Agenda

- Introduction

- Functional Requirements, Ground Commands and External Interfaces, Code Status and Plans, and Software Design Review for:
  
  Attitude Determination and Control, including GNC Executive
  
  Terminal Guidance and Control
  
  Image Processing
  
  Orbit Propagation
  
  Autonomous Navigation
  
  Support Functions for Autonomous Scheduler
  
  Delta V Thruster Control
  
  Solar Array Control
  
  Utility Routines

- Testing at SAC's Facility
Attitude Determination Functions

- Update attitude and rate from IMU data
- Incorporate star tracker measurements to initialize attitude and eliminate drift
- When spacecraft is spinning, use solar cell detector to update roll angle
- IMU redundancy management (monitor dual IMU's)
Attitude Control Modes

- Five 3-axis stabilized modes:

  Lunar Mapping: sensors toward lunar center with optional offset
  Earth Pointing: high gain antenna toward specified ground station
  Asteroid Fly-By: sensors toward target (kick motor or asteroid)
  Star Pointing: sensors toward specified star
  Inertial Pointing: arbitrary orientation commanded by ground or other module

- Three sub-modes for control laws:

  Use reaction wheels
  Use ACS jets, tight control
  Use ACS jets, loose control
Five modes that use ACS jets and are not 3-axis stabilized:

- Lifeboat: power-on mode; maintains angular velocity within software limits
- Open Loop Spin Change: fires specified jets for specified interval
- Closed Loop Spin Control: maintains angular velocity within specified limits
- Active Nutation Control: reduces spin axis nutation
- Spin Axis Precession: precesses spin axis to specified direction

One mode that uses reaction wheels and is not 3-axis stabilized:

- Lifeboat: maintains angular velocity at software specified value
GNC Executive Functions

- Process control modes requests per transition rules and restrictions
- Generate desired attitude and body rate for: Lunar Mapping; Earth Pointing; Star Pointing
- Filter large attitude changes: smooth large changes; avoid solar exclusion zone
- Monitor attitude for solar exclusion (freeze attitude if violated)
- Request star tracker measurements (when not done by DHU)
- Monitor reaction wheels for momentum dumping and failure detection (latter may be done in SCL)
- Update inertial properties as needed by ACS
- Modify ACS parameters for configuration and mass changes
Ground Commands For Attitude Determination And Control

- Select Attitude Control Mode and provide associated parameters (10 different commands)
- Enable/disable GNC star tracker data requests
- Reset attitude: reset quaternion to specified value and apply start-up logic for star tracker measurements
- Initiate momentum dump: fire ACS jets while using reaction wheels to maintain control
- Reaction wheel failure: ground detected failure
- Enable diagnostic telemetry data
<table>
<thead>
<tr>
<th>Capability</th>
<th>GNC Version</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process mode requests (partial)</td>
<td>0.1</td>
<td>na</td>
</tr>
<tr>
<td>Process mode requests</td>
<td>0.2</td>
<td>na</td>
</tr>
<tr>
<td>Generate desired quaternion (3 modes)</td>
<td>0.2</td>
<td>Done: SAC</td>
</tr>
<tr>
<td>Request star tracker measurement</td>
<td>0.2</td>
<td>TBS: SAC</td>
</tr>
<tr>
<td>Smooth large attitude maneuvers</td>
<td>0.3</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>Avoid solar exclusion zone</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Monitor sun/sensor angle</td>
<td>0.3</td>
<td>na</td>
</tr>
<tr>
<td>Initiate momentum dumping</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Update ACS parameters</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Table uploads</td>
<td>0.3</td>
<td>na</td>
</tr>
<tr>
<td>Telemetry</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Detect reaction wheel failure</td>
<td>0.3 or SCL</td>
<td>TBS: NRL-ACS</td>
</tr>
</tbody>
</table>

