Embry-Riddle Aeronautical University

Department of Physical Sciences

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# Multiple Spacecraft Autonomous Systems:

## Theoretical Research
## &
## Laboratory Experimentation

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NAVAL
POSTGRADUATE
SCHOOL

**Spacecraft Robotics**
LABORATORY

# 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)

EMBRY-RIDDLE
AERONAUTICAL UNIVERSITY

**Plans for research and teaching at Embry-Riddle**

# My story at a glance

**M. Sc. In Aerospace Engineering** from *Sapienza* University, Rome, Italy, 2002.

**Project Engineer in Mission Analysis** at *Grupo Mecanica del Vuelo*, Madrid, Spain, 2003.

**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

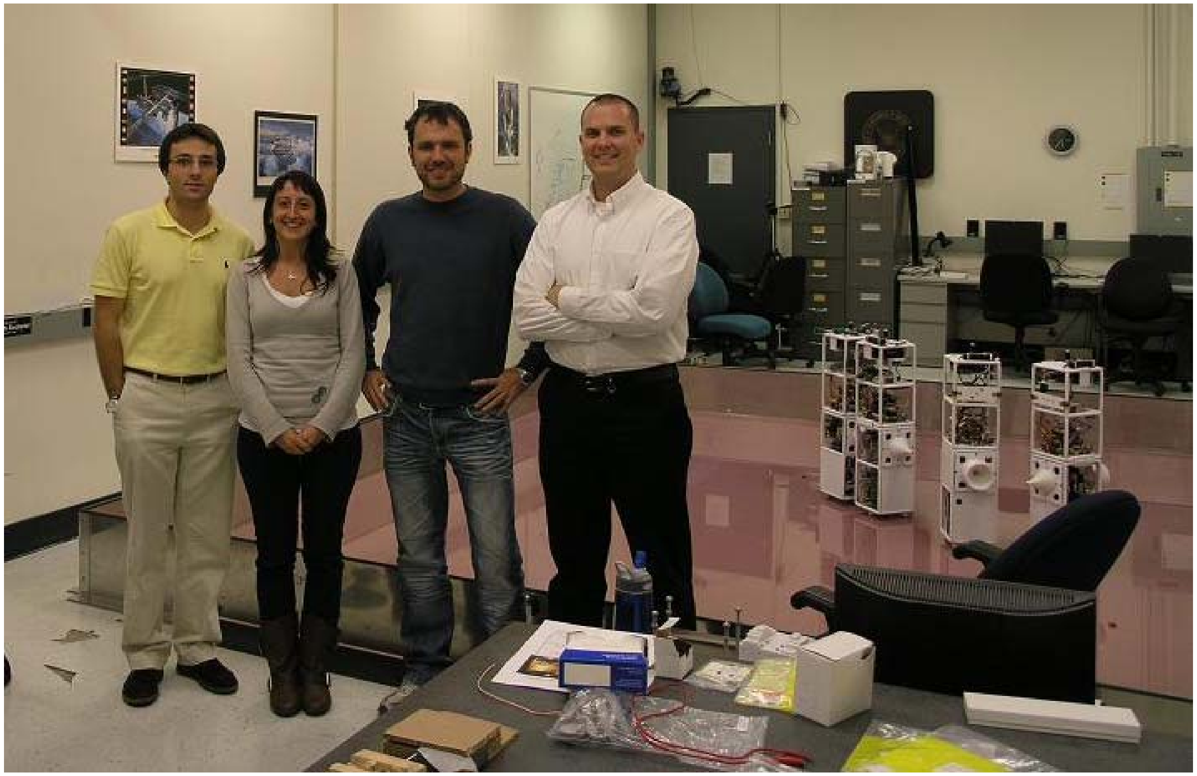
# Myself and the NPS

I am here

The SRL team

Working on the spacecraft simulators

# 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**

Credit: Defense Advanced Research Projects Agency

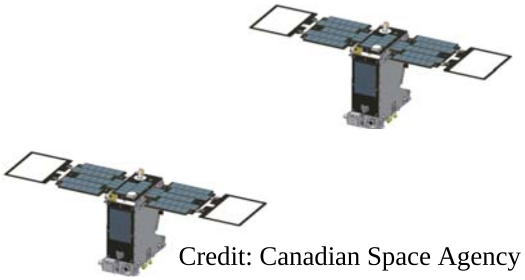
**CURRENT AND PAST**

- ☐ 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**

Credit: European space Agency



Credit: Canadian Space Agency

# 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

1) Leonard, C. L., Hollister, W. M., and Bergmann, E. V., “Orbital Formationkeeping with Differential Drag,” Journal of Guidance, Control, and Dynamics, Vol. 12, No. 1, 1989, pp. 108–113. doi:10.2514/3.20374

2) Schweighart, S. A., and Sedwick, R. J., “High-Fidelity Linearized J2 Model for Satellite Formation Flight,” Journal of Guidance, Control, and Dynamics, Vol. 25, No. 6, 2002, pp. 1073–1080.

3) Maclay, T., Tuttle, C., 2005, “Satellite Stationkeeping of the ORBCOMM Constellation Via Active Control of Atmospheric Drag: Operations, Constraints, and Performance”, Advances in Astronautical Sciences, Vol. 120, Part I, pp. 763-773.

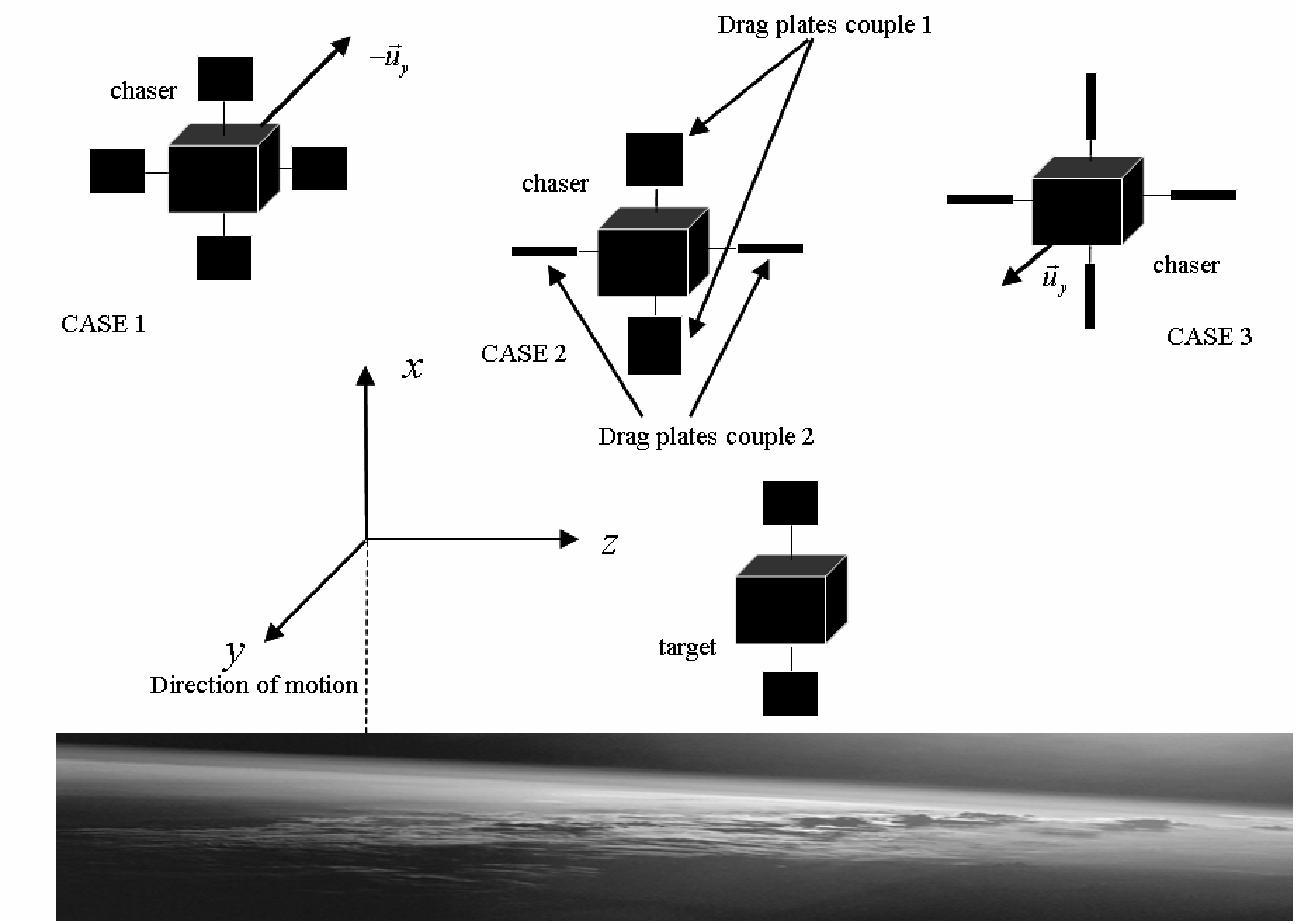
4) Palmerini, G. B., Sgubini, S., and Taini, G., “Spacecraft Orbit Control Using Air Drag,” International Astronautical Congress Paper 05-C1.6.10, 2005.

5) Campbell, M. E., “Planning Algorithm for Multiple Satellite Clusters,” Journal of Guidance, Control, and Dynamics, Vol. 26, No. 5, 2003, pp. 770–780.

6) Guelman, M., and Aleshin, M., “Optimal Bounded Low-Thrust Rendezvous with Fixed Terminal-Approach Direction,” Journal of Guidance, Control, and Dynamics, Vol. 24, No. 2, 2001, pp. 378–385.

