Multiple Spacecraft Autonomous Systems:
Theoretical Research & Laboratory Experimentation

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Outline

- Myself and the NPS team
- Goals of research on Multiple Spacecraft Autonomous Systems
- Motivation of the research topic

Theoretical Results: low propellant maneuvers by differential drag-based analytical controller (PURE RESEARCH)

Experimental Results: LQR CONTROL and INPUT ESTIMATION applied to a four spacecraft simulator assembly (APPLIED RESEARCH)

Plans for research and teaching at Embry-Riddle
My story at a glance


Ph. D. in Applied Mathematics, Aerospace Engineering focus, from Sapienza University, Rome, Italy, 2007.

Post-Doctoral appointment at NPS (my beautiful wife followed me in this latest adventure!)

- Spacecraft Robotics Laboratory Manager
- Teaching Assistant for Mechanics, Orbital Mechanics, Spacecraft Attitude Determination and Control
- Laboratory developed Theses co-advisor
Myself and the NPS

I am here

Working on the spacecraft simulators

The SRL team
Myself and international students/interns
Goals of my Research

- **Guidance, Navigation, and Control for robust autonomous multiple spacecraft rendezvous/assembly/reconfiguration**
  - Flexibility towards the evolving system
  - Scalability to an arbitrary number of spacecraft
  - Homogeneous and heterogeneous spacecraft

- **Optimize resources** to allow repeated maneuvering. Consider alternative control methods (differential drag)

- **Hardware-in-the-loop validation: sponsored research & great educational value**
Motivation and Interest

Multiple S/C systems allow for low-cost orbit insertion, reconfiguration-ability, upgrade-ability…

**NASA’S MISSIONS TO MOON AND MARS WILL BE BASED ON TWO ON-ORBIT DOCKING CAPSULES**

**CURRENT AND PAST**
- Differential drag missions:
  - **JC2Sat**: joint Canadian-Japanese
  - **InKlajn-1**: Israeli Nano-Satellite Association
- **ESA Automated Transfer Vehicle (ATV, ISS re-supply vehicle)**
- **DARPA Orbital Express**, 2007
- **NASA DART**, 2005
- National Space Development Agency of Japan’s **ETS-VII** in 1998

**FUTURE**
- **AFRL’s Autonomous Nano-satellite Guardian Evaluating Local Space (ANGELS)**
- **DARPA F6 System**
Theoretical Results: Differential Drag

- Starting references and related work
- Use differential drag to assemble small spacecraft from a distance of ~3-5 Km
- Include J2 differential effects due to long time duration maneuvers
- **Develop an analytical control policy capable of assembling N heterogeneous satellites controlled by differential atmospheric drag**
- Concept proposed for spacecraft with virtually on-off surface control capability
- Demonstrate the control policy capabilities in a complete simulation environment (orbital propagator, non-constant density, navigation errors, etc. …)
Starting References & Related Work


Concept for generating differential drag

Attitude is stabilized in the orbital frame LVLH

CASE 1

CASE 2

CASE 3

Direction of motion
Dynamics & working assumptions for analytical derivations

\[
\dot{x} = \begin{bmatrix}
0_{2\times2} & I_{2\times2}
\end{bmatrix} x + \begin{bmatrix}
0_{2\times2}
\end{bmatrix} u
\]
\[
x(t) \in \mathbb{R}^{4}, \forall x^T = [x, y, \dot{x}, \dot{y}]
\]

\[
A_1 = \begin{bmatrix}
5c^2 \omega^2 - 2\omega^2 & 0 \\
0 & 0
\end{bmatrix},
A_2 = \begin{bmatrix}
0 & 2\omega c \\
-2\omega c & 0
\end{bmatrix}
\]

\[
u^T = \begin{bmatrix}
0 & -\frac{\rho \Delta BC}{2} V_r^2
\end{bmatrix}
\]

\[
\Delta BC = BC_i - BC_T = \frac{\frac{m_i C_{Di}}{C_{Ti}} S_{Ci} - m_{ci} C_{Di} S_{Ti}}{m_i m_{ci}}
\]

Because relative velocity is negligible with respect to the orbital one

Heterogeneous spacecraft (similar parameters)

- On-off control (0-90 deg)
- Constant air density
Dynamics Model: the state vector transformation

Linear state vector transformation

\[
\begin{bmatrix}
0 & 1 & -a/d^2 & 0 \\
-ab/d^2 & 0 & 0 & -b/d^2 \\
0 & 0 & a^2/(2d^3) & 0 \\
a^2b/(2d^3) & 0 & 0 & a^3/(2d^3)
\end{bmatrix}
\]

