DESIGN AND PARAMETER IDENTIFICATION BY LABORATORY EXPERIMENTS OF A PROTOTYPE MODULAR ROBOTIC ARM FOR ORBITING SPACECRAFT APPLICATIONS.

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Outline

- Motivation
- Modular Robotic Manipulator
- Kinematic and dynamic calibration procedure
- Workspace and Manipulability

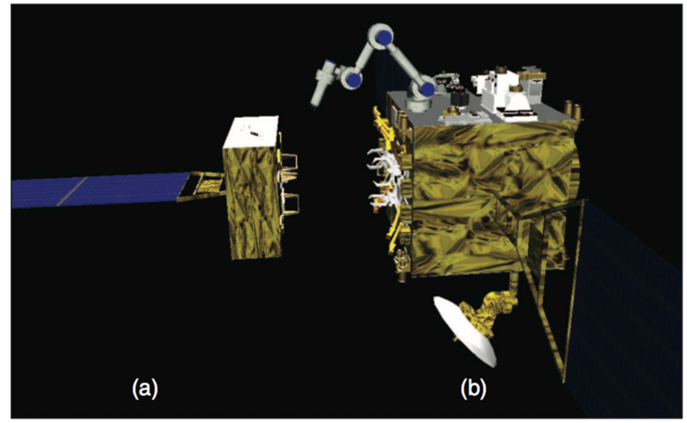
SPACECRAFT ROBOTICS LABORATORY

Motivation

Motivation:

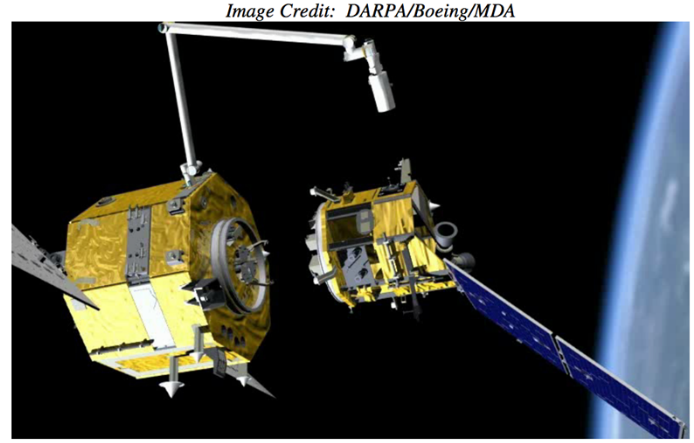
- Space robotics are useful to many missions (servicing, ADR, …).
- Complex dynamics with added base-manipulator coupling.
- Trend towards smaller spacecraft.

<u>Need for a test bed where to evaluate GNC approaches and rehearse mission scenarios.</u>



ETS-VII (1997)

Image Credit: DARPA/Boeing/MDA



DARPA's orbital express (2007)

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Dynamic HIL Testing of S/C Maneuvering

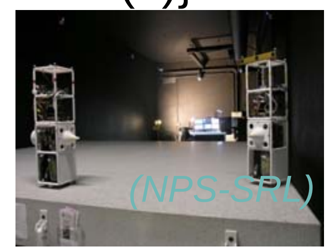
Roto-translational maneuvering

RT 1) Floating in neutral buoyancy pools

per vehicle: {dof: 6, motion type: SE(3), residual dist.: ~10^{-1} g}

RT 2) Floating over horizontal surfaces via flat air-bearing

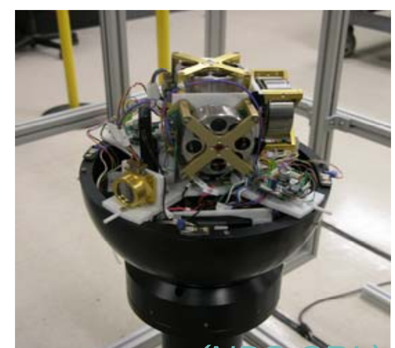
per vehicle: {typical: 3dof, R^2x R,~10^{-3} g}, {also possible: 5dof, R^2x SO(3)}



