A CubeSat Flight Demonstration of Constrained Attitude Control

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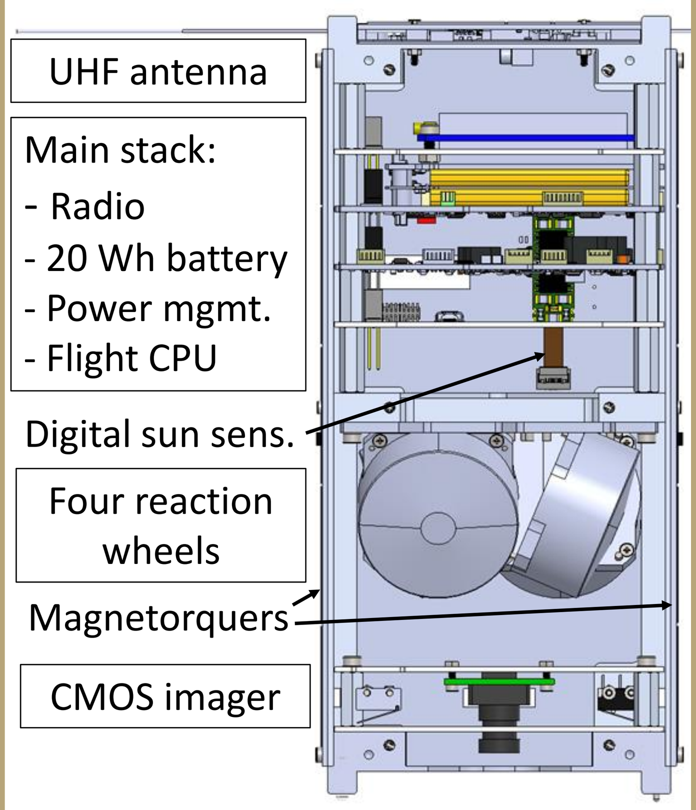
I. What is SOC-i?



Cutaway of SOC-i showing internal components in flight configuration

Satellite for Optimal Control and Imaging

- 2U CubeSat developed at University of Washington to be the first in-space demonstration of real-time optimization-based attitude control
- Our mission is to provide educational opportunities at UW and a testbed for A&A-developed control algorithms
- Selected for launch by 11th CubeSat Launch Initiative call

II. Why is constrained attitude control useful?

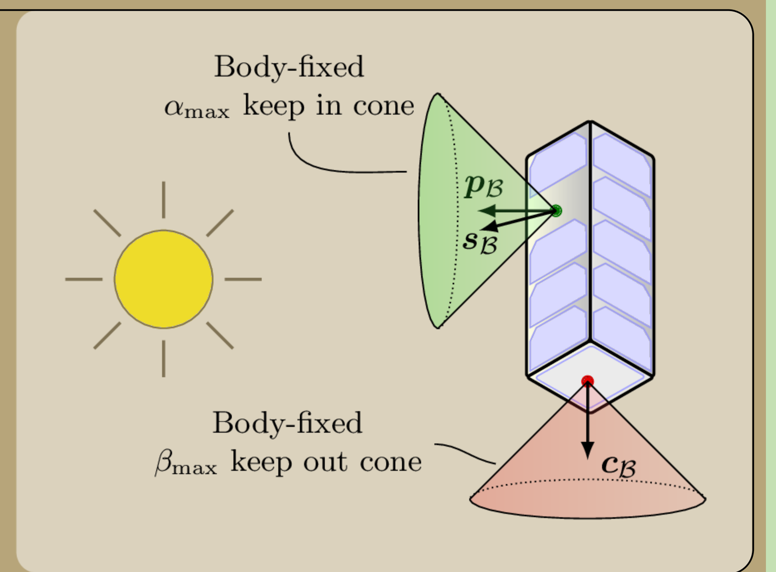
Constraints are used to align control system performance with mission requirements:

- Mission-specific constraints often define how attitude maneuvers must be executed
- Pointing inclusion/exclusion zones are not enforceable using classical control methods
- Optimization-based methods can handle these along with standard slew rate and torque limits

This can reduce risk on missions of all sizes:

- Poor maneuver planning can result in constraints being violated
- This can damage sensitive instruments or cause loss of navigation data
- Risk can be reduced by ensuring constraints are met at all times