State analytical evolution

\[
\begin{align*}
z_1 &= z_{10} + tz_{20} - \frac{bt^2}{2d^2} u_y \\
z_2 &= z_{20} - \frac{bt}{d^2} u_y \\
z_3 &= \cos(dt) z_{30} + \frac{\sin(dt)}{d} z_{40} + \frac{a^3 \left[ 1 - \cos(dt) \right]}{2d^5} u_y \\
z_4 &= -d \sin(dt) z_{30} + \cos(dt) z_{40} + \frac{a^3 \sin(dt)}{2d^4} u_y
\end{align*}
\]

\[
a = 2\omega c, \ b = (5c^2 - 2)\omega^2, \ d = \sqrt{a^2 - b}
\]
Stabilization: (based on Leonard’s work)

“saw-tooth” switching zones
Analytical Exact Rendezvous to Target

NO RESIDUAL DISTANCE IS PRESENT.
**Exact Rendezvous to Target: the solution**

\[
\Delta t^* = \frac{1}{d} \cos^{-1}\left[ \frac{1}{2} \left( 1 + \sqrt{h} - \sqrt{3 - h - \frac{2}{\sqrt{h}}} \right) \right]
\]

Generic formula for the maneuvering time

\[
h = 1 + \frac{\sqrt[3]{f}}{6g} - \frac{e_0^2}{\sqrt[3]{g} \sqrt{f}}
\]

\[
f = -54ge_0^2 + 6\sqrt{3}e_0^2 \sqrt{2e_0^2 + 27g^2}
\]

\[
g = -\frac{\sqrt{2}}{2} \frac{a^3 |u_y|}{d^5}
\]

\[
e_0 = \sqrt{z_3^2 + \left( \frac{z_4}{d} \right)^2} < \frac{13}{5} \frac{a^3 |u_y|}{d^5}
\]

CONSTRAINT: Condition to go at zero with only one sequence…

\[
e_0 = e_0 - 0.99 \left( \frac{13}{5} \frac{a^3 |u_y|}{d^5} \right)
\]

…otherwise the sequence is applied to reach an harmonic motion of smaller amplitude

**TIME TO ZERO OUT THE FULL STATE IS PREDICTABLE**
Orbital Parameters and Spacecraft Characteristics

Table 1. Simulations Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_T ) (kg)</td>
<td>10</td>
</tr>
<tr>
<td>( m_c ) (kg)</td>
<td>11</td>
</tr>
<tr>
<td>( m_e ) (kg)</td>
<td>9</td>
</tr>
<tr>
<td>( S_p ) ((m^2))</td>
<td>.35</td>
</tr>
<tr>
<td>( S_T ) ((m^2))</td>
<td>.75</td>
</tr>
<tr>
<td>( S_{e, a0} ) ((m^2))</td>
<td>.25</td>
</tr>
<tr>
<td>( S_{e, a1} ) ((m^2))</td>
<td>.25</td>
</tr>
<tr>
<td>( S_{e, a2} ) ((m^2))</td>
<td>1.25</td>
</tr>
<tr>
<td>( \Delta S_{T} ) ((m^2))</td>
<td>.7857</td>
</tr>
<tr>
<td>( \Delta S_{C_0} ) ((m^2))</td>
<td>.7105</td>
</tr>
<tr>
<td>( C_e )</td>
<td>2.2</td>
</tr>
<tr>
<td>( C_{1, 0} )</td>
<td>2.31</td>
</tr>
<tr>
<td>( C_{1, 1} )</td>
<td>2.09</td>
</tr>
<tr>
<td>( \Delta B C_{0, 0} ) ((m^2/\text{kg}))</td>
<td>.0975</td>
</tr>
<tr>
<td>( \Delta B C_{0, 1} ) ((m^2/\text{kg}))</td>
<td>.1253</td>
</tr>
<tr>
<td>( \Delta B C_{0, 2} ) ((m^2/\text{kg}))</td>
<td>-.1125</td>
</tr>
<tr>
<td>( \Delta B C_{1, 0} ) ((m^2/\text{kg}))</td>
<td>-.107</td>
</tr>
<tr>
<td>( h(t_0) ) (km)</td>
<td>356</td>
</tr>
<tr>
<td>( P_{e, 0} ) (m/s)</td>
<td>5</td>
</tr>
<tr>
<td>( \sigma_{e, 0} ) (s)</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2. Target Spacecraft Initial Conditions

- \( a_T = 6713889.83 \text{m} \)
- \( e_T = 0.01 \)
- \( i_T = 51.9412 \text{deg} \)
- \( \Omega_T = 206.3577 \text{deg} \)
- \( \omega_T = 101.0711 \text{deg} \)
- \( \nu_T = 108.0848 \text{deg} \)