Rotational (attitude) maneuvering

Floating spherical air-bearing,
a.k.a. dynamic three axis simulator

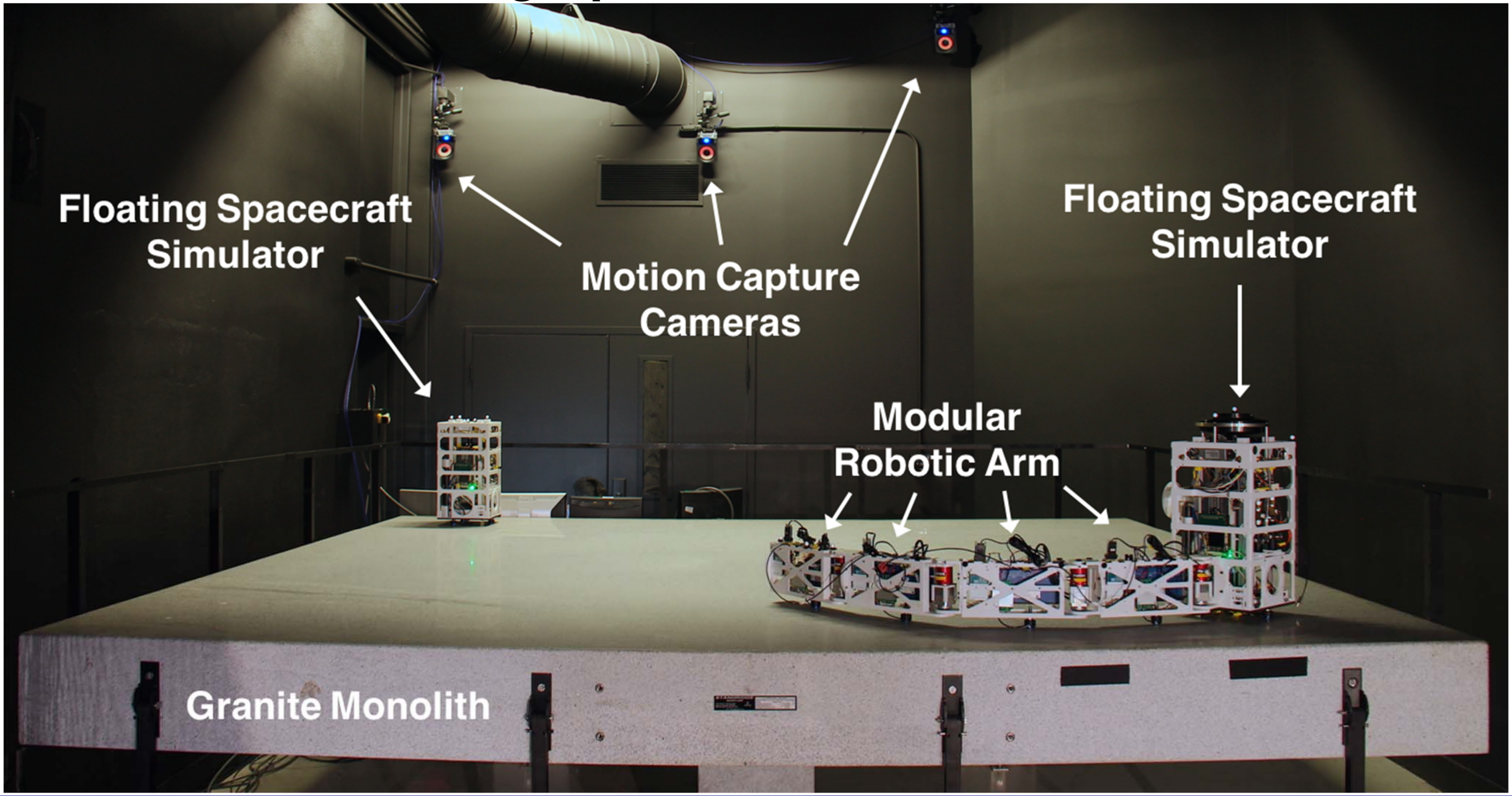
{3dof, SO(3), ~10^{-3} Nm}



Application: experimental V&V of:
RT GN&C algorithms, MB & contact dynamic model, actuators/sensors H/W and S/W (& university education!)