Notes: Version 0.1 delivered 1 March  
Version 0.2 due 26 March  
Version 0.3 due 23 April
## Attitude Determination And Control Status

<table>
<thead>
<tr>
<th>Capability</th>
<th>GNC Version</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process IMU data</td>
<td>0.1</td>
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</tr>
<tr>
<td>Open loop spin</td>
<td>0.1</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>Closed loop spin</td>
<td>0.1</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>Process star tracker data</td>
<td>0.2</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>3-axis stabilization</td>
<td>0.2</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>Lifeboat modes</td>
<td>0.2</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>Reaction wheel failures</td>
<td>0.2</td>
<td>Done: SAC</td>
</tr>
<tr>
<td>Solar cell data for roll</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>IMU redundancy management</td>
<td>0.3</td>
<td>Done: NRL-ACS</td>
</tr>
<tr>
<td>Active nutation control</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Spin axis precession</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Momentum dump</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
<tr>
<td>Attitude reset</td>
<td>0.3</td>
<td>na</td>
</tr>
<tr>
<td>Table uploads</td>
<td>0.3</td>
<td>na</td>
</tr>
<tr>
<td>Telemetry</td>
<td>0.3</td>
<td>TBS: NRL-ACS</td>
</tr>
</tbody>
</table>
Exec Software Structure (1/3)

Gnc Exec

Message Initialization
Start Cyclic Timer

Gnc Loop

Self-Schedule  GncMsgProcessing  GncCyclicProcessing  NotifyForWrap

- Contained within calling routine
- Subroutine

03/08/93 04:40 PM
# Attitude Control Mode Transition Matrix

<table>
<thead>
<tr>
<th>From:</th>
<th>To:</th>
<th>Earth Pointing &amp; Lunar Mapping</th>
<th>Inertial Pointing</th>
<th>Star Pointing</th>
<th>Asteroid Fly-By</th>
<th>Lifeboat</th>
<th>OLSRC</th>
<th>CLSRC</th>
<th>ANC</th>
<th>SAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Pointing &amp; Lunar Mapping</td>
<td>Earth Pointing &amp; Lunar Mapping</td>
<td>SAM</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Inertial Pointing</td>
<td>Inertial Pointing</td>
<td>SAM + NAV</td>
<td>SAM + NAV</td>
<td>SAM + REL</td>
<td>SAM</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Star Pointing</td>
<td>Star Pointing</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Asteroid Fly-By</td>
<td>Asteroid Fly-By</td>
<td>SAM + NAV</td>
<td>SAM + NAV</td>
<td>SAM</td>
<td>SAM</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Lifeboat</td>
<td>Lifeboat</td>
<td>SAM + ATT + NAV</td>
<td>SAM + ATT + NAV</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>OLSRC</td>
<td>OLSRC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>CLSRC</td>
<td>CLSRC</td>
<td>SAM + ATT + NAV</td>
<td>SAM + ATT + NAV</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
</tr>
<tr>
<td>ANC</td>
<td>ANC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>SAP</td>
<td>SAP</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>SAM</td>
<td>SAM</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

X = Not allowed
SAM = Message from ground or another module
NAV = Navigation data (pointing vectors to sun, earth, and moon) are available
ATT = A valid attitude has been established, i.e. attitude determination is processing star tracker data
REL = Target relative position and velocity data have been uploaded to Terminal Guidance
NUT = Nutation angle has exceeded limit (software parameter) or SAP has completed firing sequence
Attitude Determination Logic

- Compute Body Rate
- Error Checking
- Compute Incremental Quaternion
- Compute Error Quaternion
- Compute Low Pass Filter
- Compute Attitude Quaternion
- Compute Incremental Quaternion
- Error Checking
- Start Up Logic
- Error Checking
- Correct for Time Delay
- Compute Error Quaternion
- Attitude