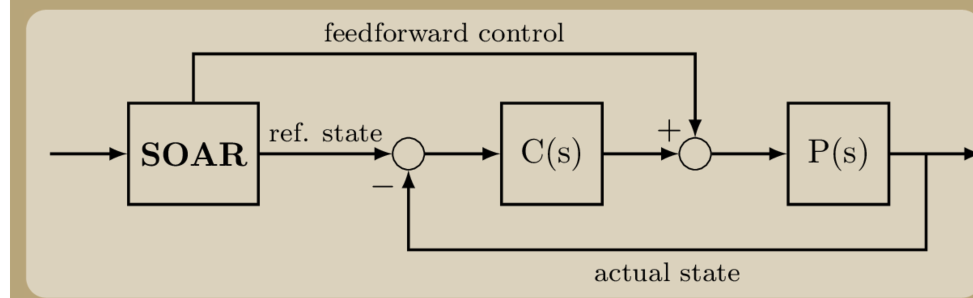
An example of constrained attitude control is to reorient while keeping the sun in view of the sun sensor but out of view of a sensitive optical instrument.



Did you know:
New Horizons pointed its LORRI imager at the sun accidentally, nearly destroying it. The control software was only designed to meet pointing constraints at the beginning and end of a maneuver, but not during the interim reorientation.

III. SOC-i Optimal Attitude Reorientation (SOAR)

SOAR is SOC-i's primary payload, the first in-space tech demo of optimization-based constrained attitude control. It provides feedforward guidance commands that reorient SOC-i while guaranteeing pointing constraints and minimizing reaction wheel power consumption.



SOAR builds on previous work done at UW. The pointing inclusion and exclusion constraints are formulated with an equivalent convex quaternion representation, and the solution process uses elements of successive convexification.

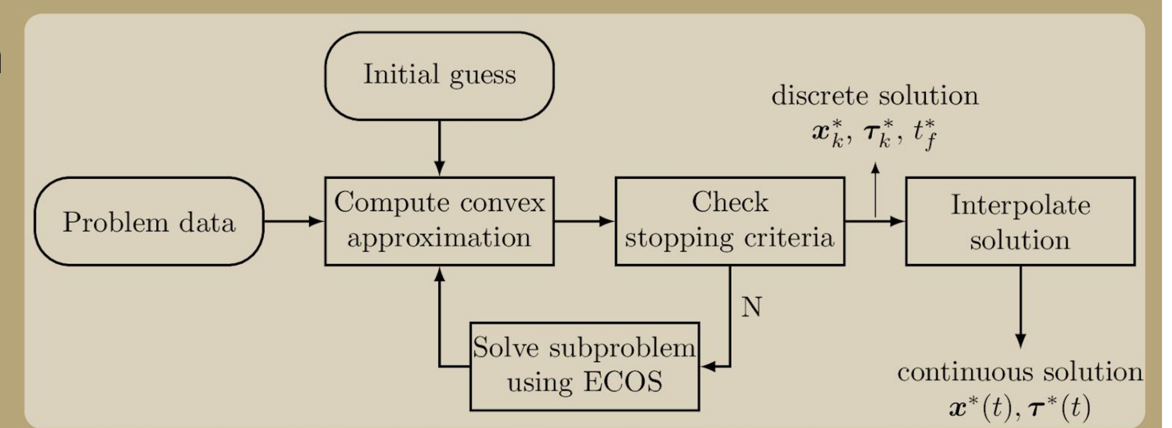
Reorientation maneuvers are executed such that:

1. The sun vector remains in the sun sensor field-of-view
2. Sun vector simultaneously remains out of the camera field-of-view
3. Actuator and slew rate limits are not violated
4. Given a target attitude, SOAR computes maneuvers on-board with no pre-loaded solution or ground intervention