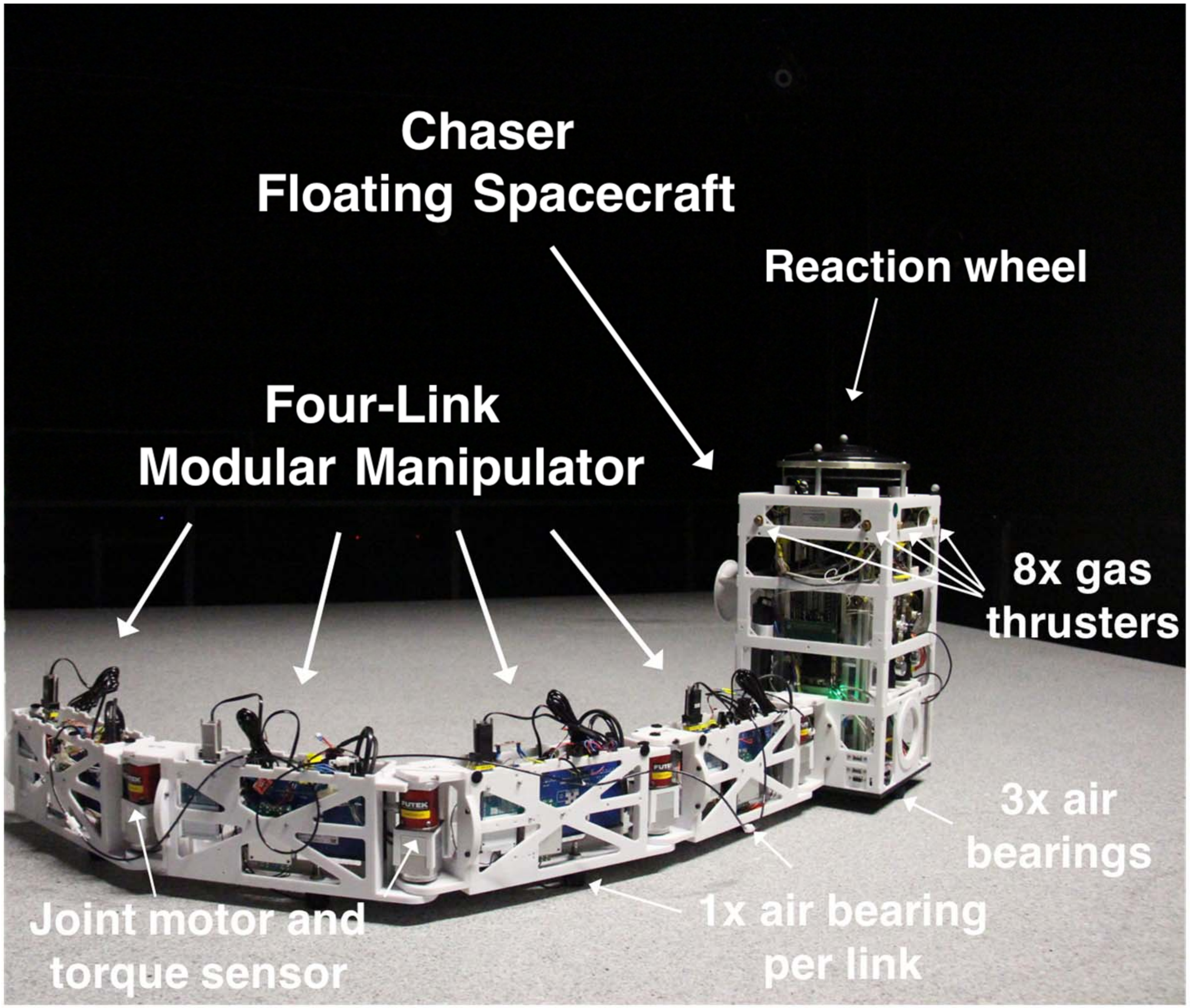
NAVAL POSTGRADUATE SCHOOL

NPS- Floating Spacecraft Simulator Test Bed



Modular Robotic Arm Overview

Overview:



Modular Manipulator Architecture and Design (1/2)

- Completely **modular design**.
  - Combination of Harmonic drive motor, encoder and driver (max of 1.8 Nm).
  - **Torque sensor** (enables compliant control).
  - Power system (battery and power regulator)
  - Microcontroller and **TCP/UDP communications**.
  - 3D printed structure.

