Modeling and Model-Based Control Design/Simulation of Flexible Space Robots using MATLAB™/Simulink™

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Key Points

A. MATLAB package: powerful simulation tool for showcasing R&D engineering challenges for complex mechanical and aerospace systems

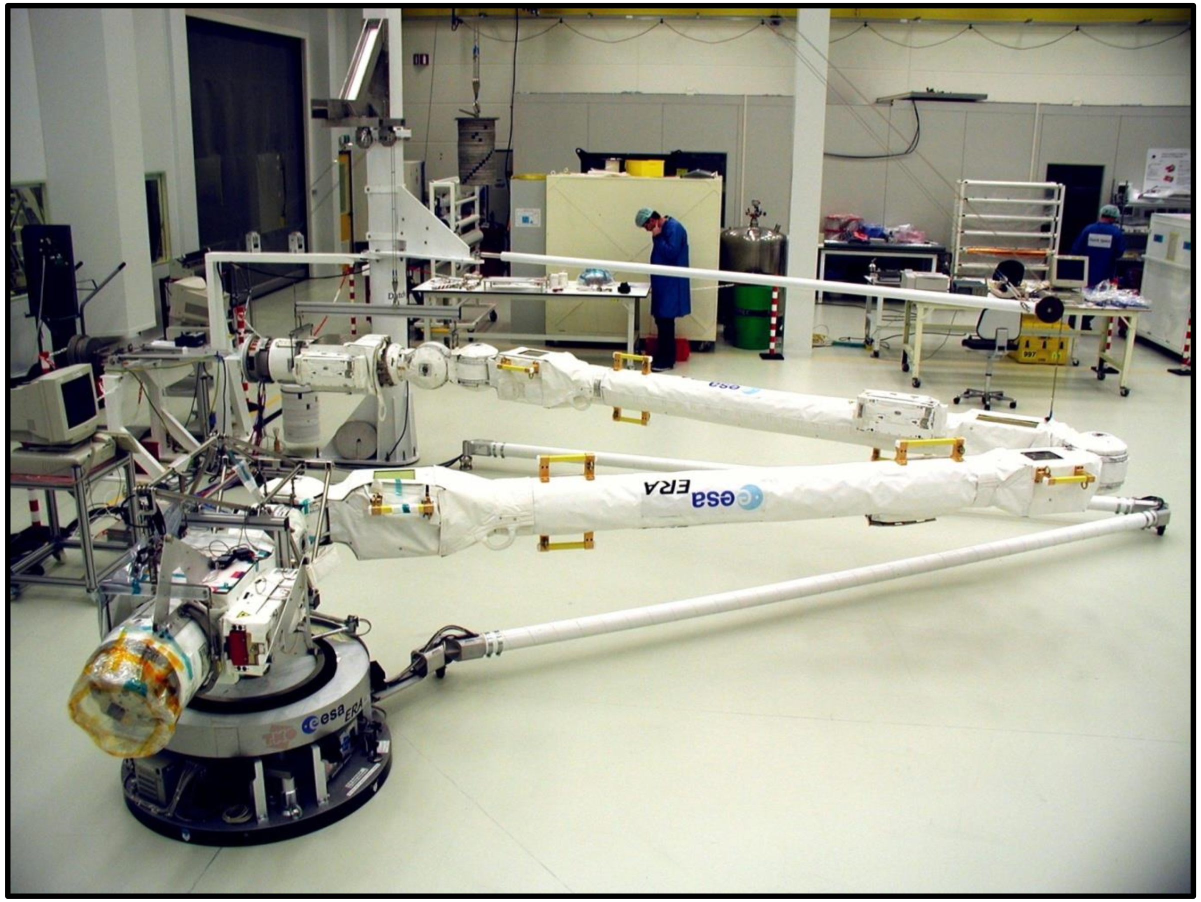
B. Robot position controls in two easy steps:
   1. feedback linearization using MATLAB/Symbolic Math Toolbox™
   2. tracking control design with MATLAB/Control System Toolbox™ e.g. with the PID Tuner App™

