BENCHMARKING THE COLLOCATION STAND-ALONE LIBRARY AND TOOLKIT (CSALT)

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AGENDA

- Motivation
- Optimal Control Problems
- CSALT
- General Optimal Control Benchmarking Results
- Low-Thrust Trajectory Design Benchmarking Results
- Summary/Future Work
MOTIVATION

- Physical systems which involve time varying control decisions can rarely be solved analytically.
- Low-thrust spacecraft trajectories cannot be designed using intuition.
- NASA Goddard’s General Mission Analysis Toolkit (GMAT) has limited capability to solve low-thrust problems.

Goals:
- Demonstrate that CSALT can solve industry-standard optimal control problems.
- Demonstrate that CSALT can solve optimal control low-thrust trajectory problems.
- Compare CSALT execution efficiency to other optimal control software packages.
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OPTIMAL CONTROL PROBLEMS

- Minimize a cost function of the form:
  \[ J = \Phi(x(t_o), t_o, x(t_f), t_f) + \int_{t_o}^{t_f} \lambda(x(t), u(t), t)dt \]

- Subject to the following set of ordinary differential equations:
  \[ \dot{x}(t) = a(x(t), u(t), t) \]

- Subject to algebraic path constraints:
  \[ p(x(t), u(t), t) \leq 0 \]

- Subject to boundary conditions:
  \[ b(x(t_o), u(t_o), x(t_f), u(t_f), t_o, t_f) \leq 0 \]
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17000 original source lines of code (SLOC) written in C++
Uses roughly 17000 SLOC from GMAT’s utility code base
Uses Boost C++ library for sparse matrix arithmetic
Uses SNOPT for nonlinear programming optimization
Will be open source released with GMAT eventually (Fall 2017 or Spring 2018)
CURRENT CSALT CAPABILITY

- Multiple collocation transcriptions
  - Trapezoid
  - Hermite-Simpson
  - Lobatto IIa of order 4, 6 and 8
  - Radau Orthogonal
- Multiple cost-function formulations
  - Mayer
  - Lagrange
  - Bolza
- Algebraic path and point constraints
- Decision vector, cost and constraint scaling
- Analytical collocation derivatives with finite differenced user point and path functions
- Automatic sparsity pattern determination
- Mesh refinement (Radau transcription only)
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HIGH LEVEL RESULTS

- Three comparison tools:
  - SOS - Sparse Optimization Suite written by Dr. John Betts
  - GPOPS-II – Gauss Pseudospectral OPtimization Software written by Dr. Anil Rao
  - PSOPT – PseudoSpectral OPtimization written by Dr. Victor Becerra
- 17 problems selected for objective function comparison
- 3 problems selected for detailed state and control comparison

<table>
<thead>
<tr>
<th>Test Case</th>
<th>“Truth” Source</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh</td>
<td>SOS</td>
<td>-4.03E-08</td>
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<tr>
<td>(Control Constraint)</td>
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<tr>
<td>Rayleigh</td>
<td>SOS</td>
<td>6.59E-08</td>
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<tr>
<td>(Control + State Constraint)</td>
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<tr>
<td>Goddard Rocket</td>
<td>SOS /GPOPS</td>
<td>-8.57E-09</td>
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<tr>
<td>Hypersensitive</td>
<td>SOS /GPOPS</td>
<td>-1.39E-06</td>
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<tr>
<td>Conway Orbit</td>
<td>SOS</td>
<td>-2.11E-08</td>
</tr>
<tr>
<td>Linear Tangent Steering</td>
<td>SOS /GPOPS</td>
<td>-1.19E-09</td>
</tr>
<tr>
<td>Brachistichrone</td>
<td>SOS /GPOPS</td>
<td>2.37E-09</td>
</tr>
<tr>
<td>Bryson Denham</td>
<td>GPOPS /PSOPT</td>
<td>-9.07E-07</td>
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<tr>
<td>Schwartz</td>
<td>PSOPT</td>
<td>4.38E+00</td>
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<tr>
<td>Interior Point</td>
<td>PSOPT</td>
<td>4.53E-08</td>
</tr>
<tr>
<td>Bryson Max Range</td>
<td>PSOPT</td>
<td>-6.57E-07</td>
</tr>
<tr>
<td>Obstacle Avoidance</td>
<td>PSOPT</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>Moon Lander</td>
<td>PSOPT</td>
<td>-4.09E-05</td>
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<tr>
<td>Rau Automatica</td>
<td>Analytic</td>
<td>4.70E-12</td>
</tr>
<tr>
<td>Hull Problem 9.5</td>
<td>Analytic</td>
<td>4.00E-12</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Problem Name</th>
<th>Tool</th>
<th>Max. Rel. State Error</th>
<th>Max. Rel. Control Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goddard</td>
<td>SOS</td>
<td>6.863e-07</td>
<td>2.191e-08</td>
</tr>
<tr>
<td>Hypers.</td>
<td>GPOPSII</td>
<td>4.305e-02</td>
<td>2.911e-01</td>
</tr>
<tr>
<td>Conway</td>
<td>SOS</td>
<td>9.814e-06</td>
<td>1.610e-02</td>
</tr>
</tbody>
</table>
- Classic problem in the literature
- Finite-thrust orbit raising
- Optimal solutions match perfectly to the scale of the graphics
- Maximum relative error in state is better than control
  - 9.841e-6 in state
  - 1.610e-2 in control
- Multi-phase problem
- Control in optimal solution is discontinuous and has bang-off structure
- Control varies in the middle phase to maintain constant terminal velocity
- CSALT solution matches very well with reference software in terms of relative error
  - $6.863 \times 10^{-7}$ in state
  - $2.191 \times 10^{-8}$ in control
HYPERSENSITIVE PROBLEM