Motor + encoder

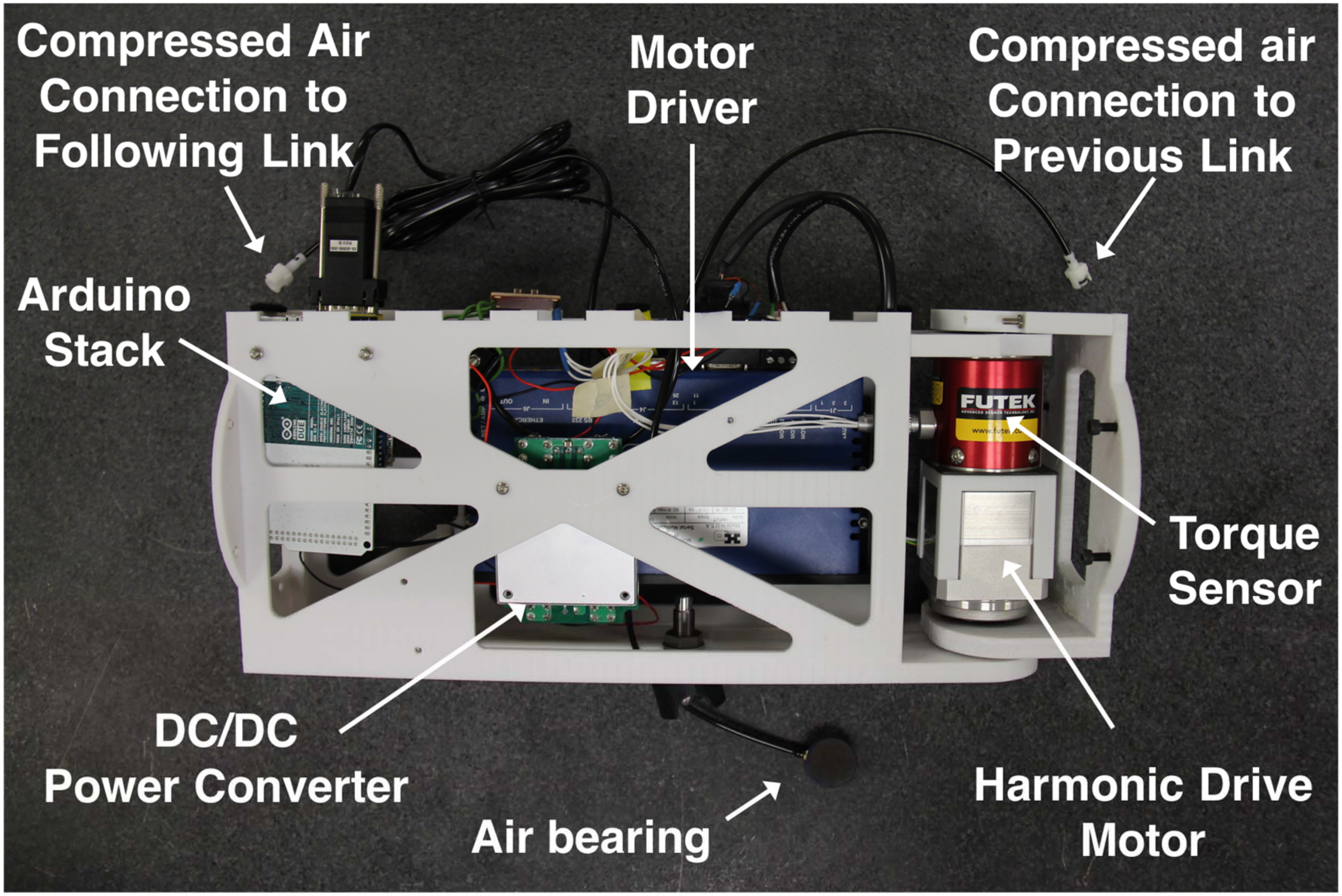
Driver

Torque Sensor

Power

Microcontroller & Communications

Modular Manipulator Architecture and Design (2/2)



Parameter Identification (1/4)