C. Rigid/flexible robot motion simulation/visualization: easy with Simulink™ and with Simscape Multibody™

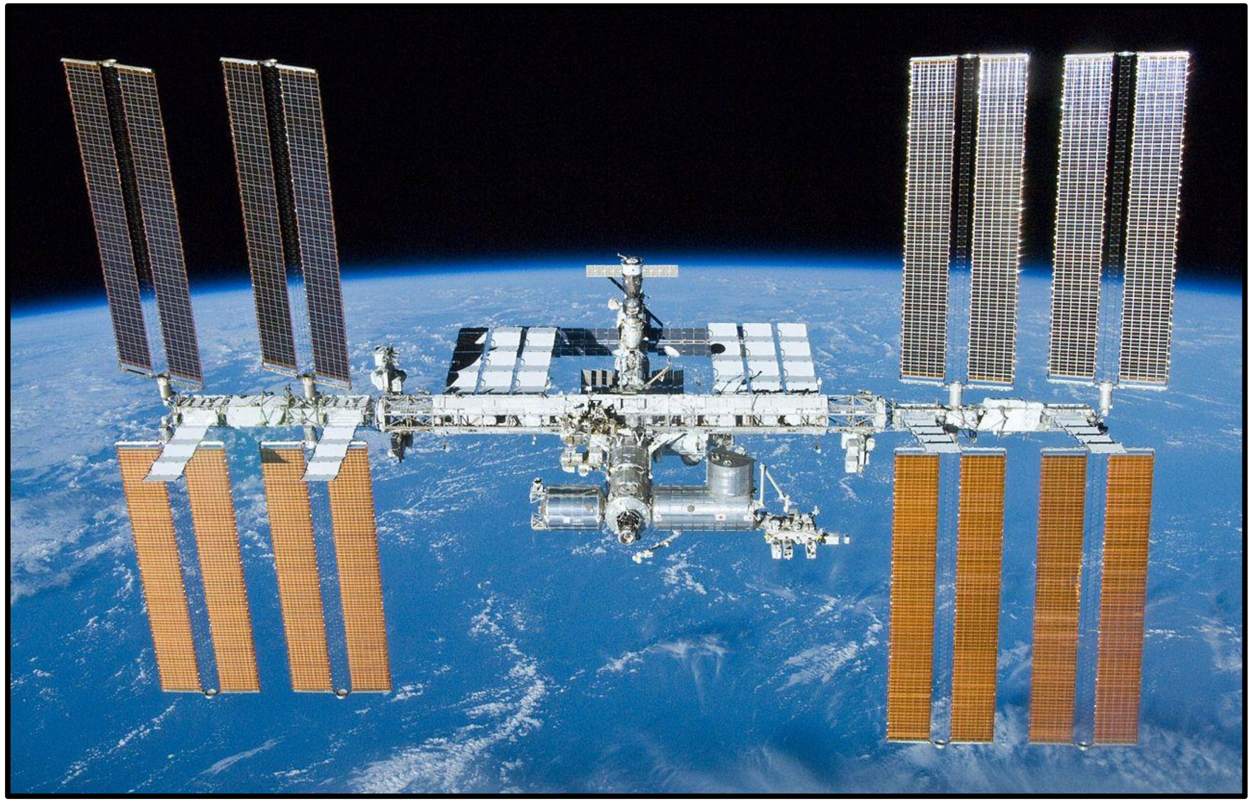
D. Accessible, affordable simulations-based experimentation for data-driven modeling, plus some existing numerical tools (e.g. MATLAB/System Identification Toolbox™)

Considerable reduction of time in assessing research-relevant problems!

Space Robot Manipulators and Large Satellites: What do they have in common?



The European Robotic Arm during ground testing
at the European Space Agency in Noordwijk, The Netherlands



The International Space Station during orbital operation

Space Robot Manipulator Controls: Multidisciplinary Research

System Identification

Hugues Garnier

System Identification for Robotics

Alexandre Janot

Control Engineering

Valentin Pascu

System Identification of Aerospace Structures

Jean-Philippe Noël

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The European Robotic Arm (ERA): Main Characteristics and Specifications

Total length (unloaded): 11.3 m

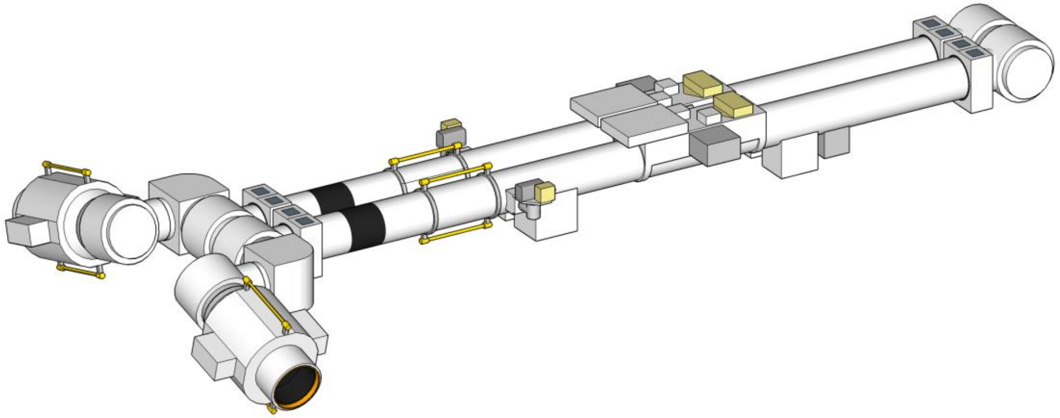
Degrees of freedom: 7

Total mass (unloaded): 630 kg

Maximum load dimensions:3x3x8.1 m

Maximum moveable mass: 8000 kg

Positioning accuracy (closed-loop): 5 mm



Most time-consuming space robotic manipulator design project to date!

Space Robot Manipulators: How do they work and what do they do?