$$
\begin{aligned}
\min_{t_f,\boldsymbol{\tau}(\cdot)} \quad & \int_{t_0}^{t_f} \boldsymbol{\tau}^\top \boldsymbol{\tau}(t)dt \\
\text{s.t.} \quad & \dot{\boldsymbol{x}} = f(\boldsymbol{x},\boldsymbol{\tau}) && \longrightarrow \text{equations of motion} \\
& \|J^{-1}\boldsymbol{h}_{\mathcal{B}}\|_\infty \le \omega_{\max} && \longrightarrow \text{slew rate limit} \\
& \|\boldsymbol{\tau}\|_\infty \le \tau_{\max} && \longrightarrow \text{torque limit} \\
& \boldsymbol{q}^T \tilde{M}_e \boldsymbol{q} \le 2 && \longrightarrow \text{exclusion constraint} \\
& \boldsymbol{q}^T \tilde{M}_i \boldsymbol{q} \le 2 && \longrightarrow \text{inclusion constraint} \\
& t_{f,\min} \le t_f \le t_{f,\max} && \longrightarrow \text{final time bounds} \\
& \boldsymbol{x}(t_0) = \boldsymbol{x}_{ic}, \quad \boldsymbol{q}(t_f) = \boldsymbol{q}_f, \quad \boldsymbol{h}_{\mathcal{B}}(t_f) = 0
\end{aligned}
$$

SOAR works by formulating a free final time, nonlinear, optimal control problem. It solves a sequence of convex optimization problems using ECOS, an open-source solver. State trajectories are produced that adhere to nonlinear rigid body equations of motion.

SOAR takes problem data and an automatically generated initial solution guess as inputs. It iteratively computes a convex approximation of the original problem and solves the resulting sub-problem (second-order cone program). The discrete-time optimal solution is interpolated to give continuous commands to the feedback controllers.

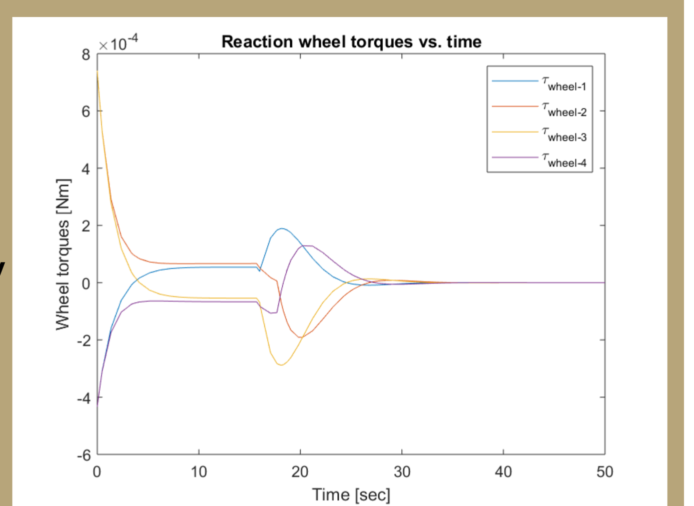


IV. Risk Mitigation with COTS Subsystems

SOC-i is AACT's first CubeSat. We have intentionally limited the scope of custom-built hardware to minimize the risk of first-mission failure that is a common pitfall for university CubeSat teams.

Guidance, Navigation, and Control (GNC)

- Active 3-axis control is required to demonstrate the SOAR technology
- 4 NanoAvionics reaction wheels, magnetorquers integrated in the ±X, ±Y, and +Z solar arrays
- 3 magnetometers, 3 gyros, and a SolarMEMS digital sun sensor for reliable fine attitude knowledge



Reaction wheel torques during a 104° reorientation maneuver with imposed constraints on max slew rate (6°/s) and torque (2.2 mNm)

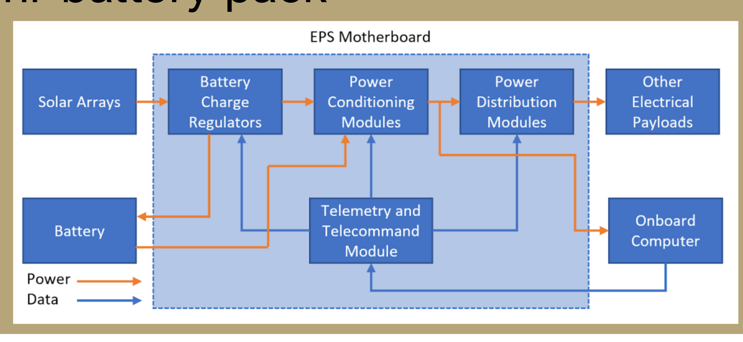
Communications


The Pacific Crest XDL Micro radio is being tested at UW currently.