Kinematic Calibration → Batch Least Square

Kinematic models determines end-effector location

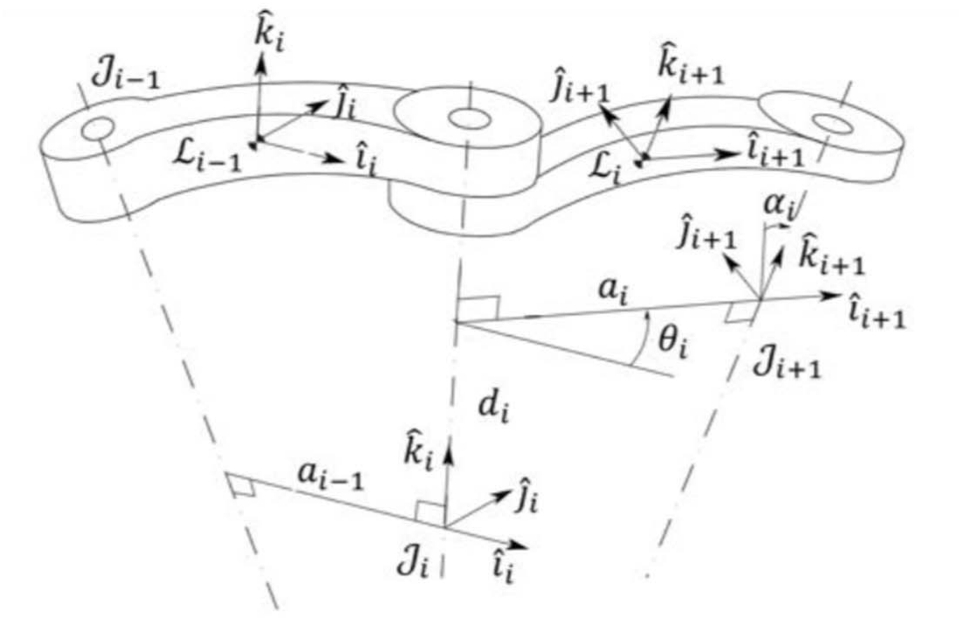
$$x_{EE} = k\left(\theta, \theta_0, a, x_{\mathcal{BJ}_1}, y_{\mathcal{BJ}_1}, \theta_{\mathcal{BJ}_1}\right)$$

Batch Least Square

$$\Delta x_{EE} = \Phi_k \Delta \xi_k$$

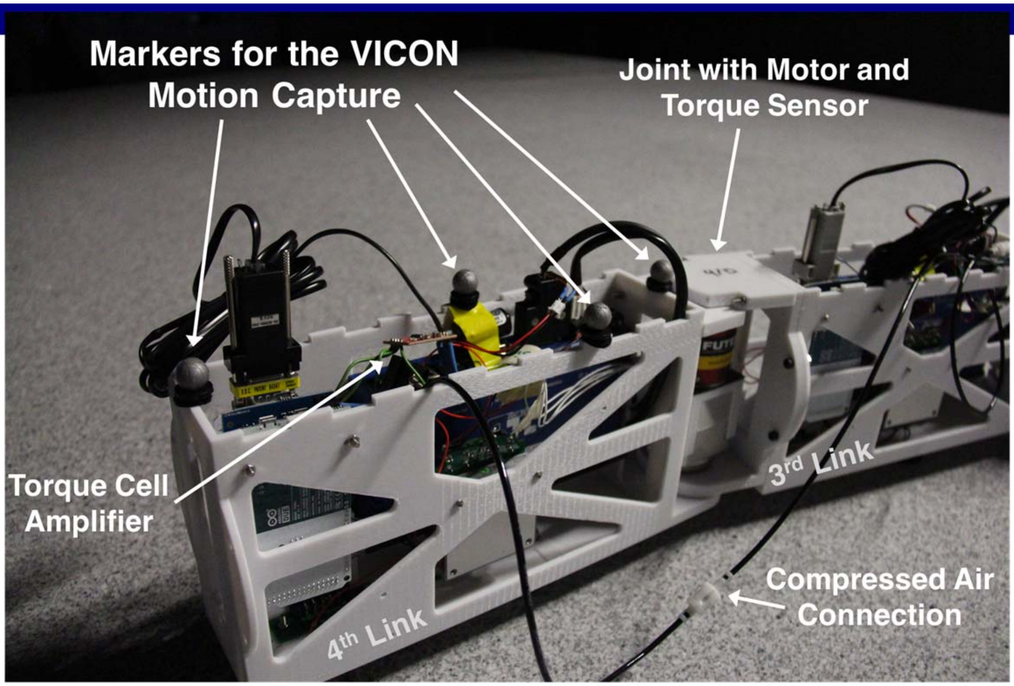
$$\Delta \xi_k = \left(\Phi_k^T \Phi_k\right)^{-1} \Phi_k^T \Delta x_{EE}$$

$$\Phi_k = \begin{bmatrix} \frac{\partial k}{\partial \theta_0}_1 & \frac{\partial k}{\partial a}_1 & \frac{\partial k}{\partial x_{\mathcal{BJ}_1}}_1 & \frac{\partial k}{\partial y_{\mathcal{BJ}_1}}_1 & \frac{\partial k}{\partial \theta_{\mathcal{BJ}_1}}_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{\partial k}{\partial \theta_0}_s & \frac{\partial k}{\partial a}_s & \frac{\partial k}{\partial x_{\mathcal{BJ}_1}}_s & \frac{\partial k}{\partial y_{\mathcal{BJ}_1}}_s & \frac{\partial k}{\partial \theta_{\mathcal{BJ}_1}}_s \end{bmatrix}$$