Robot motion control implies a certain designer workflow:

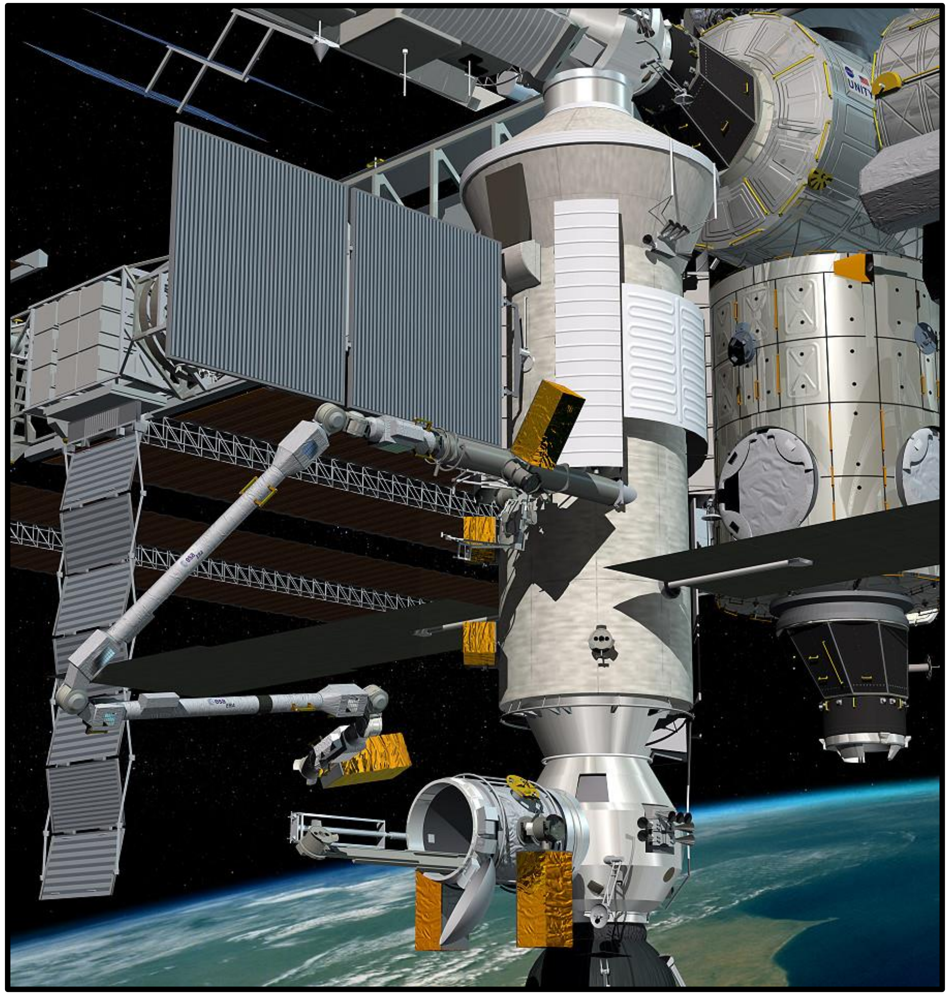
1. *Desired position* (x,y,z) of end-effector
2. *Computed trajectory* (θ) for robot joints
3. *Trajectory tracking* with robot actuators (τ)

closed-loop control → model-based design and simulation → experimental verification → experimental modelling → experimental validation

R1. Models of robot dynamics (attitude, structure, actuators)

R2. Measurement priors (location, SNR, power spectra)

Reduce experimental effort through model-based analysis!



Concept snapshot of the ERA during operation (courtesy of DLR)

Feedback Linearization of Space Robot Dynamics: Basic Theory

Euler-Lagrange equation for *space robot dynamics*:

$$M(\theta)\ddot{\theta}+C(\theta,\dot{\theta})\dot{\theta}=\tau$$

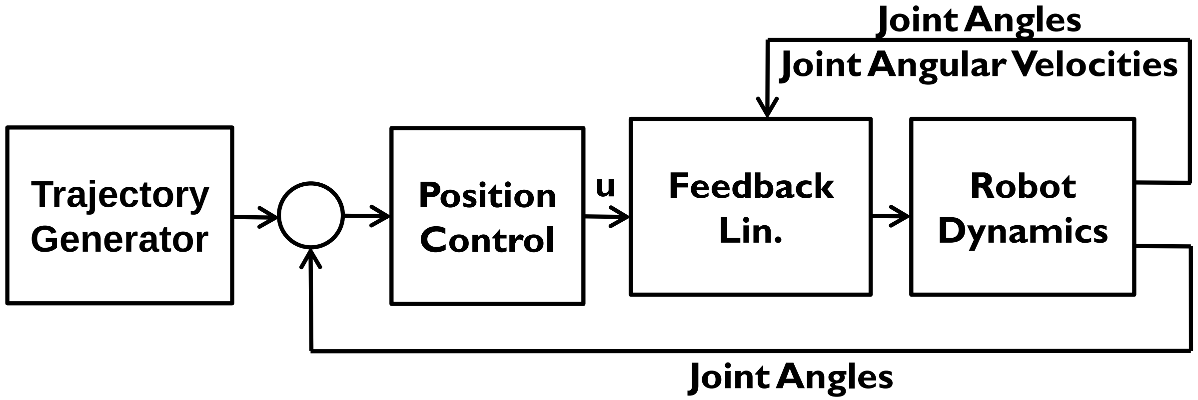
State-space representation (coupled, nonlinear):