Desired Quaternion

Star Tracker SAM

Transform from Sensor to Body Frame

ST provides quality factor (0-10) - 5 considered good threshold.
Not currently being used or downloaded = image processor will filter bad image out before GNC gets it.
Terminal Guidance And Control Functions

- Provide desired quaternion and body rate for tracking kick motor or asteroid
- Process centroid or range data to update target relative position and velocity
- Free field model for relative motion
- Processing is identical for kick motor and asteroid except for: filter parameters; yaw orientation of spacecraft
- Provide range data to Image Processing Executive for auto exposure processing

Terminal Guidance And Control Commands

- Upload target relative position and velocity
- Processing enabled via Asteroid Fly-By mode command to GNC Executive
## Terminal Guidance And Control Status

### Capability

<table>
<thead>
<tr>
<th>Capability</th>
<th>GNC Version</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image processing for centroid</td>
<td>0.3</td>
<td>TBS: LLNL code</td>
</tr>
<tr>
<td>Sensor processing for range data</td>
<td>0.3</td>
<td>TBD</td>
</tr>
<tr>
<td>Guidance filter</td>
<td>0.2</td>
<td>Done: NRL-TRAMP</td>
</tr>
<tr>
<td>Compute desired attitude and rate</td>
<td>0.2</td>
<td>Done: SAC</td>
</tr>
</tbody>
</table>
Terminal Guidance And Control Design

- Included in Attitude Determination and Control module to minimize time delays in generating attitude commands

- Message Handling
  
  Store target relative position and velocity  
  Enable/disable  
  Pass measurement to Measurement Processing if enabled, else discard

- Initialization
  
  Initialize various matrices  
  Select sign of y axis orientation

- Measurement Processing
  
  Move state vector and covariance to time of measurement  
  Update state vector and covariance  
  If tracking asteroid, update time invariant quaternion

- Attitude Commands
  
  If tracking asteroid, update y axis rotation; else, compute desired quaternion
Image Processing Overview

- Five processing functions are: star tracker; centroiding; limb detection; auto exposure; image compression
- Limb detection and image compression run only on R3000; other 3 will run on both R3000 and 1750
- Image processing software will be event driven, i.e. modules will wait on an event flag that will be set by RM when an image is available
- Two modules: star tracker; the other 4 functions
- Image Processing Executive will control the other 4 processing functions
- Image processing software reports spacecraft attitude and rate at time of image for star tracker, centroiding, and limb detection
Image Processing Executive

- Maintains internal table defining what processing is to be done
- Table is indexed by camera/filter combination and specifies which type of image processing (can be more than one type)
- Processing for each camera/filter combination can be continuous or for specified number of images
- SAM message is used to modify internal table
- Auto exposure has range compensation option (ground specifies interval between images)
- IPE receives range data from Terminal Guidance and Control
Image Processing Interfaces

- During lunar mapping, kick motor encounter, and asteroid encounter, only DHU sequencer will control image collection
- At other times, GNC Executive may request star tracker images and Autonomous Navigation may request limb images via RM function
- IPE will use RM function to indicate which camera/filter image data it wants to process
- When image from specified combination or star tracker is received, RM will set event flag (IPE or star tracker) and provide image data
- Image processing will use RM function to obtain pointer to image control block that contains: camera/filter ID; imaging time; integration interval; camera gain; pointer to beginning of image
- Star tracker, centroiding, and limb detection send SAM's to appropriate GNC module (SAM includes spacecraft attitude and rate at time of image)
- Auto exposure results are output via RM function to control next image by that camera/filter combination
- Image compression results are output via memory dump function
Image Processing Software Development

- Except for image compression, start with LLNL supplied software used to test sensors and verify algorithms
- LLNL software runs on R3000
- LLNL will also provide test cases
- SAC will modify software to operate in the flight environment (provide proper interfaces and use RM services)
- SAC will modify star tracker, centroiding, and auto exposure as necessary to run on 1750
- Code and unit testing done on PC's
- Integration done at NRL
Image Processing Software Status