Denavit-Hartenberg parameters

Parameter Identification (2/4)



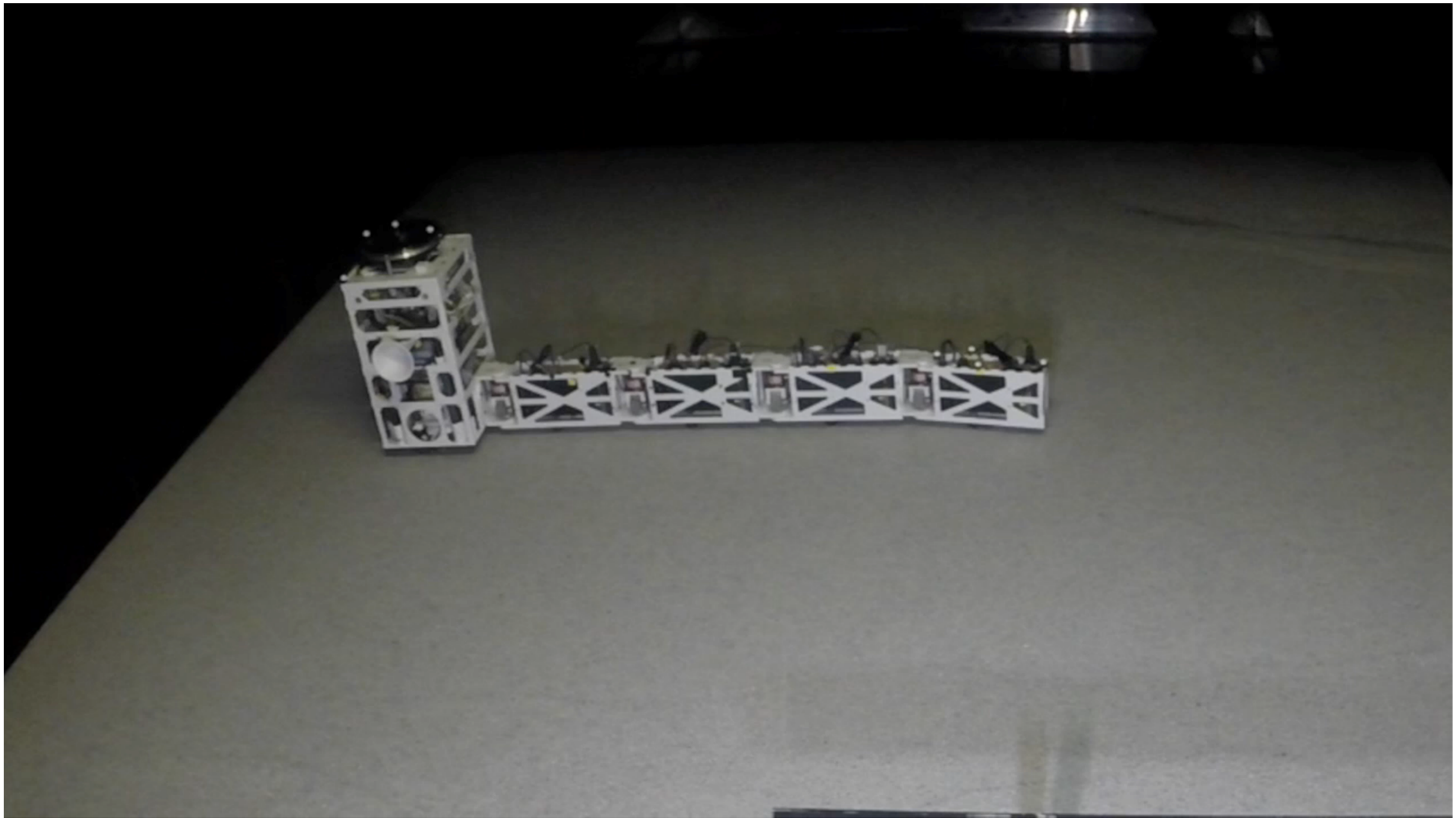
Experimental setup

Kinematic calibration results

	Link 1	Link 2	Link 3	Link 4
a_i [m]	0.3825	0.3825	0.3825	0.3351
θ_{0_i} [degrees]	0	5.801	-3.402	-1.391