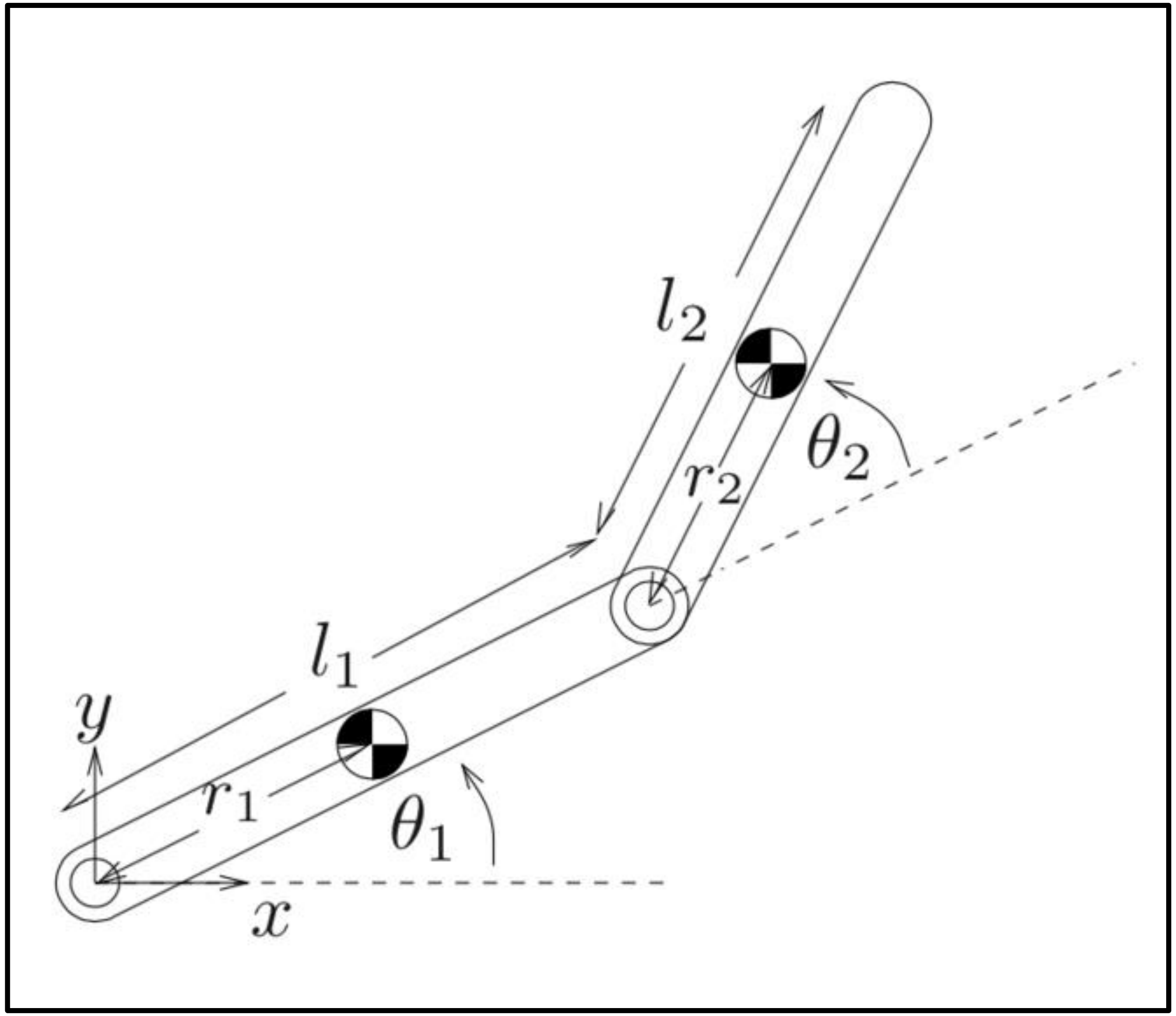
$$\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\end{bmatrix}=\begin{bmatrix}\dot{\theta}\\ -M^{-1}(\theta)C(\theta,\dot{\theta})\dot{\theta}\end{bmatrix}+\begin{bmatrix}0\\ M^{-1}(\theta)\end{bmatrix}\tau$$

Feedback linearization law:

