An Open-Source Simulation Tool for Study and Design of Spacecraft Attitude Control Systems

*Eric Stoneking*

*Feb 2, 2018*
Three Audiences for This Talk?

• The User
  – "How do I solve today's problem, today?"

• The Developer
  – "What does a sim look like on the inside?"

• The Modeler
  – "Okay, fine, but what can it do?"
42 from the User's Perspective
The User Experience

• 42 is a command-line program
• Setup performed with plain text input files
  – Simulation parameters and settings
  – Spacecraft, orbit parameters and initial conditions
• Runs with or without graphics
  – Graphics adds situational awareness
  – Sim runs faster without graphics
• Plain-text output files produced for post-run analysis
• Graphics frames may be captured
  – Stitched together into movies using other software (eg. ffmpeg)
Rapid Prototyping

• Some studies may be conducted without any C coding
• Simple attitude command profiles may be specified in Inp_Cmd.txt
• "Prototype" control law follows that profile
• Sufficient for many concept studies
  – Evaluate instrument fields of regard
  – Size wheels, magnetic torquers for environment
42: Command Script File

0.0 SC[0] qrl = [0.0 0.0 0.0 1.0]
0.0 Point SC[1].B[0] Primary Vector [0.0 0.0 -1.0] at SUN
0.0 Align SC[1].B[0] Secondary Vector [0.0 1.0 0.0] with L-frame Vector [0.0 1.0 0.0]
0.0 Point SC[2].B[0] Primary Vector [0.0 0.0 -1.0] at SC[1]
0.0 Align SC[2].B[0] Secondary Vector [0.0 1.0 0.0] with L-frame Vector [0.0 1.0 0.0]
0.0 Align SC[3].B[0] Primary Vector [0.0 0.0 1.0] with L-frame Vector [1.0 0.0 1.0]
0.0 Point SC[3].B[0] Secondary Vector [1.0 0.0 0.0] at SUN
0.0 SC[4] Cmd Angles = [-90.0 -90.0 0.0] Seq = 131 wrt N Frame
In-Depth Studies

• More in-depth studies will require C coding
  – Write your own control laws, "flight software"
    • Some examples provided as a jumping-off point
  – Add custom sensor and actuator models
  – Add output to files to support your analysis needs
Matlab + 42 = Monte Carlo

• 42 can be called from within Matlab using the `system` command

• Use Matlab as the MC executive
  – Generate initial conditions, parameters
  – Write to 42's input files
  – Run 42
  – Process and save data
  – Repeat

• Use 42 as the high-speed, high-fidelity component
Matlab/42 Example

for Irun=1:Nrun,

    % Compute initial attitude
    CRN = TRIAD(tvn(Irun,:),svn,[0 0 1],[1 0 0]);
    qrn = C2Q(CRN);

    % Write target to file
    Outdata = [TrgRA(Irun) TrgDec(Irun)];
    save -ascii ./MOMBIAS/TargetRaDec.inp Outdata

    % Write initial attitude to file
    line = sprintf('%f %f %f %f ! Quaternion\n', qrn(1),qrn(2),qrn(3),qrn(4));
    OverwriteLineInFile('./MOMBIAS/GLAST.inp',21,line);

    % Run 42 for three days.
    system('./42 MOMBIAS');

    % Record pointing histogram.
    load ./MOMBIAS/AngleToGo.42
    [HistCount(Irun,:),HistAng(Irun,:)] = hist(AngleToGo,20);

end
Flight Software Testing to Operations

• Eventually, the control laws become flight software, running outside 42 on some other computer

• 42 can communicate over sockets
  – Sim "engine" <-> Flight software
  – Sim "engine" -> Sim "display"

• Splitting engine and display enables multiple displays

• For operations support, displays may be driven by flight telemetry instead of engine
Example: Hardware-in-the-Loop Sim with Multiple Spacecraft
Will It Run On My Computer?