Parameters	Value
$x_{\mathcal{B}\mathcal{J}_1}$ [m]	0.2058
$y_{\mathcal{B}\mathcal{J}_1}$ [m]	0.0155
$\theta_{\mathcal{B}\mathcal{J}_1}$ [degrees]	18.211

Parameter Identification (3/4)



Parameter Identification (4/4)

Dynamic calibration:

Using a similar procedure but observing the reaction of the base, the dynamic parameters (i.e. Inertia) can be estimated.

$$q_{0_f} = d\left(b, m, I, \theta\left(t\right)\right)$$

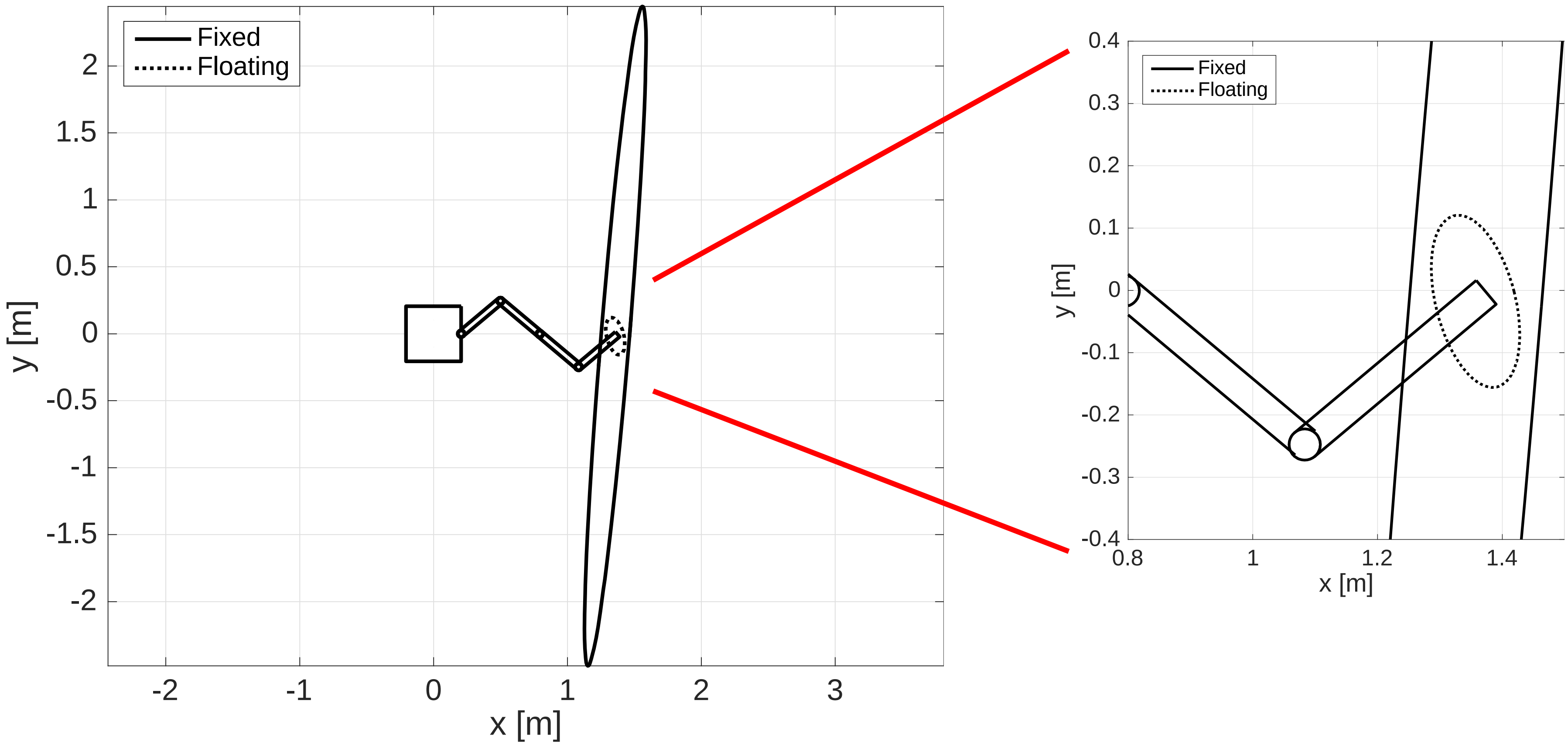
$$\Delta \xi_d = \left(\Phi_d^T \Phi_d\right)^{-1} \Phi_d^T \Delta q_{0_f}$$