# Concept for generating differential drag

## Attitude is stabilized in the orbital frame LVLH



# Dynamics & working assumptions for analytical derivations

$$\dot{\mathbf{x}} = \begin{bmatrix} 0_{2x2} & I_{2x2} \\ A_1 & A_2 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0_{2x2} \\ I_{2x2} \end{bmatrix} \mathbf{u} \qquad \mathbf{x}(t) \in \mathbb{R}^4, \forall \mathbf{x}^T = [x, y, \dot{x}, \dot{y}]$$

$$A_1 = \begin{bmatrix} 5c^2\omega^2 - 2\omega^2 & 0 \\ 0 & 0 \end{bmatrix}, \; A_2 = \begin{bmatrix} 0 & 2\omega c \\ -2\omega c & 0 \end{bmatrix} \longrightarrow$$

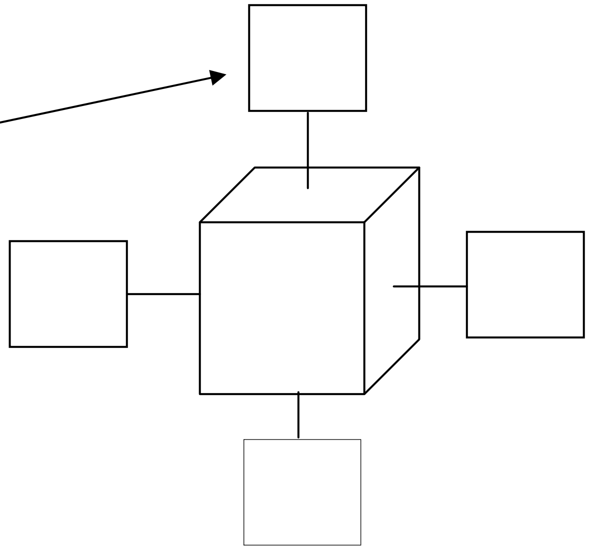
Schweighart-Sedwick Dynamics

$$\mathbf{u}^T = \begin{bmatrix} 0 & -\frac{\rho \Delta BC}{2} V_r^2 \end{bmatrix} \longrightarrow$$

Because relative velocity is negligible
with respect to the orbital one

$$\Delta BC = BC_{C_i} - BC_T = \frac{m_T C_{D_{C_i}} S_{C_i} - m_{C_i} C_{D_T} S_T}{m_T m_{C_i}} \longrightarrow$$

Heterogeneous spacecraft (similar parameters)



- On-off control (0-90 deg)
- Constant air density

# Dynamics Model: the state vector transformation

Linear state vector transformation

$$\mathbf{z}=\begin{bmatrix} 0 & 1 & -a/d^{2} & 0 \\ -ab/d^{2} & 0 & 0 & -b/d^{2} \\ 0 & 0 & a^{2}/\left(2d^{3}\right) & 0 \\ a^{2}b/\left(2d^{3}\right) & 0 & 0 & a^{3}/\left(2d^{3}\right) \end{bmatrix}\mathbf{x}$$

State analytical evolution

$$z_1 = z_{1_0} + tz_{2_0} - \frac{bt^2}{2d^2}u_y$$

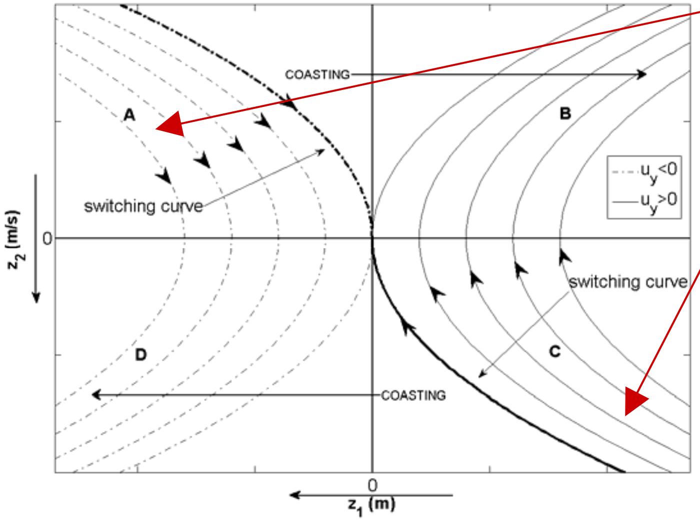
$$z_2 = z_{2_0} - \frac{bt}{d^2}u_y$$

$$z_3 = \cos\left(dt\right) z_{3_0} + \frac{\sin\left(dt\right)}{d} z_{4_0} + \frac{a^3\left[1-\cos\left(dt\right)\right]}{2d^5}u_y$$

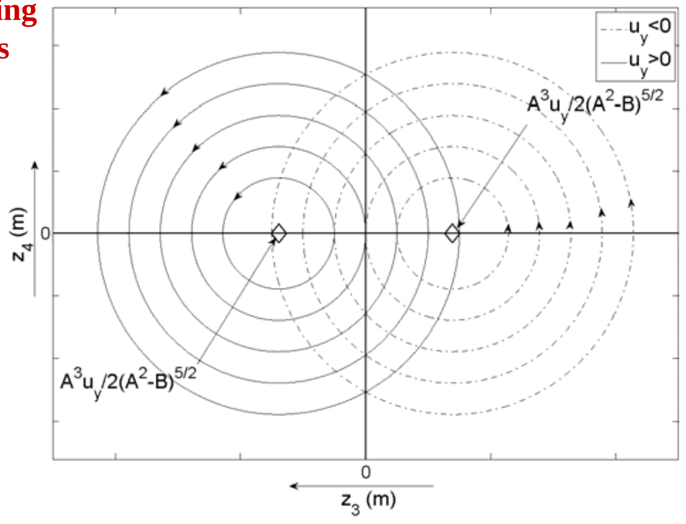
$$z_4 = -d\sin\left(dt\right) z_{3_0} + \cos\left(dt\right) z_{4_0} + \frac{a^3\sin\left(dt\right)}{2d^4}u_y$$

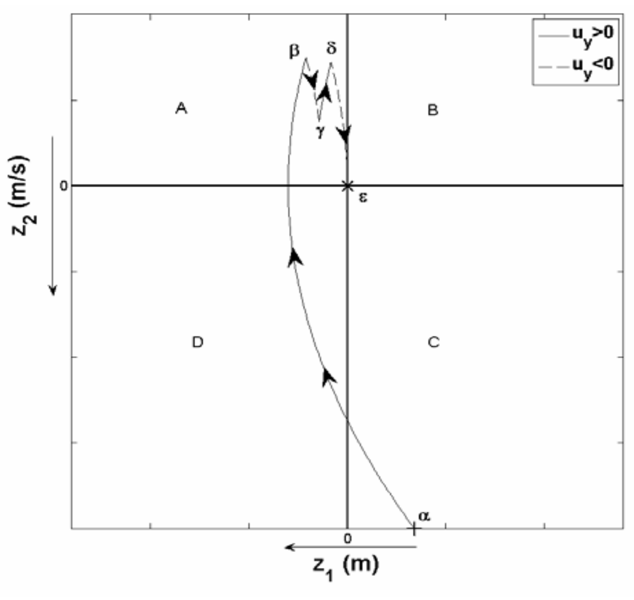
$$a = 2\omega c, b = \left(5c^2-2\right)\omega^2, d = \sqrt{a^2-b}$$

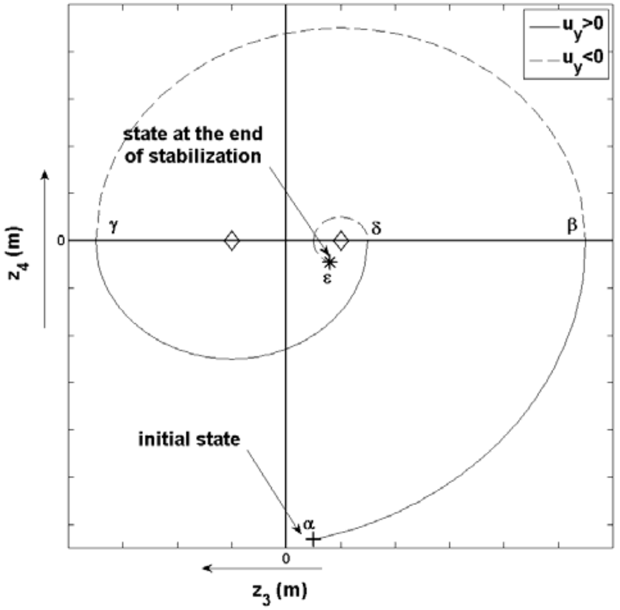
# Stabilization: (based on Leonard's work)