- SOC-i uses amateur UHF band to downlink to UW-based receiver
- Pacific Crest XDL Micro radio has flight heritage aboard EQUiSat
- EnduroSat UHF antenna is sole deployable on SOC-i with triple-redundant release mechanism

Electrical Power System

- Primarily sourced from Clyde Space with four 2U body-mount solar arrays, power distribution board, and 20 W-hr battery pack



Universal Operating Mode	BAT_V Range from EPS Motherboard	Active PDMs: CDH	RXW	MTQ	IMG	COM	SEN
Critically Low Power	<= 7.4	✓	x	x	x	x	x
Low Power	(7.4, 7.9]	✓	x	x	x	✓	✓
Nominal	> 7.9	✓	✓	✓	✓	✓	✓

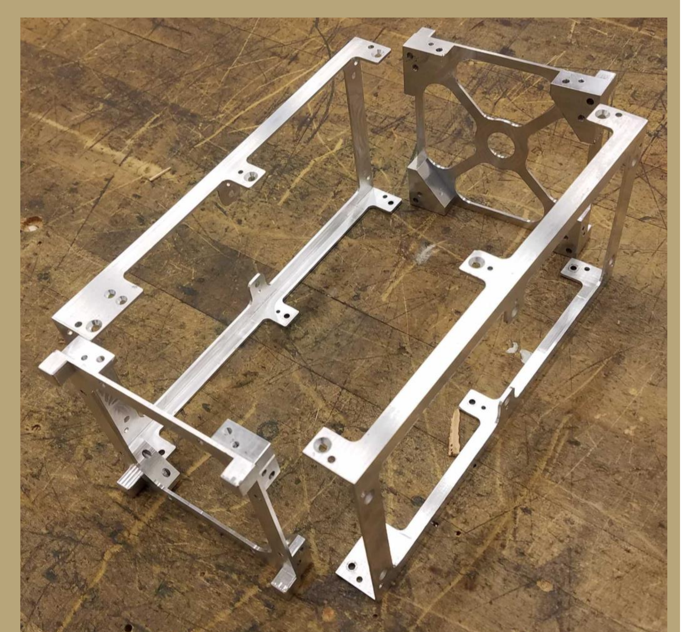
The EPS dictates all subsystem states in universal operating modes based on battery charge

V. Custom Chassis and On-Board Computer

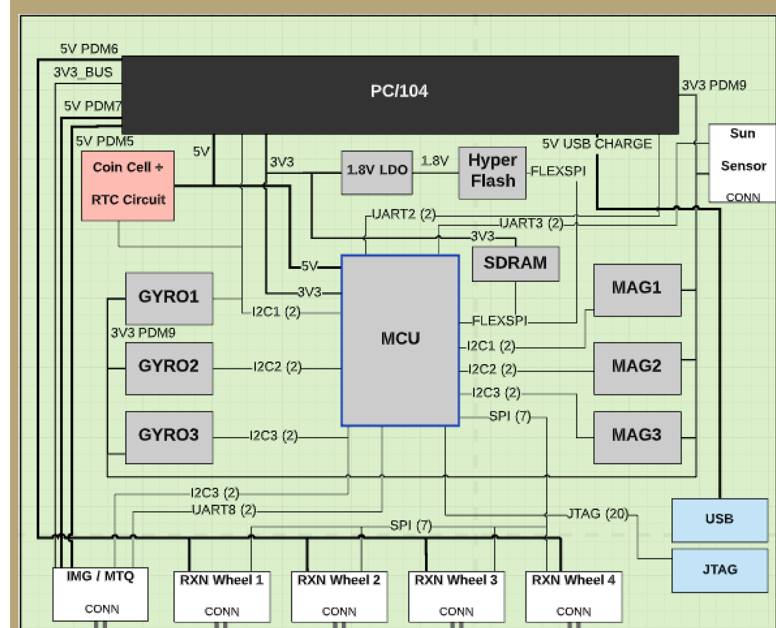
AACT has plans for future missions that will be entirely custom CubeSats carrying UW science payloads. On SOC-i, we are custom building just a few initial subsystems. This avoids over-scoping while laying the foundation for more custom subsystems in future flights.