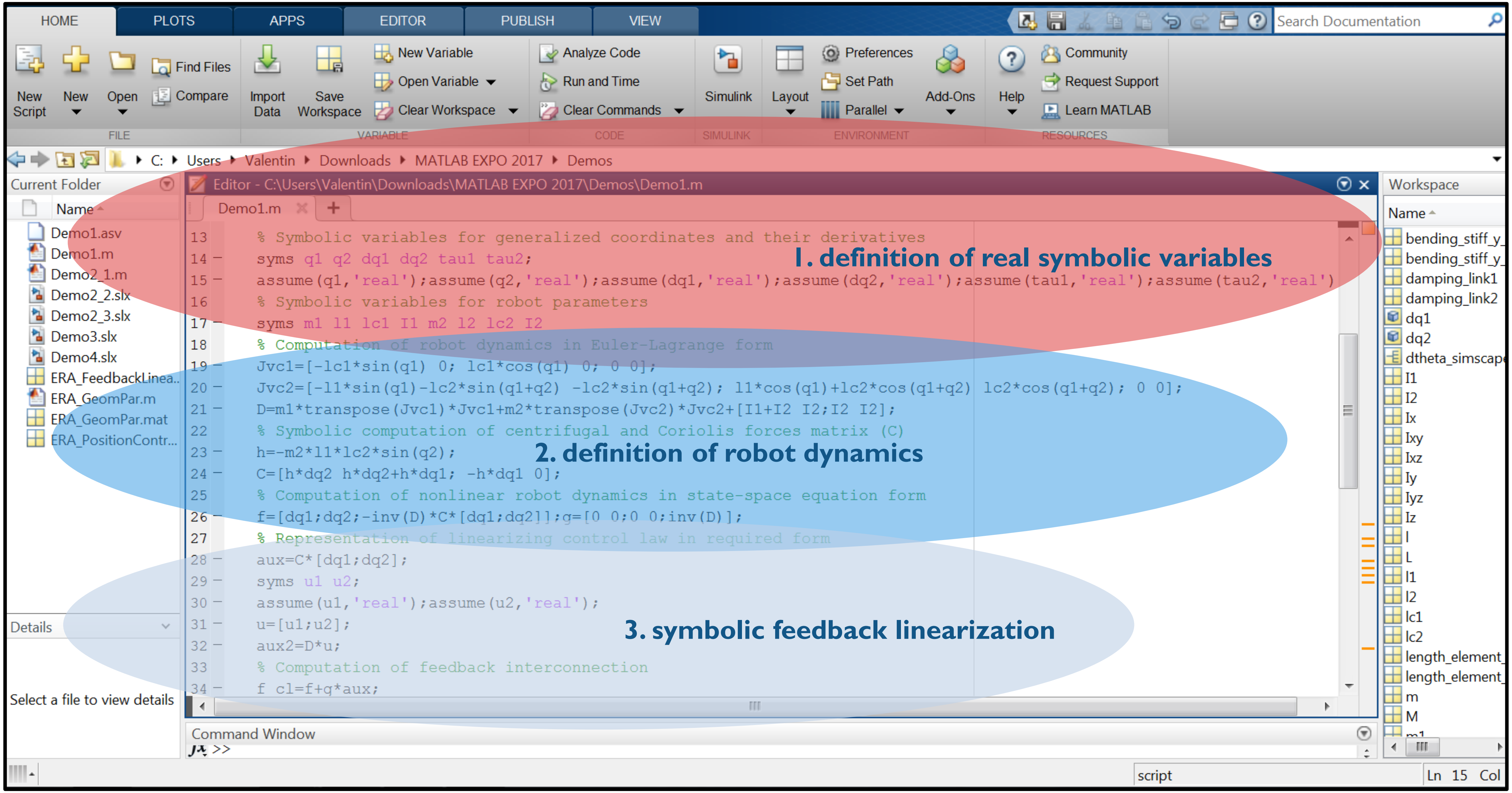
$$\tau=M(\theta)u+C(\theta,\dot{\theta})\dot{\theta}$$

for inner-loop linearization/dynamic decoupling.

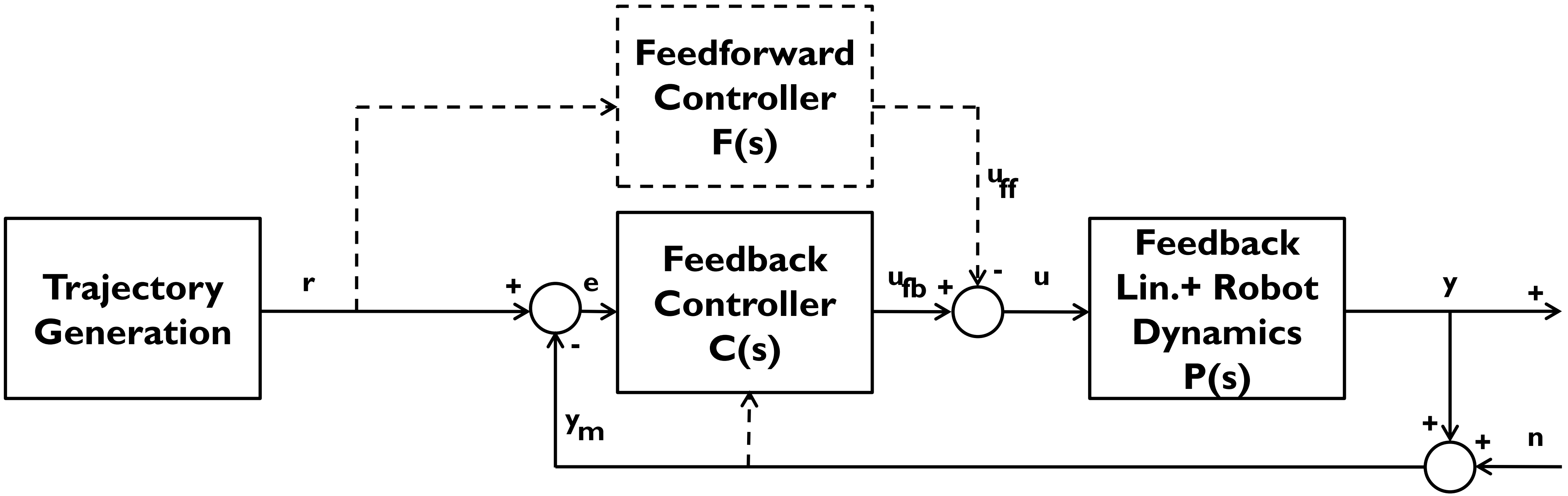




Feedback Linearization of Robot Dynamics using Symbolic Calculations



Tracking Controls: Design and Fundamental Limitations



For *F(s)=0*: standard one degree-of-freedom control loop with the tracking error e:

$$e = S(s)r + T(s)n, \quad S(s) = \frac{I}{I + P(s)C(S)}, \quad T(s) = \frac{P(s)C(s)}{I + P(s)C(s)}$$

Desired: good reference tracking i.e. *S(s)<<I* and good noise rejection i.e. *T(s)<<I*. But *S(s)+T(s)=I!*

Need for choosing a two degree-of-freedom control structure, using reference and output measurement.