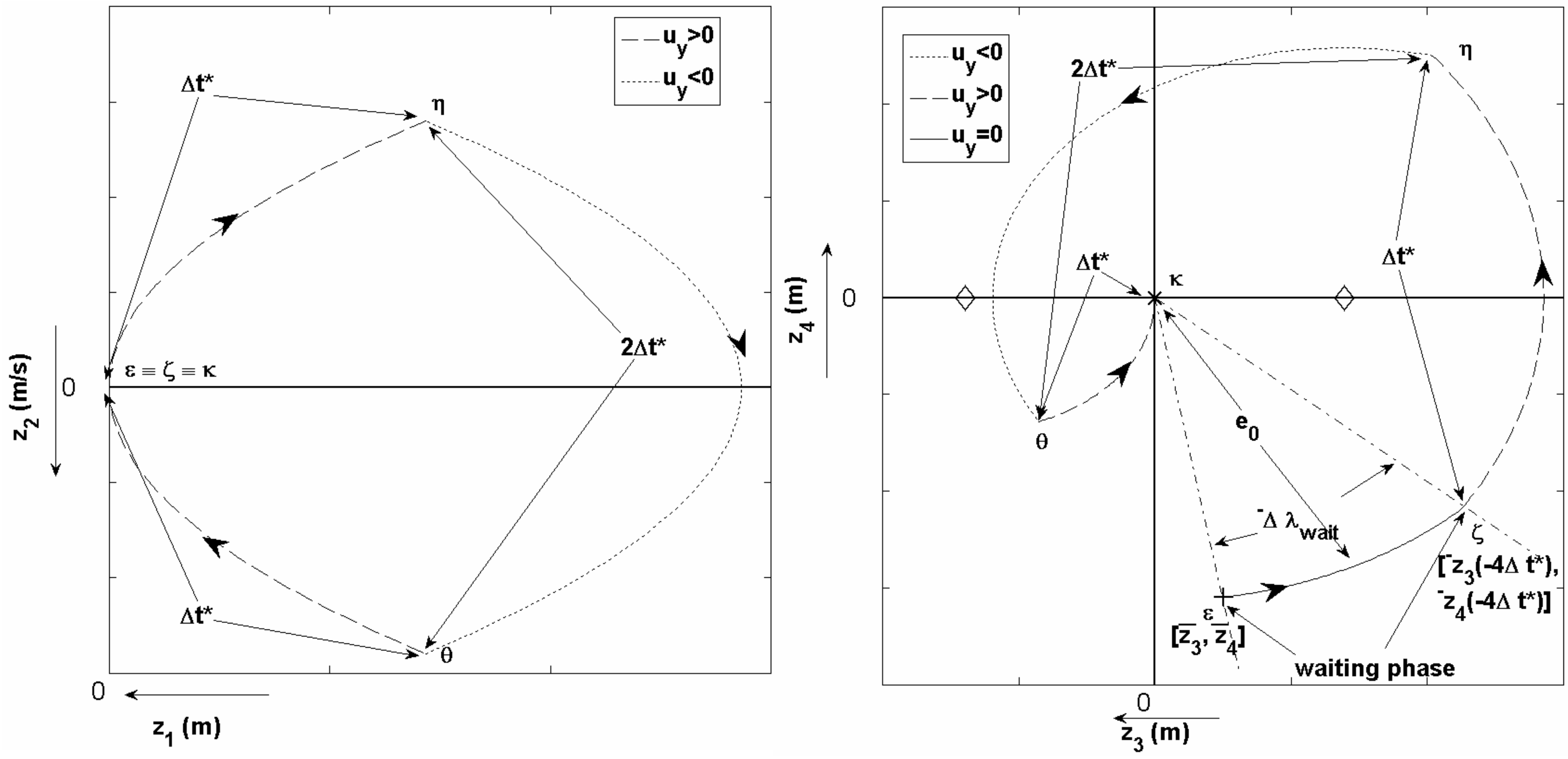
“saw-tooth” switching zones







# Analytical Exact Rendezvous to Target



NO RESIDUAL DISTANCE IS PRESENT.

# Exact Rendezvous to Target: the solution

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

→ Generic formula for the maneuvering time

$$h = 1 + {}^{\sqrt[3]{f}}\!/_{6g} - {}^{e_0^2}\!/_{g\sqrt[3]{f}}$$

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

$$g = -\frac{\sqrt{2}}{2}\frac{a^3\left|u_y\right|}{d^5} i$$

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

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

$$e_0 = e_0 - .99\left(\frac{13}{5}\frac{a^3\left|u_y\right|}{d^5}\right)$$

→ …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

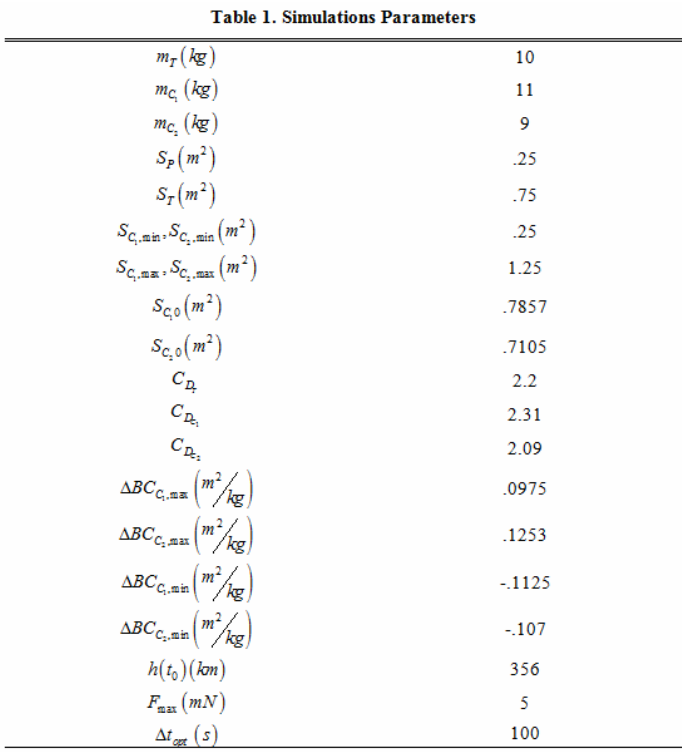


**Table 1. Simulations Parameters**

| | |
|---|---|
| $m_T\,(kg)$ | 10 |
| $m_{C_1}\,(kg)$ | 11 |
| $m_{C_2}\,(kg)$ | 9 |
| $S_P\,(m^2)$ | .25 |
| $S_T\,(m^2)$ | .75 |
| $S_{C_1,\min}, S_{C_2,\min}\,(m^2)$ | .25 |
| $S_{C_1,\max}, S_{C_2,\max}\,(m^2)$ | 1.25 |
| $S_{C_1 0}\,(m^2)$ | .7857 |
| $S_{C_2 0}\,(m^2)$ | .7105 |
| $C_{D_T}$ | 2.2 |
| $C_{D_{C_1}}$ | 2.31 |
| $C_{D_{C_2}}$ | 2.09 |
| $\Delta BC_{C_1,\max}\,\left(m^2/kg\right)$ | .0975 |
| $\Delta BC_{C_2,\max}\,\left(m^2/kg\right)$ | .1253 |
| $\Delta BC_{C_1,\min}\,\left(m^2/kg\right)$ | -.1125 |
| $\Delta BC_{C_2,\min}\,\left(m^2/kg\right)$ | -.107 |
| $h(t_0)\,(km)$ | 356 |
| $F_{\max}\,(mN)$ | 5 |
| $\Delta t_{opt}\,(s)$ | 100 |

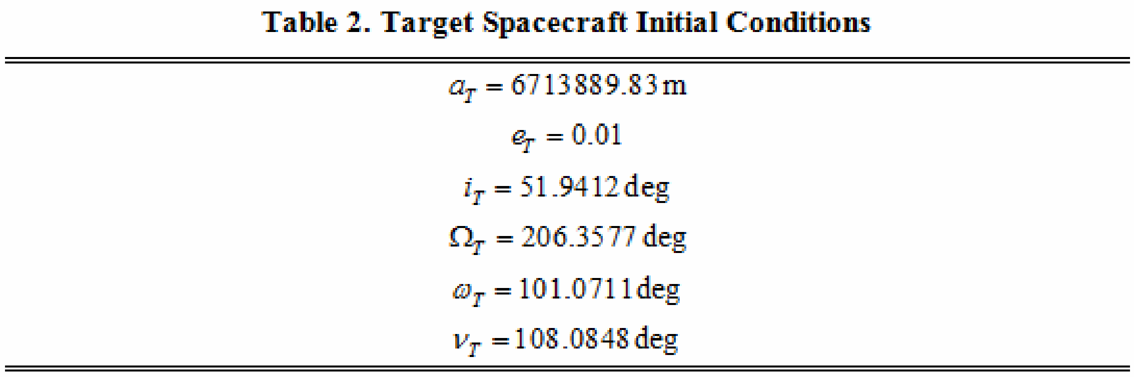


**Table 2. Target Spacecraft Initial Conditions**

$a_T = 6713889.83\,\text{m}$

$e_T = 0.01$

$i_T = 51.9412\,\text{deg}$

$\Omega_T = 206.3577\,\text{deg}$

$\omega_T = 101.0711\,\text{deg}$

$\nu_T = 108.0848\,\text{deg}$

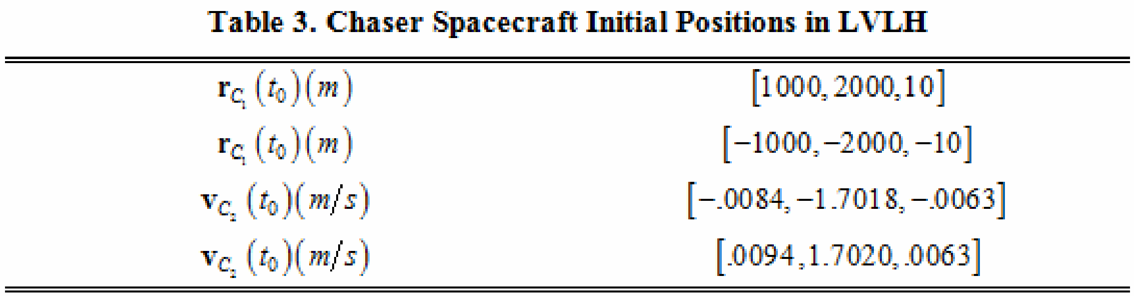
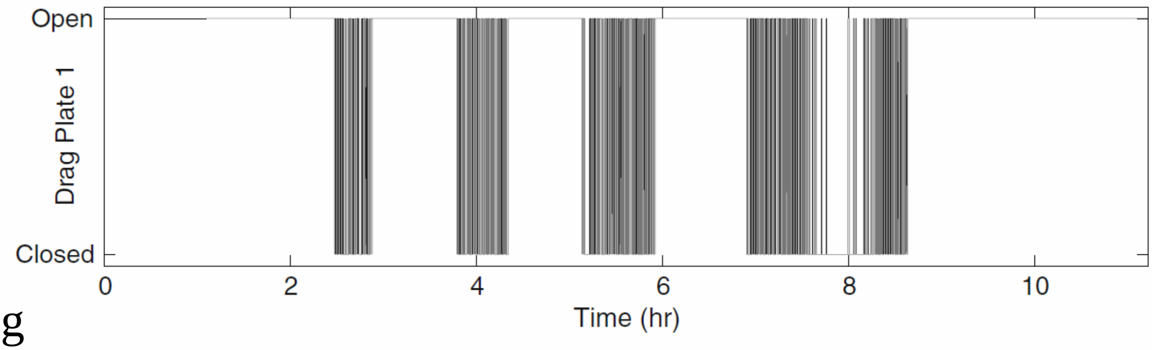


