reach 1.3 deg/sec, depending on orbit altitude. Figure 7 shows the worst-case tracker pointing error would be 12 arc seconds. The on-board Kalman filter further improves pointing performance by optimally mixing MEMS IMU data with the tracker data. The resulting error is approximately 7 arc seconds, or 0.002 deg.

![Figure 6: NST Baffle Performance](image)
One of the largest sources of error for any star tracker is dark current noise, which increases significantly with detector temperature. Most star trackers implement some sort of thermal-electric cooler, which reduces detector temperature, but at the expense of increased power consumption. The BCT star tracker implements real-time thermal-noise compensation that adapts as a function of temperature. As a result, no thermal-electric cooler is necessary. The compensation is not perfect, but the increased cross-axis error is only 2 arc-seconds, at 60 degC. The tracker can thus operate over its full operating temperature while consuming a constant power of only 1W.

**NST Photo Mode**

In addition to tracking stars and generating attitude solutions, the star camera can also operate in photo/video mode. The user can command the camera to take and store multiple images, using either the full image frame, or a region of interest (ROI). ROI’s can be sized anywhere from 9x9 pixels to the entire 1024x1280 image. The images can be downloaded to the host, either via the usual command/telemetry interface, or by an auxiliary built-in high-speed serial interface. The camera can store over 15 full-frame images, or over 15 minutes of a 64x64 ROI at 5Hz. Various photos were taken to demonstrate the image quality. Two examples are shown below, in Figure 8. The first is a daylight photo of a satellite mock-up on display in the University of Colorado LASP lobby. The other is a night-time photo of a car in a parking lot. Both images show the detail and exposure range of the camera, and show that it could be used in rendezvous and proximity operation, in addition to providing attitude.
Reaction Wheel Design

The BCT family of reaction wheels are designed for long life and low jitter. BCT designs the motors in-house to achieve the desired torque/speed characteristics, and to guarantee the desired quality and reliability. Figure 9 shows the BCT family of reaction wheels that can support CubeSats to ESPA-class and larger. The RWp015 wheels are used internally with XACT. The RWp050 through RWp500 can be used with XACT-Core, and RWp500 and RW1 are typically used with FlexCore.

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<th>RWp015</th>
<th>RWp050</th>
<th>RWp100</th>
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<td>0.050</td>
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**Imbalance Measurement**

All of the BCT reaction wheels employ a patent-pending isolation and damping system that results in extremely low induced vibration.

Imbalance waterfall plots are generated for all wheels, using our Jitter Environment Measurement System (JEMS), shown in Figure 10. Figure 11 shows typical jitter measurements for RWp500 and RW1 wheels. The results of the waterfall plots show very balanced and quiet reaction wheels, which will support very tight pointing stability requirements. The fact that the high-frequency disturbances are so small also makes spacecraft-level jitter analysis much easier, since the only disturbance of concern is the fundamental imbalance.

**Wheel Control Loop**

The reaction wheel is controlled by a very sophisticated digital controller operating at 200 Hz. Using tachometer feedback, based on the motor Hall sensors and PWM (Pulse Width Modulation) control of motor applied voltage, the control loop ensures extremely low error in providing the commanded torque. Features include:

- Full-state observer that identifies rate and friction
- Commandable adaptive identification of Hall sensor misalignments via a globally stable online alignment estimator
- Hybrid feedforward/feedback control architecture provides high bandwidth and disturbance rejection capabilities

The wheel controller achieves extremely accurate torque control, to within a small fraction of a percent. Figure 12 shows the desired and actual wheel speeds after a large torque was applied to the reaction wheel. There is no perceptible error.

![Figure 10: Jitter Environment Test System (JEMS)](image)

![Figure 11: Example Wheel Disturbances](image)
CONCLUSIONS

BCT has developed a range of high-performance attitude control system products that can support Cubesats to ESPA-class and beyond. By leveraging high reuse of flight-proven electronics and software, and high-volume manufacturing, the XACT, XACT-Core, and FlexCore attitude control systems provide a cost-effective solution for the growing small satellite market.

Flight Software

BCT uses a proven method of software development that is extremely efficient, robust, and supports near-100% code re-use across all spacecraft. BCT GN&C and software personnel worked on over 20 spacecraft programs at a variety of companies, prior to BCT. Having seen first-hand how much the traditional software development process can drive cost and schedule on any spacecraft program, BCT set out to substantially reduce that effort by automating the code generation and build process, and command/telemetry database generation as well. After years of development and refinement, the resulting table-driven, capability-rich software goes far beyond most small satellites, and is on par with any tier-1 spacecraft.

Over 95% of the flight software is auto-coded using Matlab/Simulink. Key features of the flight software are:

- Multi-rate system with real-time OS
- Commands (real-time, stored, macro)
- Telemetry (multiple selectable maps)
- Fault Protection & Autonomy
- Attitude Orientation Command
- Attitude Determination & Control
- Time Keeping
- Orbit Propagation
- High-precision reference vectors
  (e.g. Sun, moon, earth rot., mag field)
- Momentum Control
- Wheel Control
  (including high-speed servo loop)
- Thruster Control
- Table Management

Figure 12: Reaction Wheel Servo-Loop Performance