- Preliminary version of star tracker code received from LLNL; preliminary versions of other functions expected shortly
- IPE requirements memo recently completed and being reviewed by interested parties
- IPE coding underway
- Test scaffold for star tracker completed and minimum code modifications made to execute on PC
- Currently running test cases on PC
  - Generating correct blob list
  - Triangle sizes are correct
  - Working problems in star matching
  - PC clearly identifying main problems regarding rehosting to 1750
Anticipated problems in running star tracker on 1750:

- Limited program/data memory size
- Limited stack size
- Memory page limitation
- Use of byte and word pointers
- "little endian" vs "big endian"
- Integer size differences
Orbit Propagation Functions

- Propagate spacecraft position and velocity from uploaded state vector
- 3 reference frames: earth-centered; moon-centered; sun-centered (all parallel to J2000)
- Provide position and velocity to user for specified time near current time
- Provide vectors from spacecraft to earth, sun, or moon to user for specified time near current time

Orbit Propagation Commands

- Enable/disable
- Upload spacecraft position and velocity
- Change reference frame
Orbit Propagation Status

- Software delivered in GNC Version 0.1 except for table upload to change parameters
- Algorithms obtained from FORTRAN code provided by NRL TRAMP
- Unit testing done by comparing with test runs from NRL and from rerunning FORTRAN on PC
Autonomous Navigation Functions

- Operate in test or enabled mode: in test, only provide estimates in telemetry; if enabled, replace Orbit Propagation

- Based on upload data:
  - Request attitude change to point at earth or lunar limb
  - Monitor attitude until desired attitude is attained
  - Request image be obtained by specified camera/filter combination
  - After data is returned, release attitude

- Process measurements of earth or lunar limb to update spacecraft position and velocity
Autonomous Navigation Commands

- Enable/test/disable
- Upload spacecraft position and velocity
- Change reference frame

Autonomous Navigation Status

- Software to be delivered for Build 2
- Algorithms obtained from FORTRAN code provided by NRL TRAMP
- State vector propagation will use Orbit Propagation code
- Basic filter routines for updating state vector and covariance matrix will be those of Terminal Guidance and Control
Autonomous Navigation

- Measurement Received
- Allowable Time
- M. H. Tick
- Msgs From Ground
- Measurement Command
- To SPC
- Release
- To GNC Exec
- Mode Cancellation

Measurement Handler
- Allowable Measurement Time
- Window Size
- Check Window
- Window Size

Auto Nav Orbit Propagator
- A.N. Tick
- Measurements
- Msgs From SPC
- Covariance
- Mode
- AutoNav State Vector
- Msgs From Ground
- Auto Nav Parameters
- Initial State Vector

Maintain SV & PV
- State Vector
- LOS
- Pointing Vectors

 LOS LOCATOR

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Auto-Nav Measurement Handler Flow Chart

Start

Ground Msg.

Process Ground Message

GNC Msg.

Process GNC Message

ANOP Msg?

Process ANOP Message

Measurement Handler State Machine

Exit
Auto-Nav Measurement Handler State Machine

Outside Window

Idle Checking Window

Inside Window
Make Attitude Request, Set Time-Out

Waiting for Ack

NAK Received

Time-Out
Mode Release

Checking Attitude & Window

Ack Received
Set Time-Out

Attitude Correct

Measurement Request, Set Time-Out

Time-Out
Mode Release

Waiting for Measurement

Measurement Received
Set Time-Out

Delay Between Measurements

Times Up & Window Open
Command New Attitude

Mode Cancelled
Auto-Nav Orbit Propagator Flow Chart

Start

Updates = False

Measurements

N

Get Measurements

Y

t meas < t1

N

Prop to t2

Y

Prop to t meas

t1 = t meas

update state vector for meas

Updates = True

C

D

Exit

Updates? N

A

B

C

Now

Once thru loop @ C

Twice thru loop @ C

@ B state re-propagated from t1 to t2

@D

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Autonomous Scheduler Support Functions

