Spacecraft rendezvous: developing and implementing a Guidance & Control algorithm
The LAAS RT Days

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Orbital rendezvous and Goals

RdV missions

> ISS docking;

> On-orbit servicing (Space Tug): refuelling, orbits correction, debris removal.

Requirements

> Autonomy, Safety, Cost (maximizing spacecraft lifetime).
Orbital rendezvous and Goals

RdV missions
> ISS docking;
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Goals:
> To conceive an optimization-based algorithm for rendezvous optimal guidance and robust control:
  ■ Comprehensive enough to account for the above requirements;
  ■ Simple/fast enough to be on-boarded and executed in real-time during spaceflight missions;
> To provide the libraries, compilation chains and instructions to embed the proposed algorithm on a board containing a FPGA-synthesized LEON3 microprocessor.
Guidance and Control under constraints

Mission must be completed accounting for:

Thruster limitations:
- minimal magnitude;
- maximal magnitude.

Figure: Thrusters configuration.

(a) \( \| \Delta V \|_2 \leq \Delta V \)

(b) \( \| \Delta V \|_\infty \leq \Delta V \)
Mission must be completed accounting for:

Thruster limitations:
> minimal magnitude;
> maximal magnitude.

Proximity operations:
> visibility cone;
> safety distance.

Figure: Thrusters configuration.

(a) $\|\Delta V\|_2 \leq \Delta V$

(b) $\|\Delta V\|_\infty \leq \Delta V$

Figure: Visibility constraints.
Guidance and Control under constraints

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Thruster limitations:
- minimal magnitude;
- maximal magnitude.

Proximity operations:
- visibility cone;
- safety distance.

Station keeping:
- hovering zone.

Thruster limitations:
(a) $\|\Delta V\|_2 \leq \Delta \tilde{V}$
(b) $\|\Delta V\|_\infty \leq \Delta \tilde{V}$

Figure: Thrusters configuration.

Figure: Visibility constraints.

Figure: Keeping station in a hovering zone.
Innovation of the proposed algorithm

Less conservative than existing proposed methods:

"Pogo" strategy:

Figure: "Pogo" strategy.
Innovation of the proposed algorithm

Less conservative than existing proposed methods:

"Pogo" strategy:

"Teardrop" strategy:

Figure: "Pogo" strategy.

Figure: "Teardrop" strategy.
Innovation of the proposed algorithm

Less conservative than existing proposed methods:

"Pogo" strategy:

"Teardrop" strategy:

Proposed strategy:

Figure: "Pogo" strategy.

Figure: "Teardrop" strategy.

Figure: Constrained periodic relative orbits


P.R. Arantes Gilz, C. Louembet, Predictive control algorithm for spacecraft rendezvous hovering phases. ECC 2015
Optimal control formulation and MPC strategy

- Optimal control problem under states/inputs constraints;
- Finite description of constrained trajectories included in linear subspace;
- Formulation of an equivalent optimization problem;
- Stabilization via MPC strategy.

\[
\min_{\Delta V} J(\Delta V) \\
\text{s.t.}
\begin{align*}
D(\nu_1) &= D_1, \\
D^+(\nu_N) &= \Phi_D(\nu_N, \nu_1) D(\nu_1) + M(\nu_1, \ldots, \nu_N) \Delta V, \\
d^+_0(\nu_N) &= 0, \\
|\Delta V(\nu_i)|_\infty &\leq \overline{\Delta V}, \quad i \in \{1, \ldots, N\} \\
g_w(D^+(\nu_N)) &\leq 0, \quad w \in \{\bar{x}, \bar{x}, \bar{y}, \bar{y}, \bar{z}, \bar{z}\}
\end{align*}
\]

Fuel-consumption
Initial state
State propagation
Periodicity
Saturation
Hovering region

Numerical implementation and Test environment

Main characteristics:

- Main oscillator 50 MHz;
- PROM: 8 Mbyte FLASH (organized x8);
- DDR2 RAM: 128 Mbyte DDR2 RAM on board (16 bits wide interface);
- Synthesized LEON3 microprocessor, SPARC V8 architecture, Linux 2.6 environment;
- Developement of specific library and static linkage of existant ones:
  - libgfortran.so.3 (FORTRAN), libc.so.6 (C), libm.so.6 (Math. functions), sdp (CSDP)
- Cross compilers for sparc V8: fortran, gcc, g++

F. Camps, P.R. Arantes Gilz, M. Joldes, C. Louembet, Embedding a SDP-based control algorithm for the orbital rendezvous hovering phases. ICINS 2018.
Figure: Relative trajectory

<table>
<thead>
<tr>
<th>Target parameters</th>
<th>$a$ [m]</th>
<th>$e$</th>
<th>$\nu_1$ [rad]</th>
<th>$\Delta \nu$ [rad]</th>
<th>$N$</th>
<th>$\Delta V$ [m/s]</th>
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<tbody>
<tr>
<td>Hovering zone</td>
<td>6777280</td>
<td>0.00039</td>
<td>$\pi$ (apogee)</td>
<td>$\pi/2$</td>
<td>5</td>
<td>1</td>
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<table>
<thead>
<tr>
<th>Hovering zone</th>
<th>$x$</th>
<th>$\bar{x}$</th>
<th>$y$</th>
<th>$\bar{y}$</th>
<th>$z$</th>
<th>$\bar{z}$</th>
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<tbody>
<tr>
<td>Leader</td>
<td>50 m</td>
<td>150 m</td>
<td>-25 m</td>
<td>25 m</td>
<td>-25 m</td>
<td>25 m</td>
</tr>
</tbody>
</table>

Table: Mission Parameters
Real-time demonstrator

Click here for the video.
Achievements

Scientific Productions:
- A Guidance & Control application for rendezvous missions;
- Portability on spaceflight-certified embedded computer;
- Sparc V8 cross-compilation chains and libraries (CSDP);
- A Real-time demonstrator composed of:
  - LEON3 µproc board executing the algorithm executable code;
  - C-coded and open-source nonlinear relative motion simulator (available on HAL);
  - Interactive graphical windows.

Involved people:
- PhD Student: P.R. Arantes Gilz;
- Intern: B. Benetti;
- Researchers & Engineer: F. Camps, M. Joldes, C. Louembet.
Perspectives

- RTEMS: enhancement of the performances by eliminating context switching;
- Certification with synchronous programming language;
- Board the algorithm on a real satellite:
  - small satellite dedicated for scientific tests;
  - end-of-life satellite.
Questions ?