**Table 3. Chaser Spacecraft Initial Positions in LVLH**

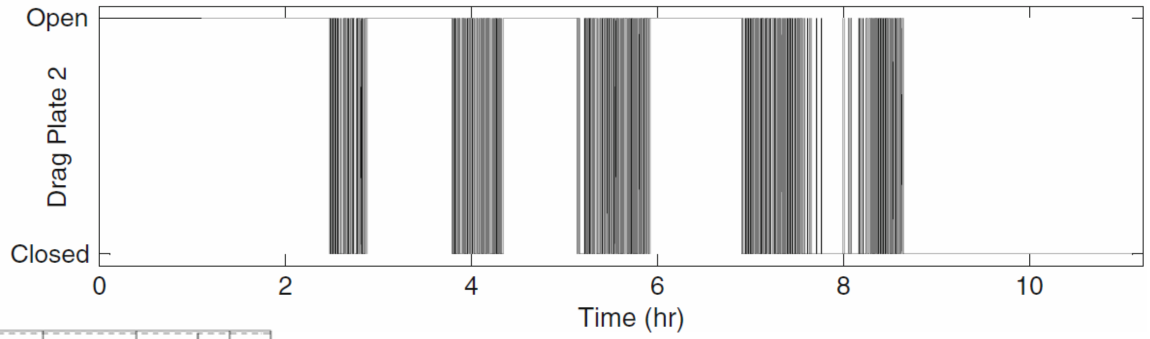
| | |
|---|---|
| $\mathbf{r}_{C_1}(t_0)(m)$ | $[1000, 2000, 10]$ |
| $\mathbf{r}_{C_1}(t_0)(m)$ | $[-1000, -2000, -10]$ |
| $\mathbf{v}_{C_2}(t_0)(m/s)$ | $[-.0084, -1.7018, -.0063]$ |
| $\mathbf{v}_{C_2}(t_0)(m/s)$ | $[.0094, 1.7020, .0063]$ |

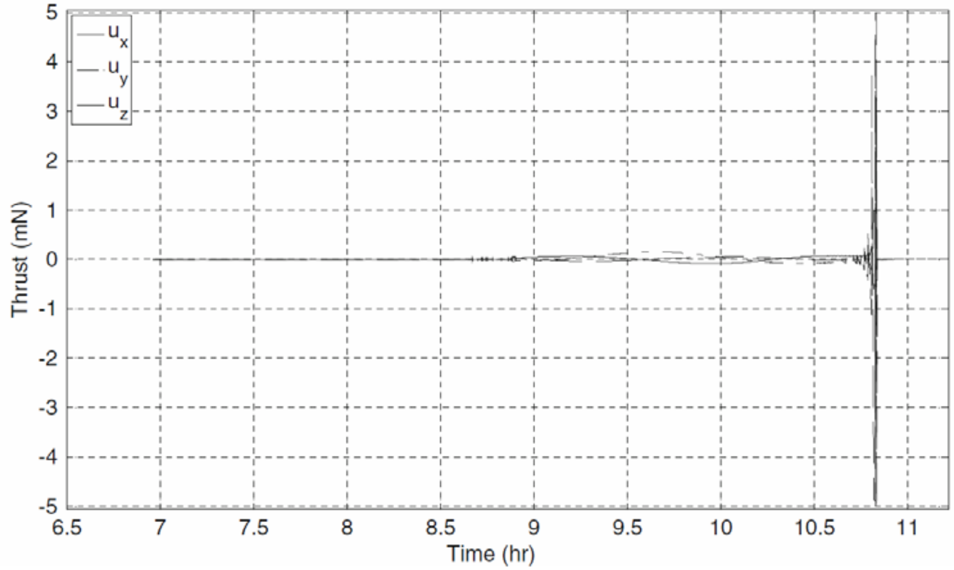
- Non constant density, 30% uncertainty
- Plates have dynamics (10 seconds)
- Full orbital model
- Navigation errors