- Provide various functions to support lunar mapping scheduler written in SCL

- Propagate lunar orbit 1 revolution in the future to predict times for 11 events: 4 for entering and exiting solar and RF shadows; 4 for approaching and leaving dark/light terminator; 1 for specific lunar latitude; 2 for passing through specific lunar altitude

- Provide function to access event table

- Provide function to return current value of: lunar latitude; lunar longitude; lunar altitude; angular distance to dark/light terminator; in/out of solar shadow; in/out of RF shadow

- Provide function to determine camera timing for specified image overlap

Autonomous Scheduler Support Commands

SAM that causes software to propagate orbit and create events table

Table upload to change event parameters, e.g. specified altitude
## Autonomous Scheduler Support Status

<table>
<thead>
<tr>
<th>Capability</th>
<th>GNC Version</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Create events table</td>
<td>0.1</td>
<td>Done: SAC</td>
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<tr>
<td>Access events table</td>
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<td>na</td>
</tr>
<tr>
<td>Current value function</td>
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<td>Done: SAC</td>
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<tr>
<td>Overlap function</td>
<td>0.3 ?</td>
<td>Done: SAC</td>
</tr>
<tr>
<td>Table upload</td>
<td>0.3</td>
<td>na</td>
</tr>
</tbody>
</table>

### Notes:
- Requirement for overlap function not clear.
- Request for additional events and current values expected this week
Autonomous Scheduler Support Data Flow

NOTE: SHADED FUNCTIONS ALSO CALLED BY CURRENT-VALUE FUNCTION
Delta V Thruster Control Functions

- Pressurize RCS: open control valves; monitor pressure every 16 ms; close valves when pressure reaches operating level; go to quiescent state

- Delta V burn:
  - Do pressure regulation from 30 seconds before burn to 30 seconds after burn
  - Output to telemetry: attitude and rates; accelerometer integrations
  - Open and close latch and flow valves
  - Terminate firing based on elapsed time or integration of x axis accelerometer (mode specified by ground command)
Delta V Thruster Control Commands

- Perform initial pressurization
- Perform delta V maneuver based on time or measured delta V (with back-up time-out)

Delta V Thruster Control Status

- Planned for GNC Version 0.3
- No open requirements or algorithm issues
Solar Array Control

FUNCTIONS:
- Rotate solar arrays based on internal estimates of spacecraft attitude and solar direction
- Modify control parameters depending on Attitude Control Mode

COMMANDS:
- Enable/disable

STATUS:
- Planned for GNC Version 0.3
- Requirements not firmly established and control logic not defined
- Algorithms are TBS: NRL-ACS
Utility Routines

- Matrix operations, e.g. multiply, multiply by transpose, copy
- Vector operations, e.g. cross product, dot product, create unit vector
- Quaternion operations, e.g. multiply, normalize, compare, quaternion to matrix, matrix to quaternion
- Above done and tested but will probably add more as need arises
Testing At SAC's Facility

- Coding and unit testing done on PC's
- Algorithm verification done at unit level testing
- Unit test cases based on:
  - NRL supplied test cases
  - NRL FORTRAN simulation code
  - Check cases generated on MathCAD
  - Manual verification of results
- Code for 1750 integrated on Micro VAX:
  - GNC modules
  - RM simulated functions
  - Spacecraft dynamics model
Testing At SAC's Facility
(concluded)

- Single module testing environment developed to verify:
  - SAM message interface for single module
  - Interfaces with vehicle dynamics model
  - Attitude determination and control algorithms
  - Closed loop transient responses

- Multi-module VAX integration to verify:
  - Interfaces between modules
  - Interfaces to RM functions
  - Mode and state transitions
  - Timing

- Micro VAX testing should continue in parallel with integration at NRL