European Robotic Arm: Control Requirements and Design Assumptions

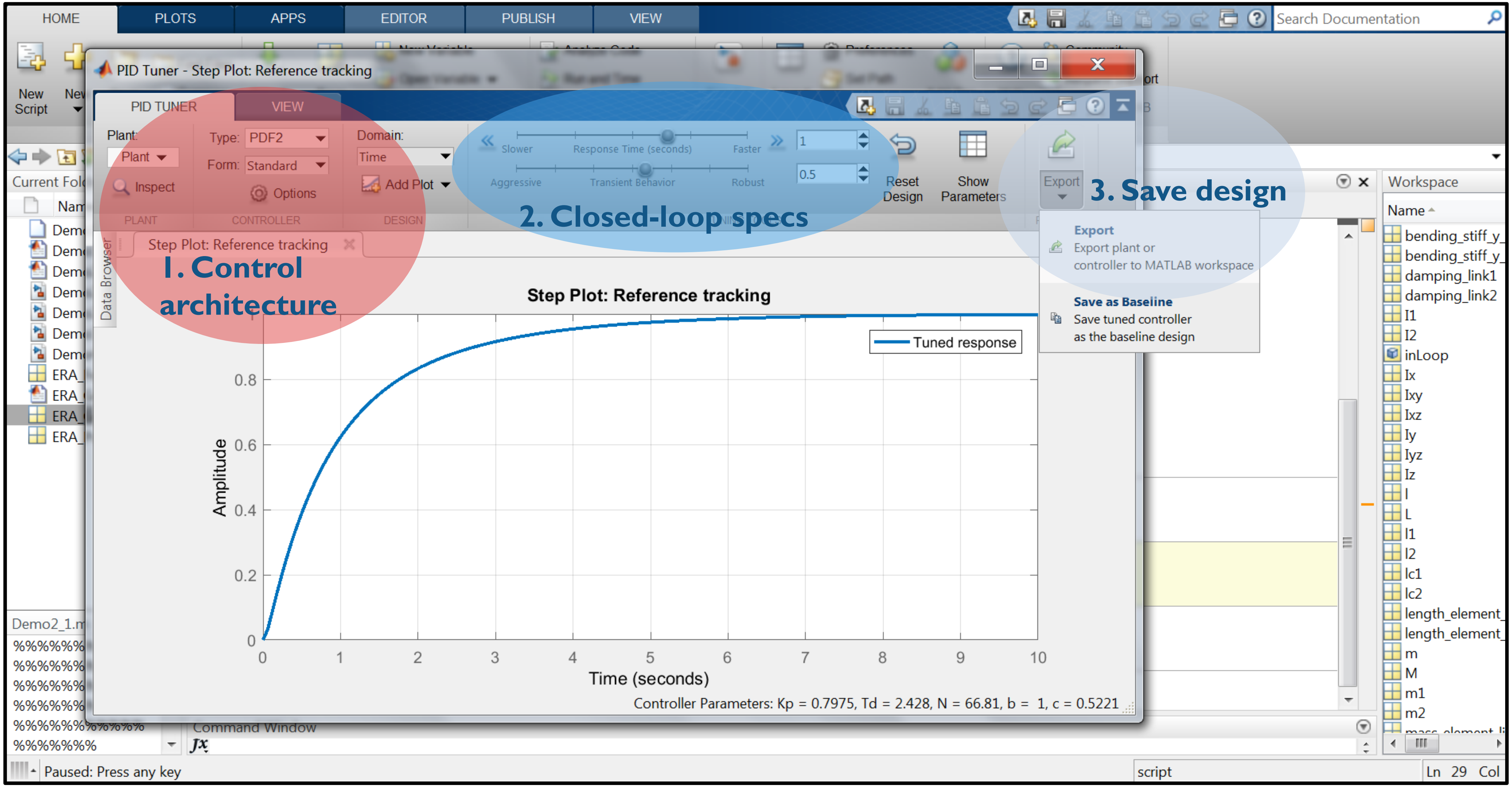
Control task: reference tracking for load positioning (tight control)

Place load from home position e.g. *(x,y)=(11.3 m, 0 m)* **to mission position e.g.** *(x,y)=(4 m, -1.65 m)*