# Simulation: 2 chasers, drag & optimal thrust



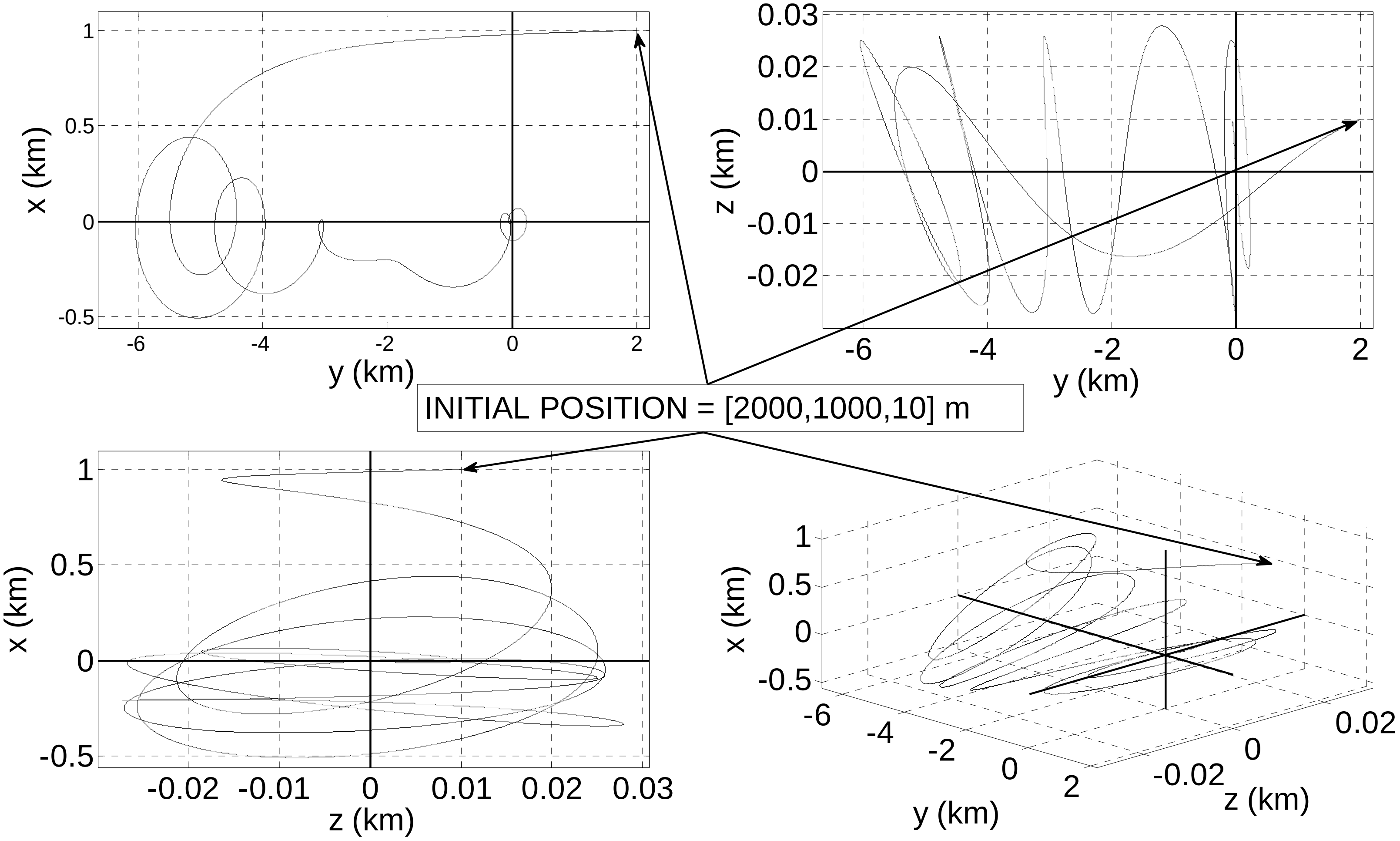
Phase 1: only differential drag





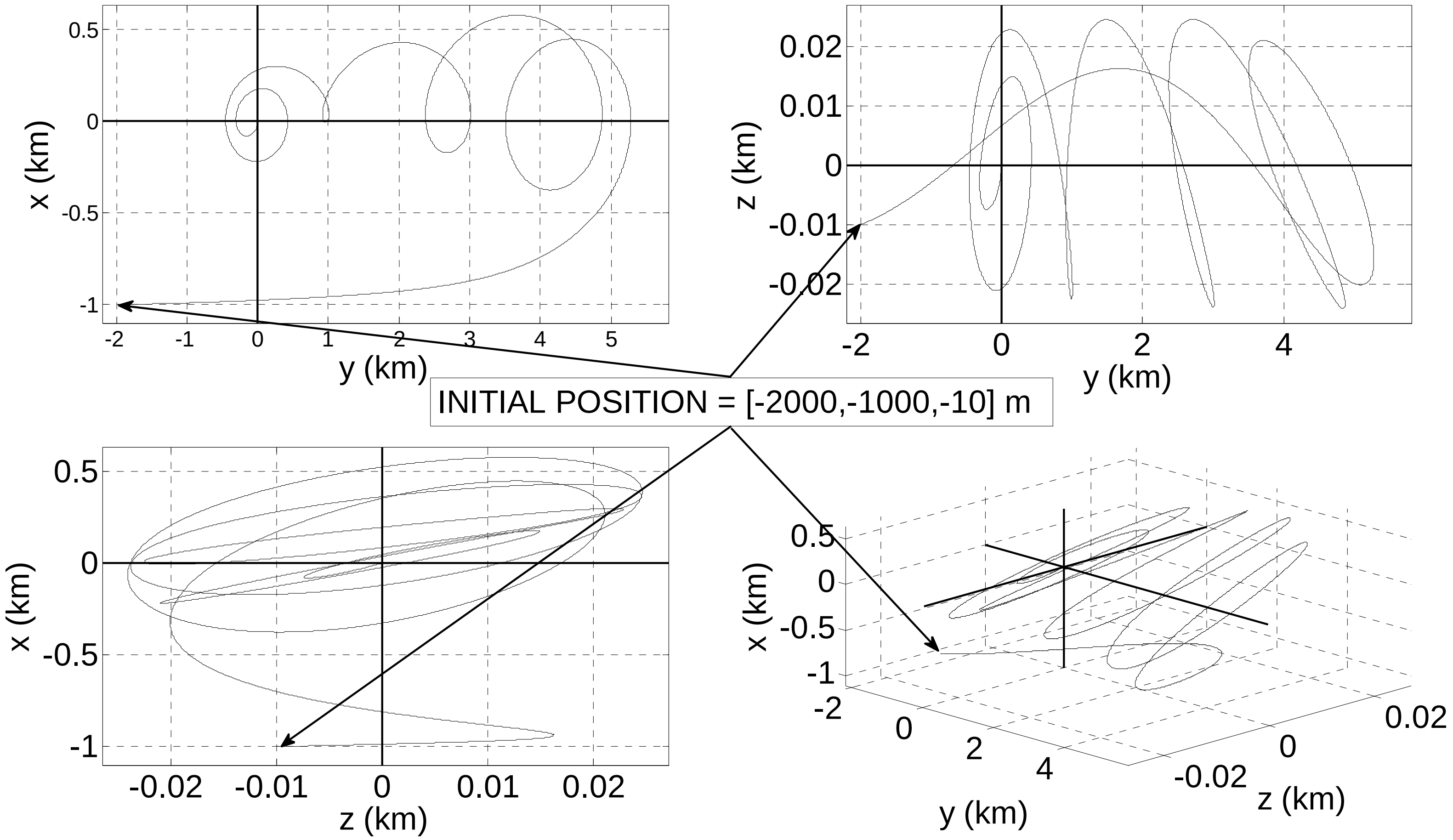
Phase 2: only thrusters

# 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

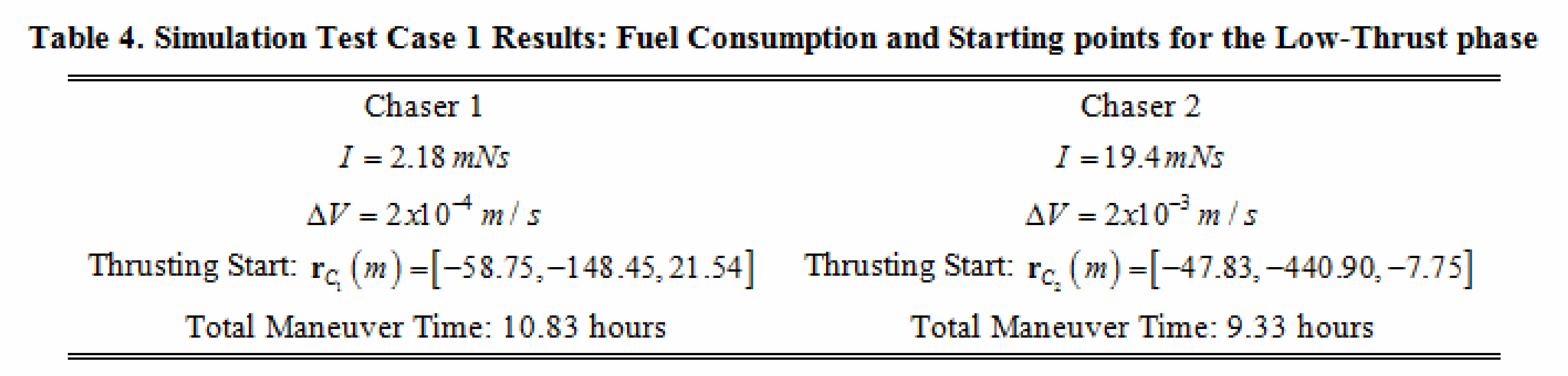


**Table 4. Simulation Test Case 1 Results: Fuel Consumption and Starting points for the Low-Thrust phase**

| Chaser 1 | Chaser 2 |
|---|---|
| $I = 2.18\ mNs$ | $I = 19.4\ mNs$ |
| $\Delta V = 2x10^{-4}\ m/s$ | $\Delta V = 2x10^{-3}\ m/s$ |
| Thrusting Start: $\mathbf{r}_{C_1}(m) = [-58.75, -148.45, 21.54]$ | Thrusting Start: $\mathbf{r}_{C_2}(m) = [-47.83, -440.90, -7.75]$ |
| Total Maneuver Time: 10.83 hours | Total Maneuver Time: 9.33 hours |

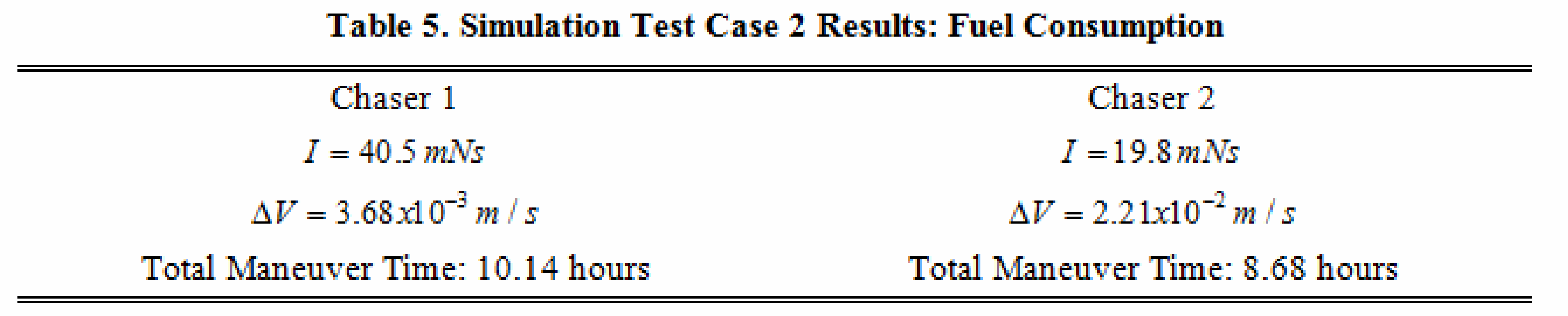
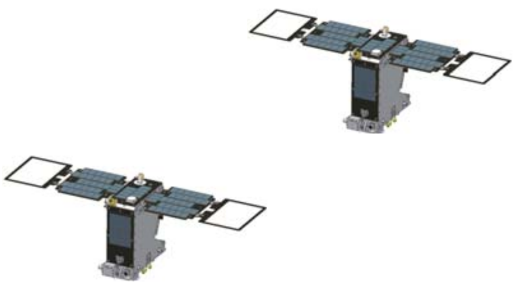


**Table 5. Simulation Test Case 2 Results: Fuel Consumption**

| Chaser 1 | Chaser 2 |
|---|---|
| $I = 40.5\ mNs$ | $I = 19.8\ mNs$ |
| $\Delta V = 3.68x10^{-3}\ m/s$ | $\Delta V = 2.21x10^{-2}\ m/s$ |
| Total Maneuver Time: 10.14 hours | Total Maneuver Time: 8.68 hours |

Saving more than 90% Delta V



# Archival Journal Publications (find them @ www.riccardobevilacqua.com)

1) **Bevilacqua, R.**, Hall, J., S., Romano, M., “Multiple Spacecraft Assembly Maneuvers by Differential Drag and Low Thrust Engines”, *Celestial Mechanics and Dynamical Astronomy*, Volume 106, Issue 1 (2010), p. 69-88.

2) **Bevilacqua, R.**, Romano, M., Curti, F., “Decoupled-natural-dynamics model for the Relative Motion of two Spacecraft without and with J2 perturbation”, accepted for publication, to appear on the *Nonlinear Dynamics and Systems Theory* (2009).

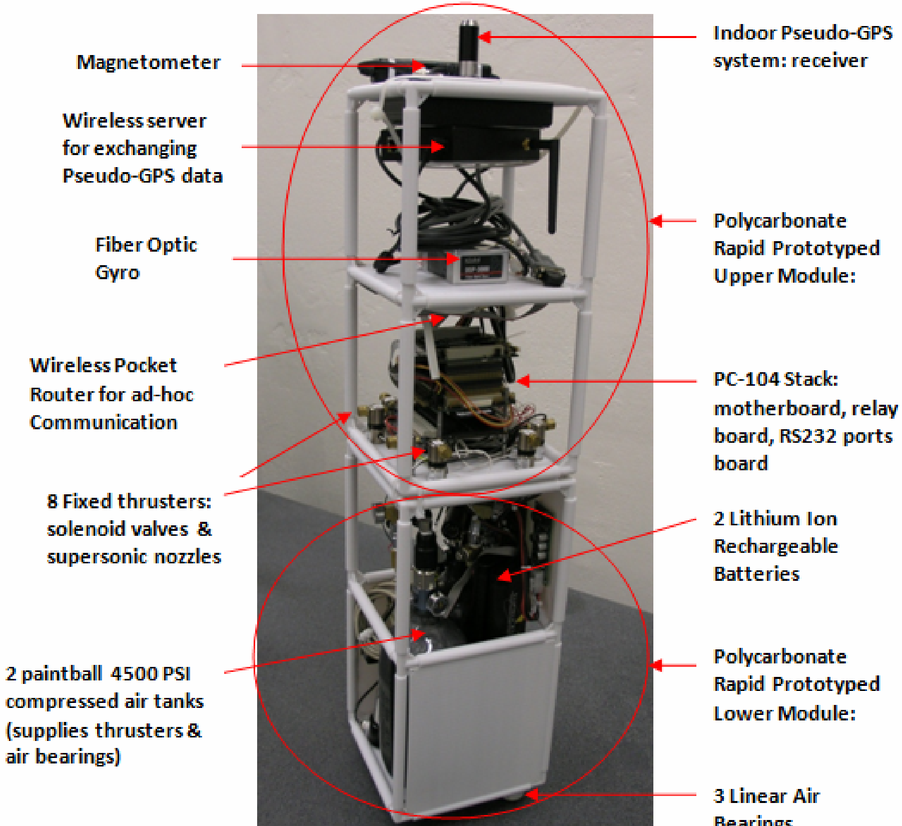
3) **Bevilacqua, R.**, Romano, M., “Non-propellant Rendezvous Maneuvers of Multiple Spacecraft by Differential Drag under J2 Perturbation”, *AIAA Journal of Guidance, Control and Dynamics*, vol.31 no.6 (1595-1607), 2008.

# 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



Magnetometer

Wireless server for exchanging Pseudo-GPS data

Fiber Optic Gyro

Wireless Pocket Router for ad-hoc Communication

8 Fixed thrusters: solenoid valves & supersonic nozzles

2 paintball 4500 PSI compressed air tanks (supplies thrusters & air bearings)

Indoor Pseudo-GPS system: receiver

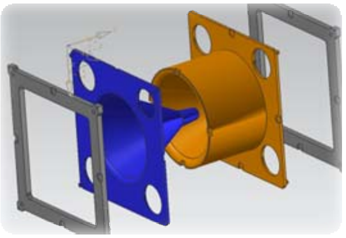
Polycarbonate Rapid Prototyped Upper Module:

PC-104 Stack: motherboard, relay board, RS232 ports board

2 Lithium Ion Rechargeable Batteries

Polycarbonate Rapid Prototyped Lower Module:

3 Linear Air Bearings



# Starting References & Related Work

1) Frost, S. A., Balas, M. J., “Adaptive Key Component Controllers for Evolving Systems,” AIAA Guidance, Navigation and Control Conference and Exhibit, 18 - 21 August 2008, Honolulu, Hawaii, AIAA 2008-6279.