Table 3. Chaser Spacecraft Initial Positions in LVLH

- \( r_{C_1}(t_0) \) (m): [1000, 2000, 10]
- \( r_{C_1}(t_0) \) (m): [−1000, −2000, −10]
- \( v_{C_1}(t_0) \) (m/s): [−.0084, −1.7018, −.0063]
- \( v_{C_1}(t_0) \) (m/s): [.0094, 1.7020, .0063]

- Non constant density, 30% uncertainty
- Plates have dynamics (10 seconds)
- Full orbital model
- Navigation errors
Simulation: 2 chasers, drag & optimal thrust

Phase 1: only differential drag

Phase 2: only thrusters
Simulation: 2 chasers, drag & optimal thrust

INITIAL POSITION = [2000,1000,10] m
Simulation: 2 chasers, drag & optimal thrust

INITIAL POSITION = [-2000, -1000, -10] m
Simulation results

Table 4. Simulation Test Case 1 Results: Fuel Consumption and Starting points for the Low-Thrust phase

<table>
<thead>
<tr>
<th>Chaser 1</th>
<th>Chaser 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I = 2.18 \text{ mN}s$</td>
<td>$I = 19.4 \text{ mN}s$</td>
</tr>
<tr>
<td>$\Delta V = 2 \times 10^{-4} \text{ m/s}$</td>
<td>$\Delta V = 2 \times 10^{-3} \text{ m/s}$</td>
</tr>
<tr>
<td>Thrusting Start: $r_C (m) = [-58.75, -148.45, 21.54]$</td>
<td>Thrusting Start: $r_C (m) = [-47.83, -440.90, -7.75]$</td>
</tr>
<tr>
<td>Total Maneuver Time: 10.83 hours</td>
<td>Total Maneuver Time: 9.33 hours</td>
</tr>
</tbody>
</table>

Table 5. Simulation Test Case 2 Results: Fuel Consumption

<table>
<thead>
<tr>
<th>Chaser 1</th>
<th>Chaser 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I = 40.5 \text{ mN}s$</td>
<td>$I = 19.8 \text{ mN}s$</td>
</tr>
<tr>
<td>$\Delta V = 3.68 \times 10^{-3} \text{ m/s}$</td>
<td>$\Delta V = 2.21 \times 10^{-2} \text{ m/s}$</td>
</tr>
<tr>
<td>Total Maneuver Time: 10.14 hours</td>
<td>Total Maneuver Time: 8.68 hours</td>
</tr>
</tbody>
</table>

Saving more than 90% Delta V


Experimental Results: Outline

- Starting references and related work
- Sub-Optimal Attitude-Position Control via Linear Quadratic Regulator
- Spacecraft Simulators at the Spacecraft Robotics Laboratory
- Specializing the LQR Problem to the 3 DOF Spacecraft Simulators
- Control during Docking: plume impingement
- Briefly on Input Estimation
- Experimental Results
Spacecraft Simulators at the Spacecraft Robotics Lab

- Ad-hoc wireless communication
- Modularity
- Small footprint (20x20 cm)
- Light weight (10 kg)
- Rapid Prototyping: fast integration of new structural parts, custom designed


Sub-Optimal Attitude-Position Control via Linear Quadratic Regulator

- Two Spacecraft Relative Motion is a linear dynamics, attitude is not
  \[
  \begin{align*}
  \dot{x} &= f(\bar{x}) + B(\bar{x}) \bar{u} \\
  \bar{x} &= \begin{bmatrix}
  X & Y & Z & \phi & \theta & \psi & \dot{X} & \dot{Y} & \dot{Z} & \dot{\phi} & \dot{\theta} & \dot{\psi}
  \end{bmatrix}^T \\
  \bar{u} &= [u_1 \ldots u_n]^T
  \end{align*}
  \]

- LQR problem: the Q and R matrices dynamically sized
  \[
  J = \int_0^\infty \left( \bar{x}_{err}^T Q_{err} \bar{x}_{err} + \bar{u}^T R \bar{u} \right) dt
  \]
  \[
  Q = \begin{bmatrix}
  1 & 0_6 & 0_6 \\
  0_6 & |\bar{r}_{goal}|^3 \cdot V \cdot I_6 \\
  0_6 & 0_6 & |\bar{r}_{goal}|^3 \cdot V \cdot I_6
  \end{bmatrix}, \quad
  R = \begin{bmatrix}
  |\bar{r}_{goal}|^2 \\
  \end{bmatrix} I_n
  \]
  \[
  \dot{x} = A_{LIN}(\bar{x}) \bar{x} + B_{LIN}(\bar{x}) \bar{u}
  \]
  \[
  \bar{u}_{LQR} = -K_{LQR} \cdot \bar{x}_{err}
  \]
Different phases of the LQR-driven control

