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Autonomous estimation of load inertial properties for a free-flyer robot

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About us

Institute for Systems and Robotics (ISR-Lisbon)
http://welcome.isr.tecnico.ulisboa.pt/

- RD&I institution, affiliated to **Instituto Superior Técnico (IST)**
- Multidisciplinary advanced research on the areas of **Robotic Systems** and **Information Processing**
- **Research domains**: Systems and Control Theory, Robotics, Signal Processing, Computer Vision, Optimisation, AI and Intelligent Systems, Biomedical Engineering.

Space CoBot project

http://space-cobot.isr.tecnico.ulisboa.pt/

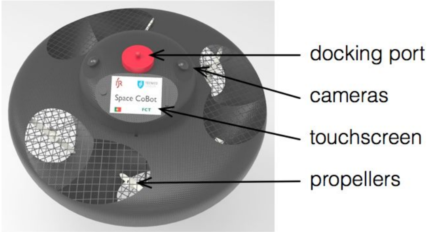
- Spin-in of terrestrial collaborative robots to the space environment
- Crew on ISS is limited, with a tight work schedule
- Robots collaborate with astronauts aboard the ISS

Space CoBot project

http://space-cobot.isr.tecnico.ulisboa.pt/

Project strategy:

- Research on free-flyer robots -- platform agnostic
  Focus on:
  - Mobile manipulation
  - Human-robot interaction
  - Motion planning under uncertainty
  - Validation on ISS (e.g., SPHERES, Astrobee)



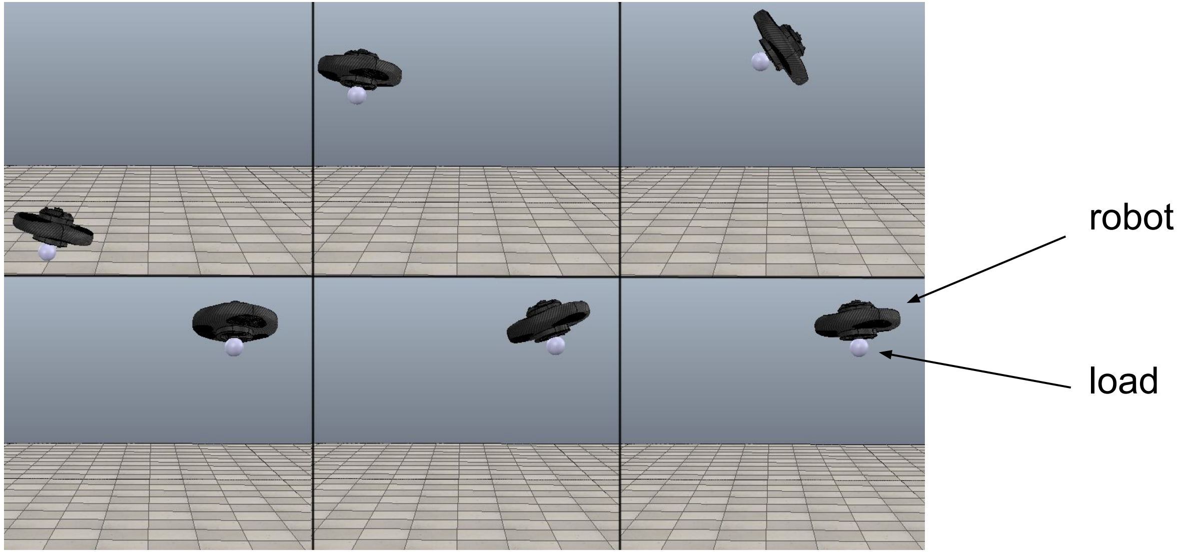
[IROS16]

- Development of the Space CoBot prototype
  Focus on:
  - Low-level control
  - Validation on Earth
    (e.g., passive gimbal, air-bearing table, parabolic flights)

Problem statement

- Transporting an unmodeled load causes large tracking errors
- Modeling a load requires a good estimate of it inertial properties

Reference trajectory with constant attitude:



Problem statement

- Consider a free-flyer robot in microgravity grasping an arbitrary object.
- **Goal**: to estimate, from measurements, the inertial properties of the joint robot-load, assumed a rigid body
- Inertial parameters considered:
  - Total mass
  - Center of mass
  - Moment of inertia

Approach

Overview of the algorithm:

1. Obtain an excitatory trajectory maximizing information gain
2. Follow that trajectory using an MPC controller
3. Fit the actual trajectory to an analytical function
4. Use linear least-squares to estimate inertial parameters:

$$\mathbf{W}\boldsymbol{\pi} = \mathbf{b}$$

Regressor matrix:
$$\mathbf{W} = \begin{bmatrix} \boldsymbol{\gamma}(X(1), \dot{X}(1), \ddot{X}(1)) \\ \vdots \\ \boldsymbol{\gamma}(X(N), \dot{X}(N), \ddot{X}(N)) \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} \tau(1) \\ \vdots \\ \tau(N) \end{bmatrix}$$

Force and torque:
$$\boldsymbol{\tau} = \begin{bmatrix} \mathbf{F} \\ \mathbf{M} \end{bmatrix}^T$$