- Stressing case to the mesh refinement algorithm
- Dynamics rapidly change near the boundary conditions, but are nearly constant in between
- Relative errors are larger than desirable
  - 4.305e-2 in state
  - 2.911e-1 in control
- Believed to be due to interpolation to common discretization times (and away from the collocation points)
- This is supported by the relative error between SOS and GPOPS-II (3.54e-1 and 1.037 in state and control respectively)
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MARS TRANSFER

- CSALT was compared to solutions presented by Horsewood and Dankanich*
- Direct transfer from Earth to Mars using 2 ion engines
- Qualitatively identical solutions were found using all 3 software tools
- The final solutions all match to the expected margin of error of the modeling techniques

- CSALT was compared to solutions presented by Horsewood and Dankanich*

- Repeat of the Dawn mission
  - Earth to Mars low-thrust transfer
  - Mars flyby
  - Rendezvous with Vesta
  - Low-thrust transfer to Ceres

- CSALT found a qualitatively improved solution compared to the other two tools
  - At a cost of ~220 days of additional flight time, 160 extra kg of dry mass could be delivered to Ceres using less propellant

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### Table 5. Earth to Mars solutions comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Malto</th>
<th>HILTOP</th>
<th>CSALT</th>
</tr>
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<tbody>
<tr>
<td><strong>Leg 1 Earth-Mars</strong></td>
<td></td>
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<tr>
<td>Launch C₃ (km²/s²)</td>
<td>5.1529</td>
<td>5.2285</td>
<td>1.4819</td>
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<tr>
<td>Launch declination (deg)</td>
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<td>28.5</td>
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<td>Launch mass (kg)</td>
<td>1,114.4</td>
<td>1,105.2</td>
<td>1243.0</td>
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<tr>
<td>Flight time (days)</td>
<td>510</td>
<td>510</td>
<td>527</td>
</tr>
<tr>
<td>Arrival mass (kg)</td>
<td>1,039.8</td>
<td>1,032.7</td>
<td>1180.2</td>
</tr>
<tr>
<td>Propellant used (kg)</td>
<td>74.6</td>
<td>72.4</td>
<td>62.8</td>
</tr>
<tr>
<td><strong>Leg 2 Mars-Vesta</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swingby vₑ (km/s)</td>
<td>4.10</td>
<td>4.11</td>
<td>4.49</td>
</tr>
<tr>
<td>Passage altitude (km)</td>
<td>300</td>
<td>300</td>
<td>300</td>
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<tr>
<td>Flight time (days)</td>
<td>894</td>
<td>827.7</td>
<td>903.1</td>
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<tr>
<td>Arrival mass (kg)</td>
<td>907.3</td>
<td>901.4</td>
<td>1,079.0</td>
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<tr>
<td>Propellant used (kg)</td>
<td>132.5</td>
<td>131.3</td>
<td>101.2</td>
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<tr>
<td>Stay time (days)</td>
<td>270</td>
<td>336.3</td>
<td>270</td>
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<tr>
<td><strong>Leg 3 Vesta-Ceres</strong></td>
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<td>Flight time (days)</td>
<td>1,038</td>
<td>1,038</td>
<td>1,230</td>
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<tr>
<td>Arrival mass (kg)</td>
<td>807.2</td>
<td>802.3</td>
<td>960.1</td>
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<tr>
<td>Propellant used (kg)</td>
<td>100.1</td>
<td>99.1</td>
<td>118.9</td>
</tr>
<tr>
<td><strong>Total Propellant (kg)</strong></td>
<td><strong>307.2</strong></td>
<td><strong>302.8</strong></td>
<td><strong>282.9</strong></td>
</tr>
<tr>
<td>Mission duration (days)</td>
<td><strong>2,711</strong></td>
<td><strong>2,711</strong></td>
<td><strong>2,930</strong></td>
</tr>
</tbody>
</table>
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CSALT is a mature software package capable of solving a variety of optimization problems with high accuracy.

CSALT has been successfully benchmarked against industry standard tools in both general engineering problems and for the solution of low-thrust trajectories.

Future Work
- Static and integral decision parameters and integral constraints
- Second derivatives of the collocation
- Improve performance
- Full integration into GMAT