• Most likely

• 42 is open-source, available for download from Sourceforge.net/projects/fortytwospacecraftsimulation

• For MacOS and linux, installation is very easy
  – Unzip archive
  – Put 42 folder wherever you want it
  – Edit Makefile to make sure it has your platform correct
  – make and run

• For Windows, there are some external dependencies
  – MinGW, msys provide a linux-style terminal window
  – glew, freeglut required to support graphics
  – Full instructions provided in 42/Docs/Install-msys.txt
42 from the Developer's Perspective
A Basic Simulation Loop

- **Initialize**
  - Read user inputs
  - Set up
- **Ephemeris**: Where is everything?
  - Sun, Earth, Moon, etc
  - Orbits
  - Spacecraft
- **Environment Models**: What forces and torques exerted by the environment?
- **Sensor Models**
  - Input truth
  - Output measurements
- **Flight Software Models**
  - Input Measurements
  - Process Control Laws, etc
  - Output Actuator Commands
- **Actuator Models**
  - Input Commands
  - Output Forces and Torques
- **Dynamics**: How does S/C respond to forces and torques?
  - Integrate dynamic equations of motion over a timestep
  - Advance time to next step
42's Software Architecture

Simulation Initial Conditions and Control (ASCII Input)

Truth (ASCII Output)

Simulation Models

Environment Models

Ephemeris Models

Utility Functions (No Global Data)

Global data structures

Dynamics Models

Sensor and Actuator Models

Environmental Forces & Torques

Control Forces & Torques

Dynamic States

FSW data structure

Flight Software Models

Cmd Model (ASCII Input)

Tlm Model (ASCII Output)

OpenGL Graphics Output

Mouse, Keyboard Input

SimStep()
Good Conventions Make Code Readable, Debuggable

- Choose standard notation to make code readable, unambiguous
  - Think about how notation morphs from the written page to code
- Make code document itself
  - It's much easier to debug

Table 1: Common Reference Frames

<table>
<thead>
<tr>
<th>Frame</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Inertial Frame ($N =$ Newton)</td>
</tr>
<tr>
<td>$L$</td>
<td>Local Vertical-Local Horizontal</td>
</tr>
<tr>
<td>$R$</td>
<td>Command Frame ($R =$ Reference)</td>
</tr>
<tr>
<td>$B$</td>
<td>Body Frame</td>
</tr>
</tbody>
</table>

Table 2: Commonly-used Expressions

<table>
<thead>
<tr>
<th>Written</th>
<th>Spoken</th>
<th>Coded</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N^B$</td>
<td>Angular velocity of $B$ in $N$</td>
<td>wbn, SC[i].B[j].wn</td>
</tr>
<tr>
<td>$\dot{N}^B$</td>
<td>Velocity of $B^*$ in $N$</td>
<td>SC[i].B[j].vn</td>
</tr>
<tr>
<td>$R_{CN}$</td>
<td>DCM of $B$ in $N$ (or from $N$ to $B$)</td>
<td>CBN, SC[i].B[j].CN</td>
</tr>
<tr>
<td>$Q^N$</td>
<td>Quaternion of $B$ in $N$ (or from $N$ to $B$)</td>
<td>qbn, SC[i].B[j].qn</td>
</tr>
<tr>
<td>$\dot{v}$</td>
<td>Components of $v$ in $A$, $v$ expressed in $A$</td>
<td>va</td>
</tr>
</tbody>
</table>