2U Chassis

- Goals: (1) provide easy access to SOC-i internals and (2) be easily adaptable to 1U or 3U sizes
- Consists of 2 identical rail walls, 2 distinct endplates, and stiffness rib
- Initial design by senior capstone
- Manufactured entirely by students, machining is underway pending COVID-19 shop closures


The chassis is comprised of modular rail walls and endplates (rib omitted)

On-board Computer



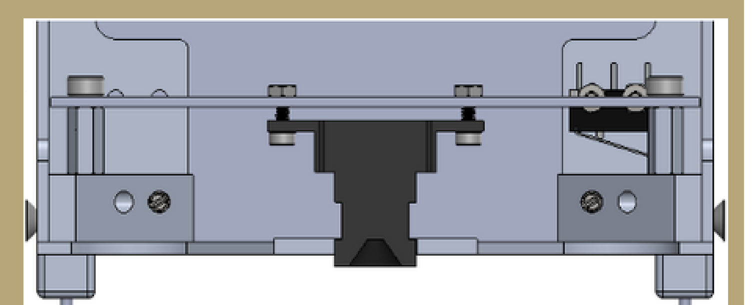
The OBC houses the microprocessor, GNC sensors, data interfaces, and real-time clock

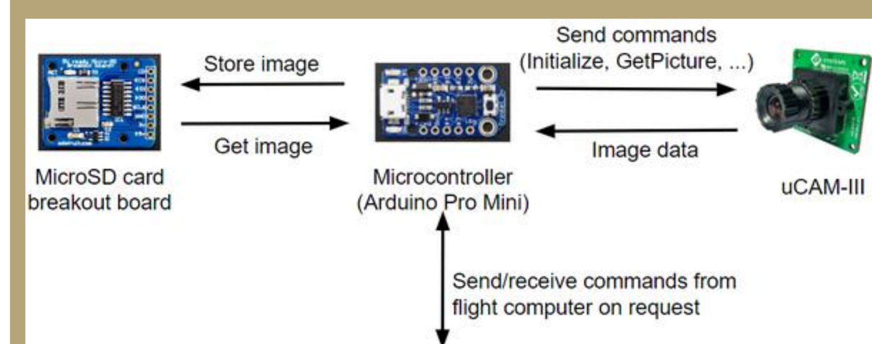
- Custom student design adapted from NXP i.MRT1050 dev board
- Microprocessor based on ARM Cortex-M7 platform
- Utilizes I2C, UART, and SPI for peripheral interfacing
- Firmware/software uses FreeRTOS for task execution

VI. Imaging Payload (IMG)

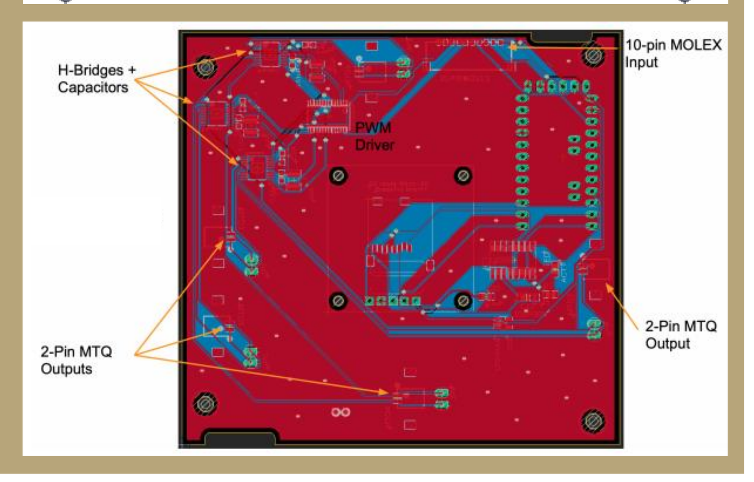
SOC-i has accurate pointing capability, making it an ideal platform for space-based imaging. A basic CMOS camera is being flown as a secondary payload to provide images from space for outreach purposes.

- Mounted to -Z face of SOC-i to keep sun out of field of view
- Board is designed to house IMG hardware and magnetorquer control circuitry, currently being fabricated





The IMG subsystem is comprised of cheap, COTS elements as a simple instrument demonstration.



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