2) Dong, S., Allen, K., et al., “Self-assembling wireless autonomously reconfigurable module design concept,” ACTA Astronautica, vol. 62, pages 246-256, Jan 2008.

3) Romano, M., Friedman, D.A., Shay, T.J. , “Laboratory Experimentation of Autonomous Spacecraft Approach and Docking to a Collaborative Target,” AIAA Journal of Spacecraft and Rockets, Vol. 44, No. 1, pp. 164-173, January-February 2007.

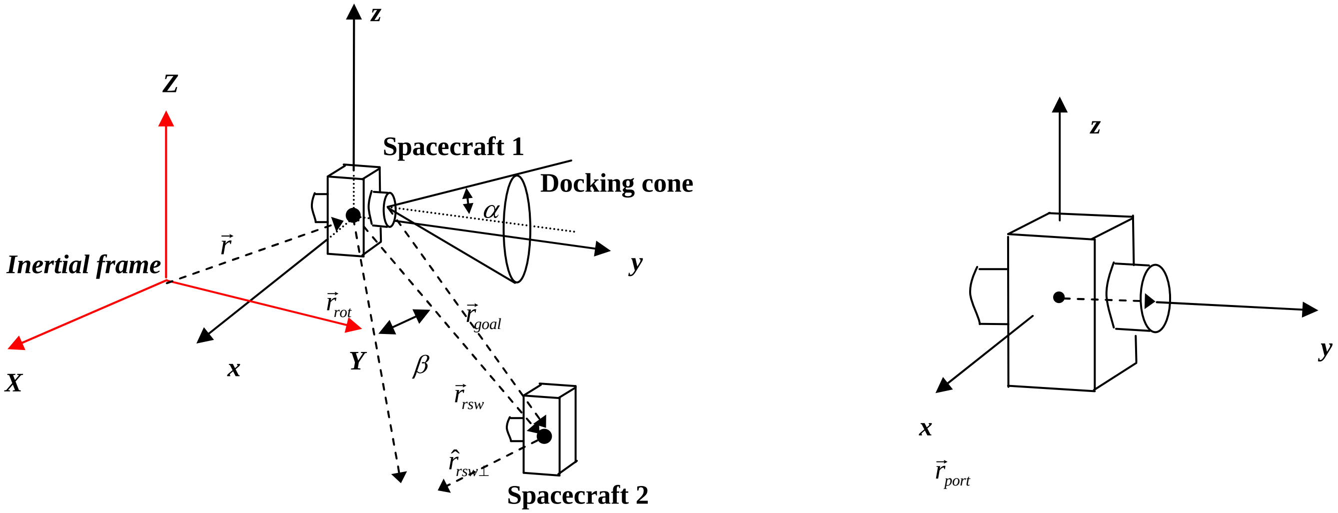
4) Toglia, C., Kettler, D., Kennedy, F., Dubowsky, S., “A Study of Cooperative Control of Self-Assembling Robots in Space with Experimental Validation,” 2009 IEEE International Conference on Robotics and Automation, May 12 - 17, 2009, Kobe, Japan.

# Sub-Optimal Attitude-Position Control via Linear Quadratic Regulator

- Two Spacecraft Relative Motion is a linear dynamics, attitude is not

$$\dot{\vec{x}} = f\left(\vec{x}\right) + \boldsymbol{B}\left(\vec{x}\right)\vec{u}$$

$$\vec{x} = \left[X \quad Y \quad Z \quad \phi \quad \theta \quad \psi \quad \dot{X} \quad \dot{Y} \quad \dot{Z} \quad \dot{\phi} \quad \dot{\theta} \quad \dot{\psi}\right]^T \qquad \vec{u} = \left[u_1 \quad \dots \quad u_n\right]^T$$



- LQR problem: the Q and R matrices dynamically sized

$$J = \int_0^\infty \left(\vec{x}_{err}^T \boldsymbol{Q} \vec{x}_{err} + \vec{u}^T \boldsymbol{R} \vec{u}\right) dt$$

$$\dot{\vec{x}} = \boldsymbol{A}_{LIN}\left(\vec{x}\right)\vec{x} + \boldsymbol{B}_{LIN}\left(\vec{x}\right)\vec{u} \longrightarrow$$

Linearized about current command

$$\boldsymbol{Q} = \begin{bmatrix} \dfrac{1}{\left|\vec{r}_{goal}\right|} \cdot I_6 & 0_6 \\ 0_6 & \left|\vec{r}_{goal}\right|^3 \cdot V \cdot I_6 \end{bmatrix}, \qquad \boldsymbol{R} = \frac{\left|\vec{r}_{goal}\right|}{a^2} I_n \xrightarrow{\qquad\qquad} \vec{u}_{LQR} = -\boldsymbol{K}_{\boldsymbol{LQR}} \cdot \vec{x}_{err}$$

# Different phases of the LQR-driven control

- ☐ <u>RENDEZVOUS</u> $\left|\vec{r}_{rsw}\right| > r_{dock}$

- ☐ <u>DOCKING APPROACH</u> $\left|\vec{r}_{rsw}\right| \leq r_{dock}$

  a. within the docking cone

    - $\left|\vec{r}_{rsw}\right| > r_{imp}$ keep maneuvering
    - $\left|\vec{r}_{rsw}\right| \leq r_{imp}$ impingement: thrusters off