- **RENNEDZVOUS** \( |\vec{r}_{rs} | > r_{dock} \)

- **DOCKING APPROACH** \( |\vec{r}_{rs} | \leq r_{dock} \)
  
  a. within the docking cone
     - \( |\vec{r}_{rs} | > r_{imp} \) keep maneuvering
     - \( |\vec{r}_{rs} | \leq r_{imp} \) impingement: thrusters off
  
  b. outside docking cone \( \rightarrow \) orbiting to gain time while attitude is corrected
Real Time onboard OS and Rapid Prototyping of Executables

Programming and simulations on Simulink

Automatic generation of C code for RTAI Linux (simulators onboard OS)

Compilation of the C code into a real time executable
Specializing the LQR Problem to the 3 DOF Simulators: one spacecraft

\[ \vec{u} = [u_1, u_2, u_3, u_4]^T \]

\[ A = \begin{pmatrix} 0_{3\times3} & I_{3\times3} \\ 0_{3\times3} & 0_{3\times3} \end{pmatrix}, \quad B = \begin{pmatrix} \cos(\vartheta) & \cos(\vartheta) & -\sin(\vartheta) & -\sin(\vartheta) \\ \frac{m}{\sin(\vartheta)} & \frac{m}{\sin(\vartheta)} & \frac{m}{\cos(\vartheta)} & \frac{m}{\cos(\vartheta)} \\ \frac{-r}{J_z} & \frac{r}{J_z} & \frac{r}{J_z} & \frac{-r}{J_z} \end{pmatrix}, \quad C = I_{6\times6}, D = 0_{6\times4} \]

\[ B_{LIN} = \begin{pmatrix} 0 & \cos(\vartheta) - \sin(\vartheta)(\vartheta - \vartheta_{des}) & -\sin(\vartheta_{des}) + (\cos(\vartheta_{des}))(\vartheta - \vartheta_{des}) & 0 \\ 0 & \sin(\vartheta) + (\cos(\vartheta_{des}))(\vartheta - \vartheta_{des}) & \cos(\vartheta_{des}) - \sin(\vartheta_{des})(\vartheta - \vartheta_{des}) & 0 \\ 0 & \frac{m}{\sin(\vartheta)} & \frac{m}{\cos(\vartheta)} & 0 \\ \frac{-r}{J_z} & \frac{r}{J_z} & \frac{r}{J_z} & \frac{-r}{J_z} \end{pmatrix} \]

Linearizing attitude about current commanded orientation
Specializing the LQR Problem to the 3 DOF Simulators: two spacecraft

Control during docking 6 & 7 are shut off

Mass and mass distribution along with number and location of engines are the only new values

Combined Center of Mass (C.O.M.) shift
Input Estimation for S/C Relative Navigation

What if sensors’ updates are slow (e.g.: every 2 seconds) + random interruptions?

Each S/C needs to estimate where its target fellow is, between updates

…BUT IT DOES NOT KNOW THE OTHER S/C MANEUVERS…

Experimental Results: full experiment with four spacecraft simulators

VIDEO

http://www.vimeo.com/8357179


3) Curti, F., Romano, M., **Bevilacqua, R.**, “Model Based Thruster Commanding for Rotational and Translational Control of a Spacecraft”, submitted for possible publication on the *AIAA Journal of Guidance, Control and Dynamics*.
Plan for Research at Embry-Riddle

- **Differential Drag**: extend to eccentric LVLH & use JC2Sat feedback

- **Build a 6 degrees of freedom spacecraft simulators test-bed…potential extension: robotic manipulators installed**

- **Complete the guidance and relative tracking**
  - GUIDANCE (high level consensus reaching on sequence of assembly);
  - NAVIGATION (Input-Estimation spacecraft relative tracking).

- **Develop Sub-Optimal Real Time** technique, experiment, and compare with open source solvers as GPOPS

- **Space debris mitigation** with space robots

- Interdisciplinary possibilities:
  - Collaboration with Nonlinear Dynamical Control Systems and Spacecraft Engineering Research Lab on under-actuation and failures
  - Collaboration with Atmospheric Physics Research Lab. and Computational Atmospheric Dynamics Lab for differential drag developments
  - Start/Expand nano-satellites and CubeSats programs
  - Develop Embry-Riddle program on small satellites for real flight!