Table 3: Common Constructions

<table>
<thead>
<tr>
<th>Written</th>
<th>Coded</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_U = A_G B^U$</td>
<td>MxV(CAB, vb, va)</td>
</tr>
<tr>
<td>$A_U = B^{G}_U A^G$</td>
<td>VxM(vb, CBA, va)</td>
</tr>
<tr>
<td>$A_U = (R^G)^T B^U$</td>
<td>MxV(CBA, vb, va)</td>
</tr>
<tr>
<td>$A_R = B^G (R^G)^T$</td>
<td>VxMT(vb, CBA, va)</td>
</tr>
<tr>
<td>Convert $R_{CN}$ to $Q^N$</td>
<td>C2Q(CBN, qbn)</td>
</tr>
<tr>
<td>Convert $Q^N$ to $R_{CN}$</td>
<td>Q2C(qbn, CBN)</td>
</tr>
<tr>
<td>Convert Euler Angles (2-1-3 Sequence) to DCM</td>
<td>A2C(213, ang1, ang2, ang3, C)</td>
</tr>
<tr>
<td>$N_C R = (R^N)^T$</td>
<td>MxMT(CBN, CNB, CBN)</td>
</tr>
<tr>
<td>$R_C R = R_{CN} R_{CR} (R_{CN})^T$</td>
<td>QxMT(CBN, CNB, CBN)</td>
</tr>
<tr>
<td>$Q_C R = Q_{CN} \otimes N_C R$</td>
<td>QxQT(qbn, qrn, qbr)</td>
</tr>
</tbody>
</table>
Reference Frames are Important!

- In any dynamics problem beyond the spinning top, a systematic approach to reference frames and the relationships between them is vital.
- For 42, we define several fundamental reference frames, and notational conventions to keep quaternions and direction cosines sorted out.
Reference Frames (1 of 2)

- Heliocentric Ecliptic (H)
  - Planet positions expressed in this frame
- Each world has an inertial (N) and rotating (W) frame
  - For Earth, N = ECI (True of date), W = ECEF
  - N is the bedrock for orbits, S/C attitude dynamics
  - Full Disclosure: Although True-of-Date <-> J2000 conversions are provided, the distinction is not always rigorously made
    - Star vectors provided in J2000 (from Skymap), converted to H
    - Planet ephemerides are assumed given in true-of-date H
    - Transformation from N to W is simple rotation, implying N is True-of-Date
    - TOD ↔ J2000 conversions in envkit.c
Reference Frames (2 of 2)

- Each reference orbit has a reference point R
  - For two-body orbit, R moves on Keplerian orbit
  - For three-body orbit, R propagates under influence of both attracting centers (as point masses)
  - S/C orbit perturbations integrated with respect to R
- Associated with each R is a LVLH frame (L) and a formation frame (F)
  - F is useful for formation-flying scenarios
  - F may be offset from R, may be fixed in N or L
- Each spacecraft has one or more Body (B) frames and one LVLH frame (L)
  - L(3) points to nadir, L(2) points to negative orbit normal
  - SC.L is distinct from Orb.L, since SC may be offset from R
Representing Attitude

- There are several ways to represent the rotation between two reference frames
  - Direction Cosines
  - Euler Angles
  - Quaternions (aka Euler Parameters)
  - and more
- They all have their strengths and weaknesses
  - Learn them all!
## Strengths and Weaknesses of Attitude Representations

<table>
<thead>
<tr>
<th>Representation</th>
<th>Strengths</th>
<th>Weaknesses</th>
<th>Best Used For</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction Cosines</td>
<td>• Work well with vectors &lt;br&gt;• Easy to catenate rotations &lt;br&gt;• Moderately intuitive (dot products) &lt;br&gt;• No singularities</td>
<td>• 9 params for 3 DOF</td>
<td>• Transforming Vectors</td>
</tr>
<tr>
<td>Quaternions</td>
<td>• Efficient (4 params for 3 DOF) &lt;br&gt;• No singularities</td>
<td>• Not intuitive</td>
<td>• Propagating Equations of Motion</td>
</tr>
<tr>
<td>Euler Angles</td>
<td>• Intuitive &lt;br&gt;• 3 params for 3DOF</td>
<td>• Singularities &lt;br&gt;• 24 Variants</td>
<td>• Input, Output &lt;br&gt;• Gimballed Joints</td>
</tr>
</tbody>
</table>
Notation for Quaternions, DCMs