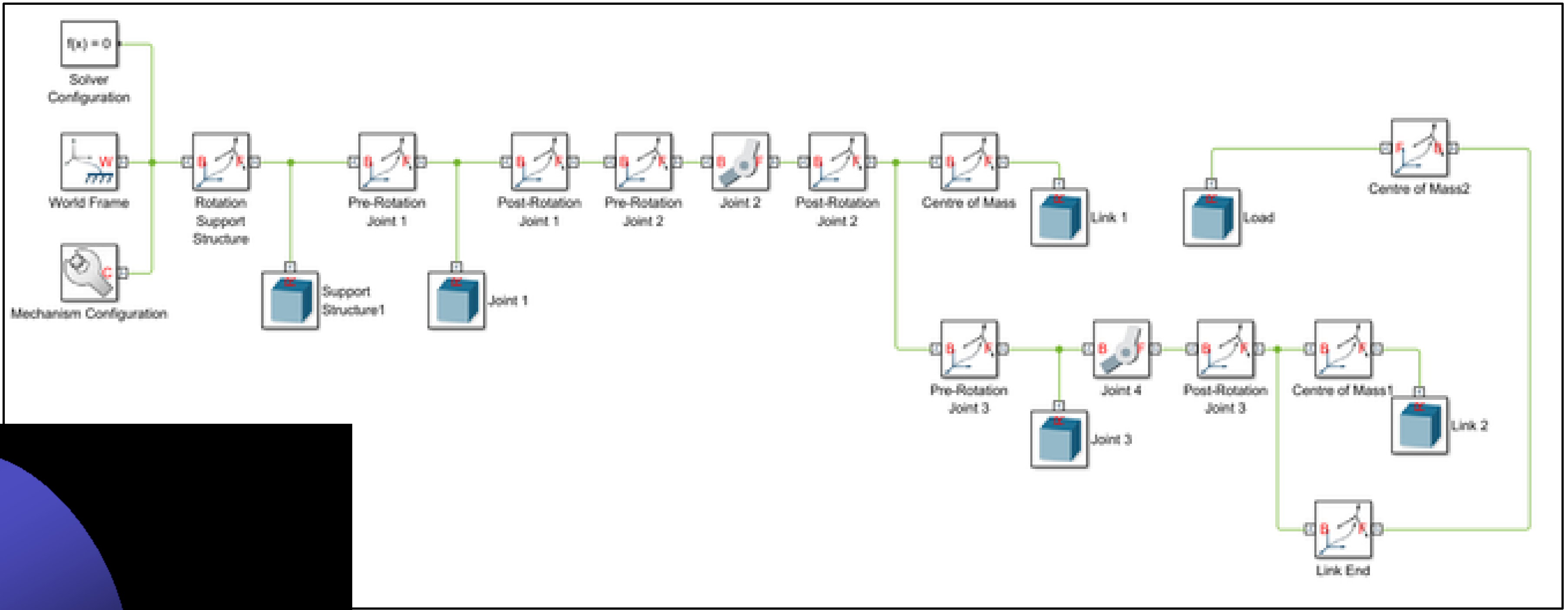
Closed-loop tracking specs:
- steady-state in max. 20 seconds (firm)
- no steady-state error, no overshoot (firm)
- motion decoupling between two links (firm)
- link 1 can move slower, if necessary

Design assumptions:
- reference trajectory available, given in joint space *(0°, 0°)* to *(45°, -135°)*
- one single load with known mass and inertia
- motor torques directly commanded
- rigid body motion only (assumption not met later on)

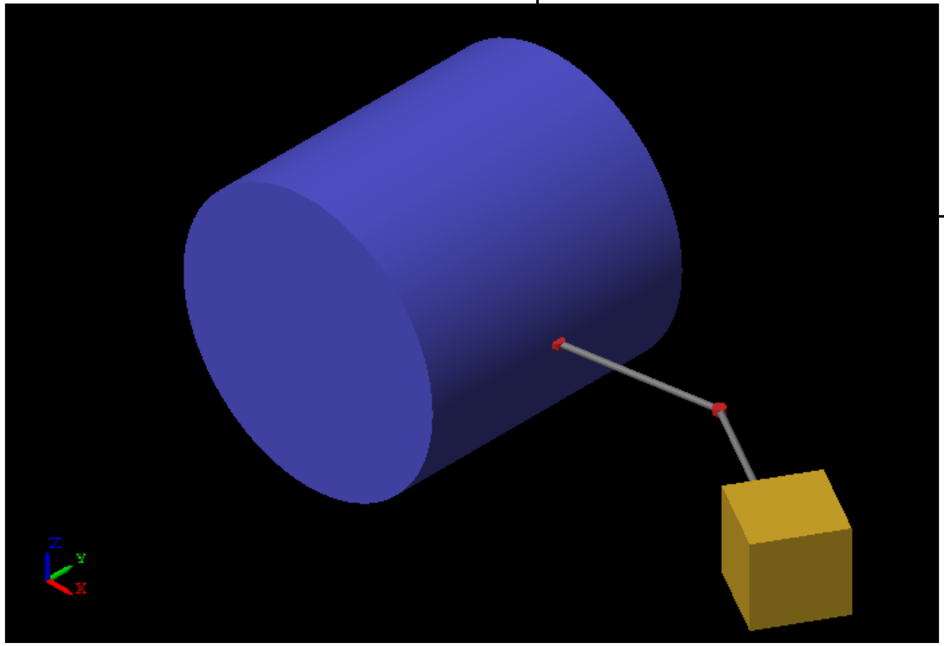
Interactive Decoupled Tracking Control Design using the PID Tuning GUI



Multibody Dynamics Visualization using Simscape Multibody™



Simulated robot motion can also be visualized in MATLAB™ with little extra work!