  b. outside docking cone ⟶ orbiting to gain time while attitude is corrected

# Real Time onboard OS and Rapid Prototyping of Executables

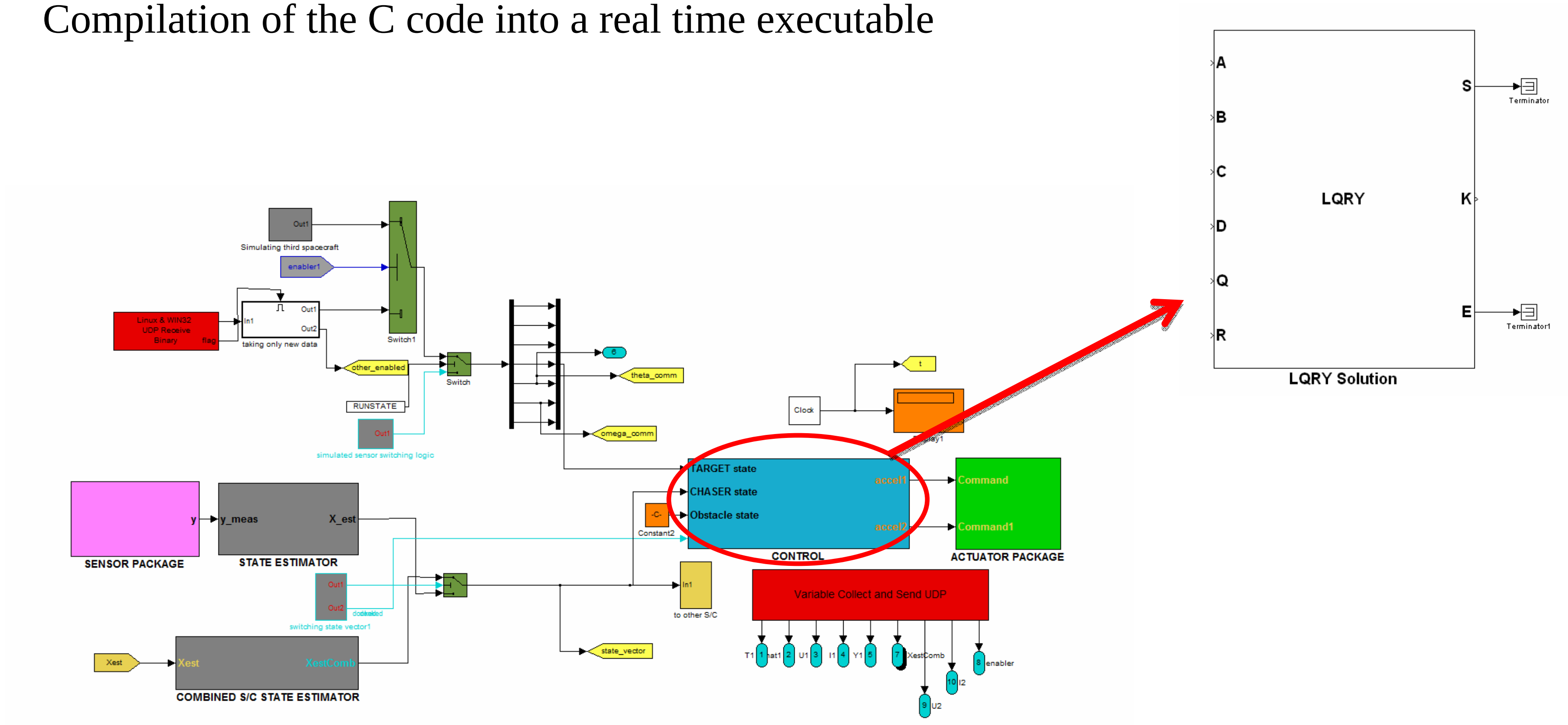
Programming and simulations on Simulink

↓

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

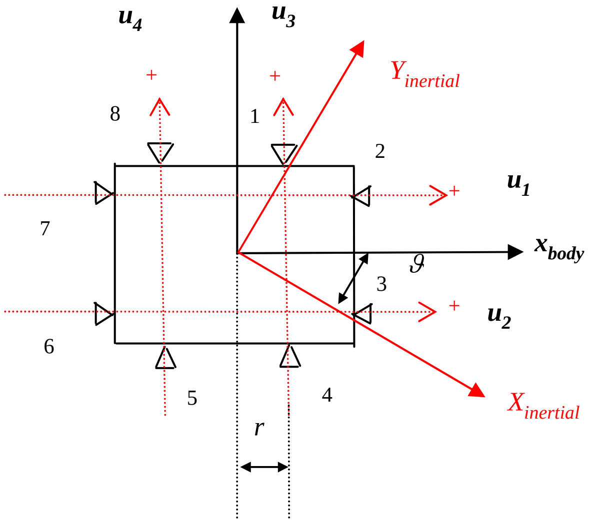
↓

Compilation of the C code into a real time executable



# Specializing the LQR Problem to the 3 DOF Simulators: one spacecraft

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

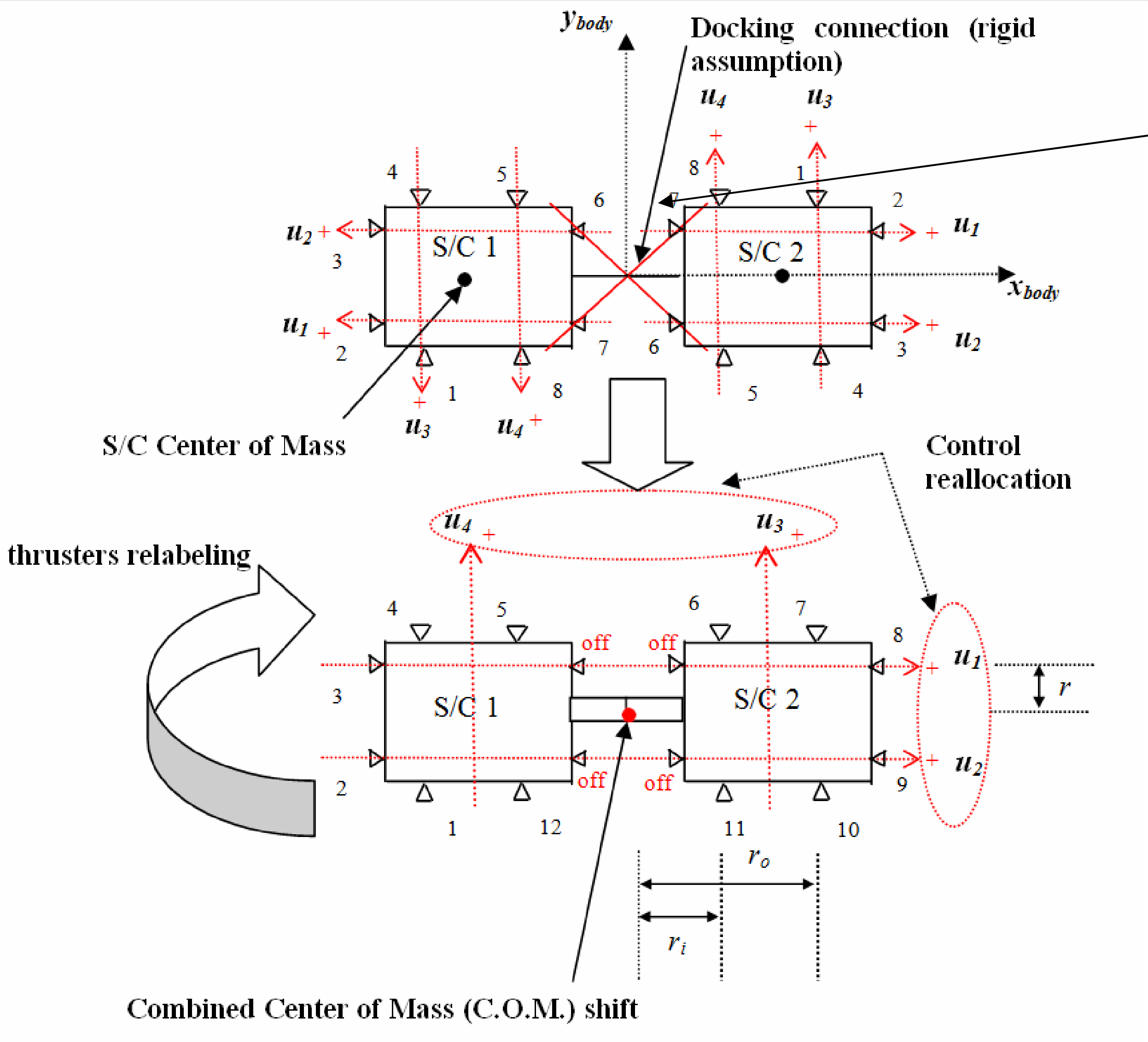


$$A = \begin{pmatrix} 0_{3x3} & I_{3x3} \\ 0_{3x3} & 0_{3x3} \end{pmatrix}, B = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{\cos(\vartheta)}{m} & \frac{\cos(\vartheta)}{m} & \frac{-\sin(\vartheta)}{m} & \frac{-\sin(\vartheta)}{m} \\ \frac{\sin(\vartheta)}{m} & \frac{\sin(\vartheta)}{m} & \frac{\cos(\vartheta)}{m} & \frac{\cos(\vartheta)}{m} \\ \frac{-r}{J_z} & \frac{r}{J_z} & \frac{r}{J_z} & \frac{-r}{J_z} \end{pmatrix}, C = I_{6x6}, D = 0_{6X4}$$

$\downarrow$ Linearizing attitude about current commanded orientation

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

# 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

# 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…

↓

Kalman Filter for Relative Position, Velocity, and <u>ESTIMATING THE OTHER S/C CONTROLS (INPUTS): THEY BECOME PART OF THE ESTIMATED STATE</u>

# Experimental Results: full experiment with four spacecraft simulators

VIDEO

http://www.vimeo.com/8357179

# Archival Journal Publication (two pending) (find them @ www.riccardobevilacqua.com)

1) **R. Bevilacqua**, J. Hall, J. Horning, M. Romano, Ad-hoc Wireless Networking and Shared Computation based upon Linux for Autonomous Multi-Robot Systems, *AIAA Journal of Aerospace Computing, Information, and Communication*. Vol. 6, No 5, pp. 328-353, May 2009. Doi: 10.2514/1.40734.

2) **Bevilacqua, R.,** Lehmann, T., Romano, M., “Development and Experimentation of a LQR/APF Control for Autonomous Proximity Maneuvers of Multiple Spacecraft,” submitted for publication to *Acta Astronautica*.

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**.

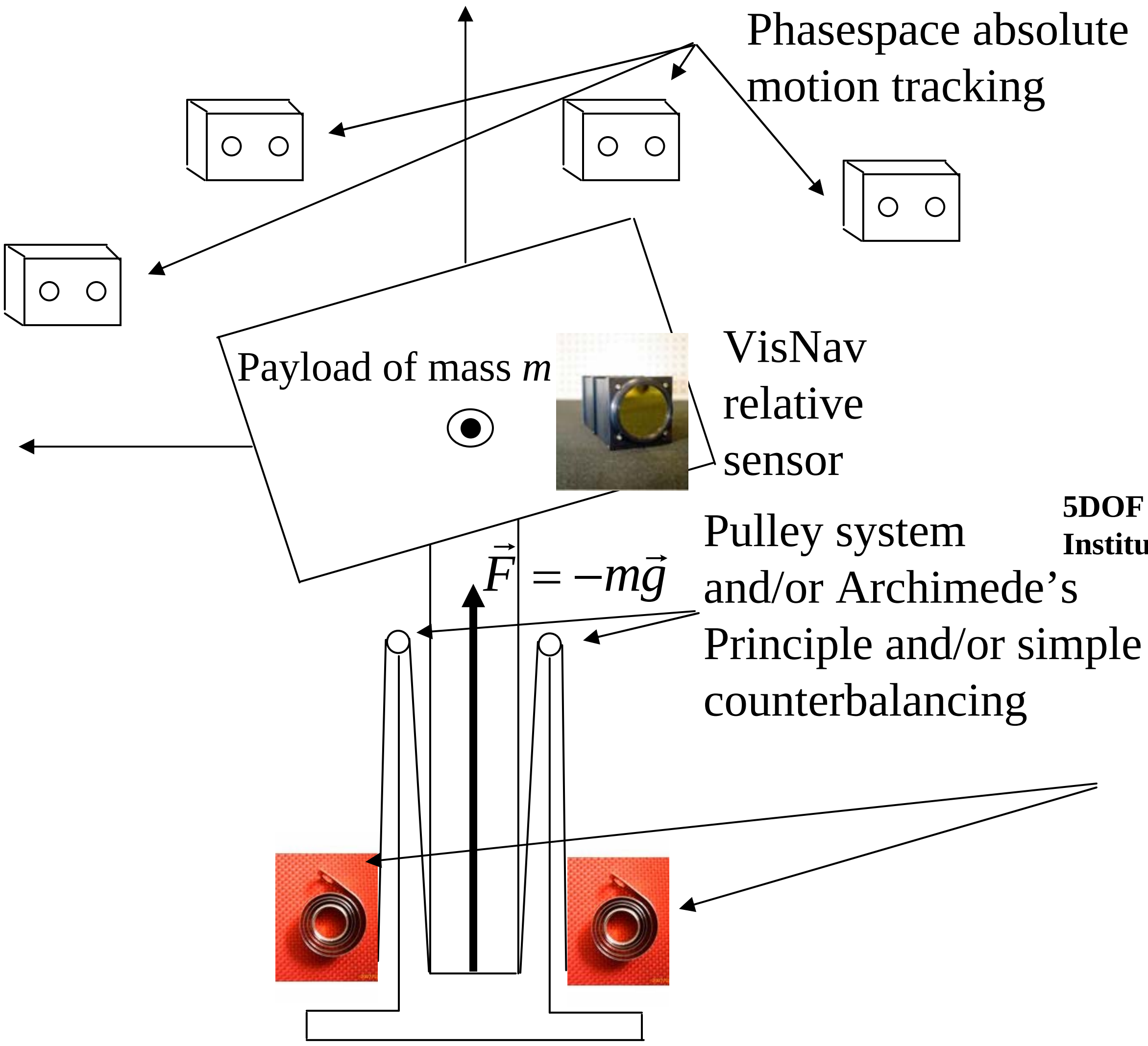
- ☐Establish a collaboration between Embry-Riddle and **MIT** (I have been partially involved with the SPHERES project)