Inertial parameters:
$$\boldsymbol{\pi} = \begin{bmatrix} m & m\mathbf{p}_{off} & J_{xx} & J_{xy} & J_{xz} & J_{yy} & J_{yz} & J_{zz} \end{bmatrix}^T$$

1. Excitatory trajectory optimization

Optimization problem:

- Cost function: J_1 or J_2
- Variable space: Truncated Fourier series coefficients
- Constraints: bounded position and velocity

J_1 = condition number of the regressor matrix

J_2 = log determinant of the Fisher information matrix

2. Trajectory tracking

Nonlinear Model Predictive Control (NMPC)

$$\begin{aligned}
\underset{X(\cdot),u(\cdot)}{\text{minimize}} \quad & \sum_{T=t}^{t+t_h} (\|e(X_{des}(T), X(T))\|_Q^2 + \|u(T)\|_P^2) \\
& + \|e(X_{des}(t+t_h), X(t+t_h))\|_{Q_N}^2 \\
\text{subject to:} \quad & \dot{X} = f(X(t), u(t)) \\
& u_{min} \leq u(t) \leq u_{max}
\end{aligned}$$

ACADO Toolkit was used to generate the controller code.

3. Trajectory fitting

- Executed trajectory differs from the reference trajectory
- Localization data can be noisy
- **Truncated Fourier series coefficients are re-estimated from data**
- From this expansion, first and second derivatives can be analytically computed
- In addition, multiple periods can be averaged over

4. Inertial properties estimation

Estimated using a straightforward linear least squares over the executed trajectory and forces/torques:

$$\mathbf{W}\boldsymbol{\pi} = \mathbf{b}$$

$$\mathbf{W} = \begin{bmatrix} \boldsymbol{\gamma}(X(1), \dot{X}(1), \ddot{X}(1)) \\ \vdots \\ \boldsymbol{\gamma}(X(N), \dot{X}(N), \ddot{X}(N)) \end{bmatrix}$$

$$\mathbf{b} = \begin{bmatrix} \tau(1) \\ \vdots \\ \tau(N) \end{bmatrix}$$

Force and torque:

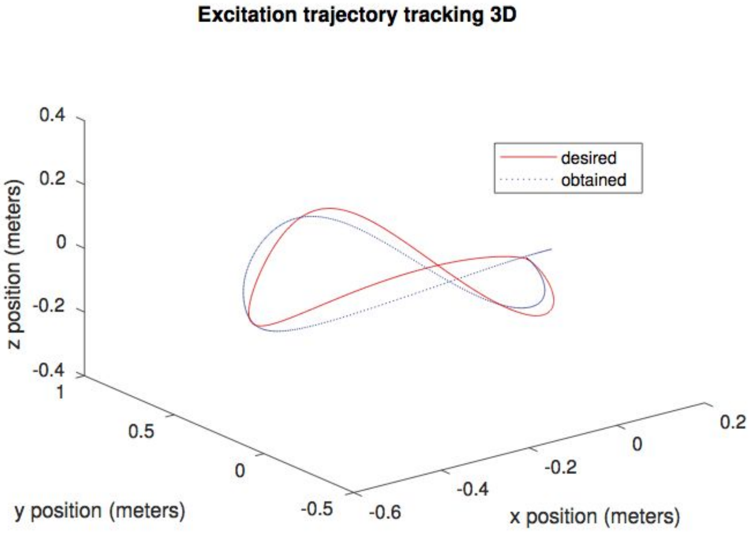
$$\boldsymbol{\tau} = \begin{bmatrix} \mathbf{F} \\ \mathbf{M} \end{bmatrix}^T$$

Inertial parameters:

$$\boldsymbol{\pi} = \begin{bmatrix} m & m\mathbf{p}_{off} & J_{xx} & J_{xy} & J_{xz} & J_{yy} & J_{yz} & J_{zz} \end{bmatrix}^T$$

$$\hat{\pi} = (\mathbf{W}^T\mathbf{W})^{-1}\mathbf{W}^T\mathbf{b}$$

Simulation results



Criterion	Mass error (kg)	Offset error norm (m)	Inertia error RMS $(kg.m^2)$
J_1	0.1279 (1.639%)	0.0129	0.0220
J_2	0.0627 (0.803%)	0.0172	0.0210

TABLE I: Parameter estimation errors with exciting trajectories generated from the two criteria

Robot mass = 6.047 kg

Unmodeled payload = 1 kg

COM offset induced (m) = $\begin{bmatrix} 0.05 & 0.03 & 0.02 \end{bmatrix}$

Monica Ekal, Rodrigo Ventura, “On Inertial Parameter Estimation of a Free-Flying Robot Grasping An Unknown Object”, Proc. International Conference on Control, Decision and Information Technologies (CoDIT), 2018 [*accepted*]

Conclusions and future work

Conclusions:

- Presented a method to estimate inertial parameters from data
- Preliminary results validate the approach

Future work:

- Improve robustness to noise, saturation, and transients
- Integrate with rendezvous maneuver
- Validate on Astrobee (simulation and on station)