- **GOOD MANAGEMENT IS A MUST**
External Collaborations

- Keep the ongoing collaboration with **School of Aerospace Engineering, University “Sapienza” of Rome, Italy**.

- Continue interaction with **Canadian Space Agency**

- Establish a collaboration between Embry-Riddle and the **Naval Postgraduate School**.

- Establish a collaboration between Embry-Riddle and **MIT** (I have been partially involved with the SPHERES project)

- Establish a collaboration between Embry-Riddle and **WVU** (new satellites refueling center coming soon)

- Establish a collaboration between Embry-Riddle and the **University of Florida** on Optimization of Multiple Spacecraft Maneuvers.

- Establish a collaboration between Embry-Riddle and the **CalPoly/Mathworks** for software support for CubeSats
6 DOF Spacecraft Simulator

Phasespace absolute motion tracking

Payload of mass \( m \)

VisNav relative sensor

Pulley system and/or Archimede’s Principle and/or simple counterbalancing

\[ \vec{F} = -mg \]

Granite / Epoxy / “Hockey” table / Synthetic Ice

Constant force springs

CHECK TRANSFER FUNCTION

5DOF simulator Research Center of Pneumatics Harbin Institute of Technology, Harbin, China
Year I (building 1st simulator & search for ext. funds)

<table>
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<tr>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
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<th>JUN</th>
<th>JUL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS student/s design in CAD the Simulator and possibly docking interface</td>
<td>The electronics needed are clear</td>
<td>One Conference paper</td>
<td>All Subsystems functional</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PhD student chooses and acquires hardware for the simulator. He/She also works with me to design the “zero gravity” system</td>
<td>Bevilacqua decides on the floatation floor: possibly CoreFlow air blowing table</td>
<td>Assembly of the testbed</td>
<td>Preliminary Experimentation (TBD)</td>
<td></td>
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</tr>
<tr>
<td>Dr. Bevilacqua supervises all activities as Thesis Advisor + sets up the software environment + the position sensing system, and the first experiment based on developed theory (possibly sub-optimal and/or target tracking)</td>
<td>PROPOSALS FOR FUNDS: search BAs from NRO, AFRL, DARPA, NSF...and more. Topics: depending on BAA and related to multiple spacecraft GNC (detumbling uncontrolled objects, cleaning space from debris, ...)</td>
<td>One journal paper on the new 6 DOF testbed</td>
<td></td>
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</tbody>
</table>
Year II (we have funds!)

<table>
<thead>
<tr>
<th>AUG</th>
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<th>JUL</th>
</tr>
</thead>
</table>

- **Build the second spacecraft simulator** (PhD student works with me on it)
- The testbed is ready for more simulators
- Perform research and experimentation on Guidance, Relative Navigation and Optimal Control utilizing Two spacecraft simulators
- Establish and consolidate collaborations with external institutions that could be fruitful in terms of joint research and funds.
- I will keep continuing my search for funds...look into the NSF Career Award and other options

*Journal Paper (Journal of Field Robotics)*
Proposals for Funds


- NRO (Director’s Innovation Initiative: [https://dii.westfields.net/](https://dii.westfields.net/))


- [www.grants.gov](http://www.grants.gov)

- [http://www.library.uiuc.edu/iris/](http://www.library.uiuc.edu/iris/)

- …this comes from my experience at NPS…and I know Embry-Riddle can rely on private funding, NSF, and more.
Teaching at Embry-Riddle

- **Existing courses**
  - **BS**
    - ES 204 Dynamics
    - MA 245 Differential Equations and Matrix Methods
    - PS 215 Physics I
    - PS 208 Physics II
    - PS 219 Physics III
    - EP 340 Introduction to Space Systems Design
    - EP 393 Spaceflight Dynamics
    - EP 394 Space Systems Engineering
  - **MS**
    - EP 505 Advanced Spacecraft Dynamics and Control
    - EP 600 Experimental Methods in Space Science
    - MSE 545 Specification and Design of Real-Time Systems
    - MSE 655 Performance Analysis of Real-Time Systems

- **Proposed courses**
  - Spacecraft Attitude Dynamics
  - Advanced Attitude Determination and Control
  - DESIGN OF SPACECRAFT GNC FOR REAL-TIME TESTING
My areas of interest

- Spacecraft Instrumentation
- Spacecraft Systems Engineering
- Dynamics and Control of Aerospace Systems
- Space Robotics/Autonomous Systems

Courses

- EP 702 Theoretical Mechanics and Astrodynamics
- EP 705 Optimal Dynamical Systems
- EP 707 Nonlinear Dynamical Control Systems
- EP 709 Stochastic Systems in Engineering Physics