- The rotation from frame $A$ to frame $B$ may be described by the direction cosine matrix

\[ B C_{ij}^A = \hat{b}_i \cdot \hat{a}_j \]

- Given the components of a vector in $A$, its components in $B$ may be found by the multiplication

\[ B v = B C_{AA}^A v \]

- In C, we write the DCM as CBA to preserve order of superscripts, eg

\[ M x V ( CBA, va, vb ) \]

- Quaternions are another way to describe rotations. We use a parallel notation:

\[ Q x V ( qba, va, vb ) \]

- These and similar conventions promote concise, *unambiguous* code
42 from the Modeler's Perspective
Features

- **Multiple spacecraft, anywhere in the solar system**
  - Two-body, three-body orbit dynamics
  - One sun, nine planets, 45 major moons
  - Minor bodies (comets and asteroids) added as needed
    - Bennu, Eros, Itokawa, Wirtanen, etc

- **Supports precision formation flying**
  - Several S/C may be tied to a common reference orbit
  - Encke’s method or Euler-Hill equations used to propagate relative orbit states
    - Precision maintained by judicious partitioning of dynamics
      - Add big things to big things, small things to small things

- **Clean FSW interface facilitates FSW validation**
  - As flight software matures, it can be migrated out of 42
  - Used by GLAST project for independent validation of vendor’s (autocoded) GNC flight software
Environment Models

- **Planetary Ephemerides**
  - From Meeus, “Astronomical Algorithms”
  - Good enough for GNC validation, not intended for mission planning
    - Use GMAT or ODTBX for that

- **Gravity Models** have coefficients up to 18th order and degree
  - Earth: EGM96
  - Mars: GMM-2B
  - Luna: GLGM2

- **Planetary Magnetic Field Models**
  - IGRF up to 10th order (Earth only)
  - Tilted offset dipole field

- **Earth Atmospheric Density Models**
  - MSIS-86 (thanks to John Downing)
  - Jacchia-Roberts Atmospheric Density Model (NASA SP-8021)
  - NRLMSISE00 (Update to MSIS-86, extended down to ground)

- **Simple exponential Mars atmosphere density model**
  - New models easily incorporated as the state of the art advances
Dynamics Models

- Full nonlinear “6DOF” (actually N-DOF) dynamics

- Attitude Dynamics
  - One or many bodies
    - Tree topology (no kinematic loops)
  - Each body may be rigid or flexible
  - Joints may combine rotational and translational DOFs
    - May be gimballed or spherical
  - Slosh may be modeled as a pendulum (lo-fi, quick to implement and run)
    - 42 may run concurrently with Star-CCM CFD software for hi-fi slosh
  - Wheels embedded in Body[0]
  - Torques from actuators, aerodynamic drag, gravity-gradient, solar radiation pressure, joint torques

- Orbit Dynamics
  - Two- or three-body orbits
  - Encke or Euler-Hill (Clohessy-Wiltshire) for relative orbit motion (good for formation flying, prox ops)
  - Forces from actuators, aerodynamic drag, non-spherical gravity, third-body gravity, solar radiation pressure
The Bleeding Edge

- 42 is under constant development
- Here are some capabilities that are still provisional or under development
  - Contact forces (provisional)
    - Applied to some problems, not robust
  - Self-shadowing (provisional)
    - Passed first sanity checks, but some bugs persist
  - Flight in atmosphere (provisional)
    - Pieces in place, no rigorous test problem yet
  - Fluid slosh using Smoothed Particle Hydrodynamics (under development)
    - Needs parallelization to be practical
  - Interfaces to cFS, COSMOS (under development)
    - cFS is open-source flight software system from GSFC
    - COSMOS is open-source ops (cmd/tlm, etc) from Ball
Conclusion

• 42 is intended to support the ACS design cycle from concept to operations
  – Rapid prototyping for concept studies
  – High fidelity for validation, design
  – Plays well in integration, ops ecologies
• Notation, conventions are the key to building a large software tool over time
• $F = ma$. All the rest is just accounting.