The control loop can be closed with previously-designed Simulink™-based controllers.

Multibody-based simulations can (in)validate previous steps!

Simulating Vibrations in Flexible Multibody Systems

Mechanical vibrations: mathematically modeled with partial differential equations

For simulation and control design - approximate by ordinary differential equations:

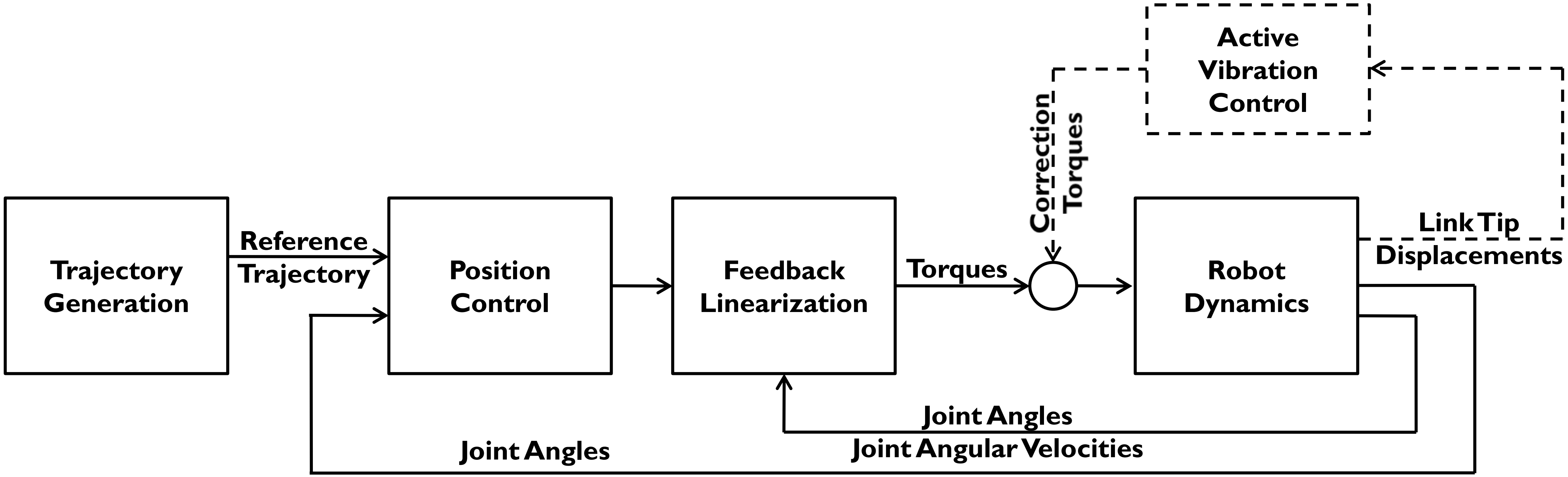
- **empirically, using e.g. lumped parameter modeling**

  + intuitive, simple to implement in multibody modeling software e.g. Simscape Multibody™
  - limited accuracy even for fine grids, can be difficult to tune

- **numerically, using e.g. finite element analysis**

  + accurate method, dedicated software e.g. NASTRAN™, MATLAB/PDE Toolbox™
  - computationally intensive, specifications not always trivial (e.g. meshing)

System Identification for Active Vibration Controls



Main idea: design an additional control loop to *damp the vibrations using correction torques*.

Model of the link flexibility dynamics necessary, best achieved from *experimental data*.

Main issues: 1. choice of point of excitation, design of excitation (the experiment design problem)
2. choice/design of data-driven modeling approach (the identification method problem)
3. model assessment and uncertainty quantification (the model validation problem)

In line with the *control objective* (desired closed-loop performance translates to model properties).

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Concluding Remarks

- Model-based analysis with MATLAB™ and Simulink™/Simscape™ greatly accelerates the research engineering process: extensive, versatile tools (1-2 man-months for ERA)
- Symbolic calculations possible: alternative to *pen and paper* derivations and allow avoidance of errors
- Simple, intuitive linear controller design and analysis of results using the available apps
- Fast prototyping for multibody dynamics (rigid/flexible) using Simulink™/Simscape™
- Algorithms for data-driven modeling available in the MATLAB/System Identification™ toolbox, regularly updated with validated novel algorithms

Related Works and Background Material

Vibration suppression beyond flexible robots – an ubiquitous control challenge:

- improved aeroelastic response of aerospace structures (aircraft, wind turbines)
- improved drivetrain damping (automotive, wind turbines)
- fatigue reduction in large base-fixed structures (wind turbines, civil structures)

Some background material for further reading:

[1] M.W. Spong, S. Hutchinson and M. Vidyasagar – Robot Modeling and Control, Wiley, 2006.

[2] H. Cruijsen et. al – The European Robotic Arm: A High-Performance Mechanism Finally on its Way to Space, 42nd Aerospace Mechanics Symposium, NASA Goddard Space Flight Center, 2014.

[3] S. Skogestad and I. Postlethwaite – Multivariable Feedback Control: Analysis and Design, Wiley, 2005.

[4] J.-N. Juang – Identification and Control of Mechanical Systems, Cambridge University Press, 2001.

Thank you for your attention!