- ☐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

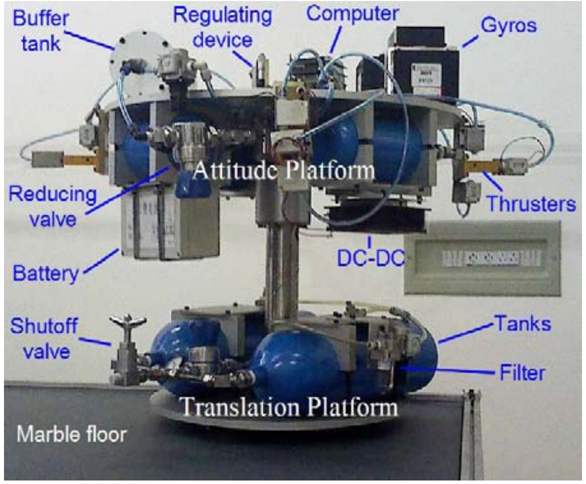
Payload of mass *m*

VisNav relative sensor

$\vec{F} = -m\vec{g}$

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

Granite / Epoxy / "Hockey" table / Synthetic Ice

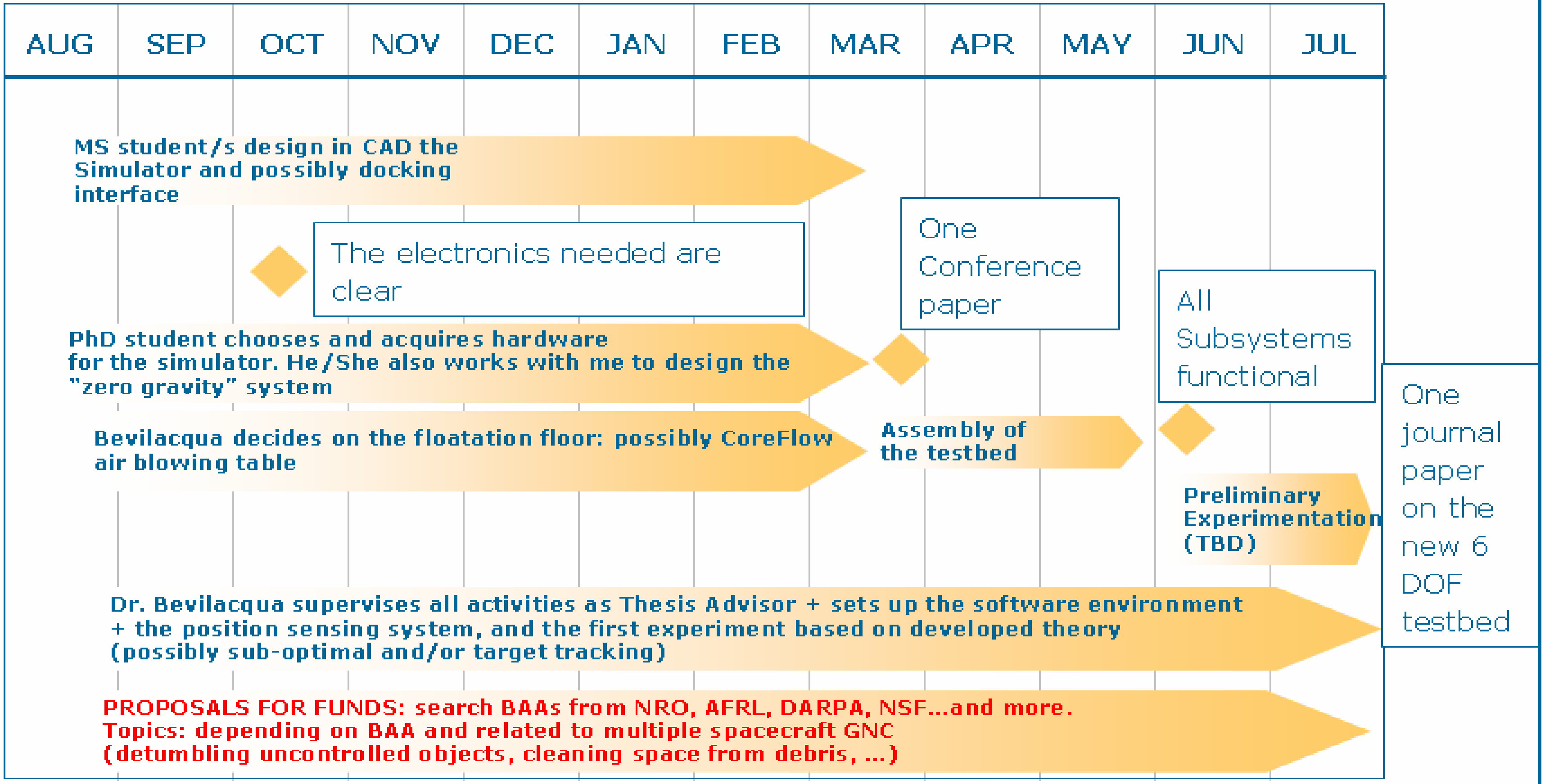


**5DOF simulator Research Center of Pneumatics Harbin Institute of Technology. Harbin, China**

Constant force springs

**CHECK TRANSFER FUNCTION**

# Year I (building 1$^{st}$ simulator & search for ext. funds)



AUG SEP OCT NOV DEC JAN FEB MAR APR MAY JUN JUL

MS student/s design in CAD the Simulator and possibly docking interface

The electronics needed are clear

One Conference paper

All Subsystems functional

PhD student chooses and acquires hardware for the simulator. He/She also works with me to design the "zero gravity" system

Bevilacqua decides on the floatation floor: possibly CoreFlow air blowing table

Assembly of the testbed

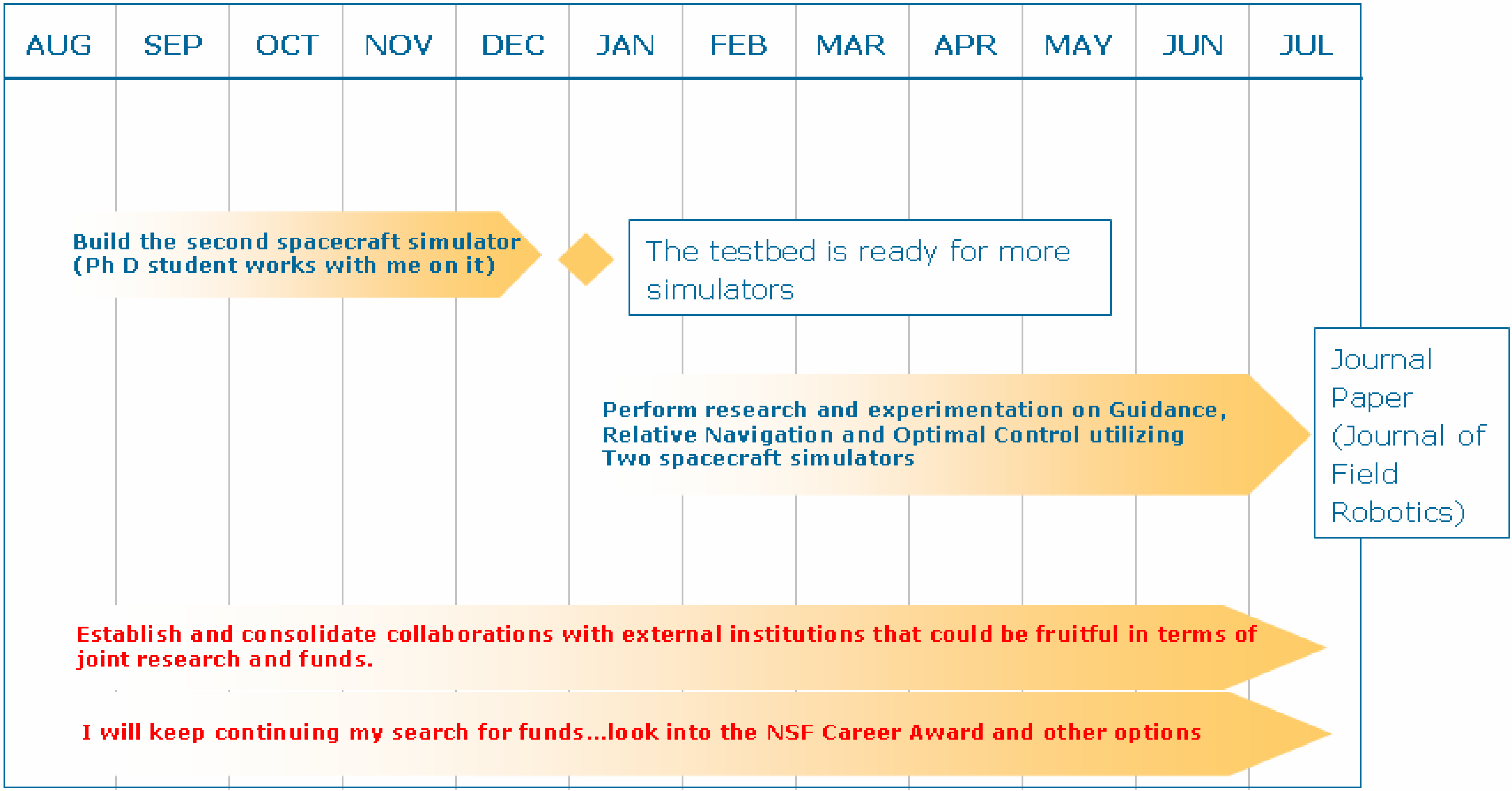
Preliminary Experimentation (TBD)

One journal paper on the new 6 DOF testbed

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)

PROPOSALS FOR FUNDS: search BAAs from NRO, AFRL, DARPA, NSF…and more. Topics: depending on BAA and related to multiple spacecraft GNC (detumbling uncontrolled objects, cleaning space from debris, …)

# Year II (we have funds!)



**Build the second spacecraft simulator (Ph D 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**

Journal Paper (Journal of Field Robotics)

**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**

# Proposals for Funds

- DARPA (www.FedBizOpps.gov , explore and register to receive real-time notifications)
- NRO (Director's Innovation Initiative: https://dii.westfields.net/)
- AFRL (www.FedBizOpps.gov)
- NASA (NSPIRES website for solicited proposal, http://prod.nais.nasa.gov/pub/pub_library/unSol-Prop.html, for unsolicited)
- NSF (http://www.nsf.gov/funding/azindex.jsp?start=S, example: CubeSat weather program)
- www.grants.gov
- 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

# The new Ph.D. program at Embry-Riddle

**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 |