$$\Delta q_{0_f} = \hat{q}_{0_f} - \tilde{q}_{0_f}$$

$$\Phi_d = \begin{bmatrix} \frac{\partial d}{\partial b}_1 & \frac{\partial d}{\partial m}_1 & \frac{\partial d}{\partial I}_1 \\ \vdots & \vdots & \vdots \\ \frac{\partial d}{\partial b}_s & \frac{\partial d}{\partial m}_s & \frac{\partial d}{\partial I}_s \end{bmatrix}$$

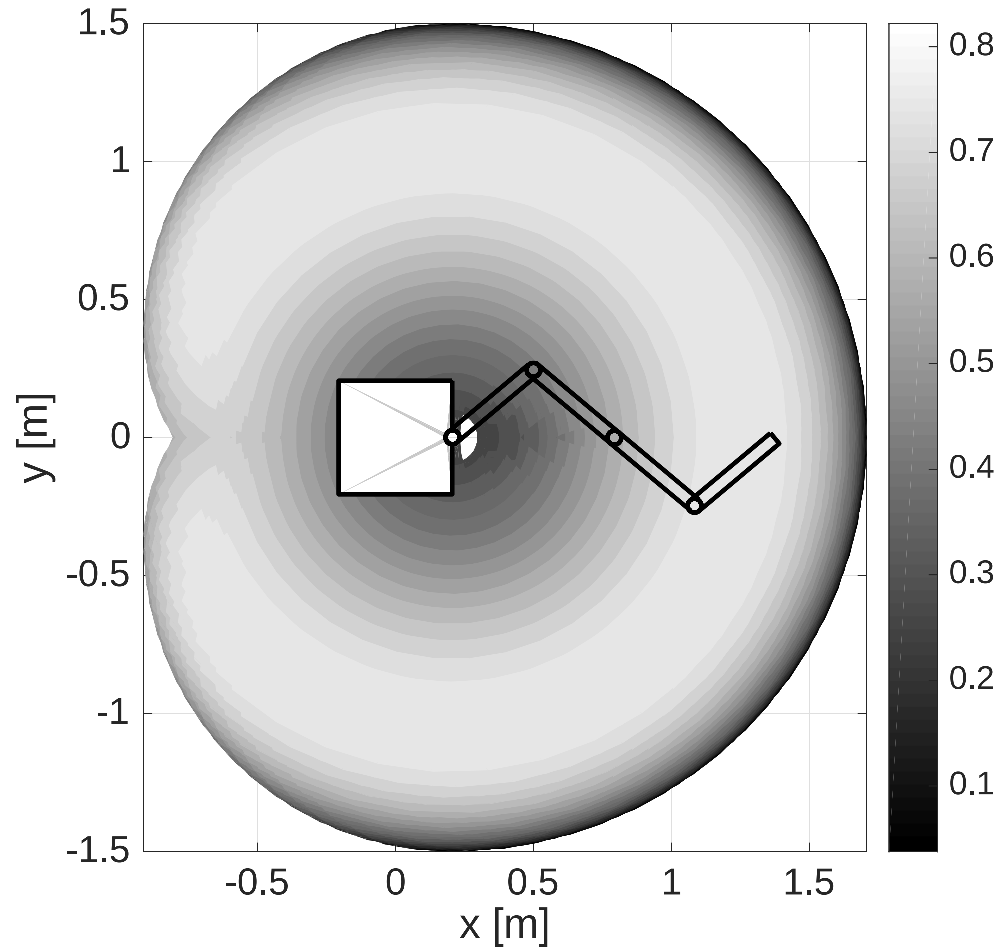
		Link 1	Link 2	Link 3	Link 4
Measured →	m_i [kg]	2.88	2.88	2.88	2.88
Assumed →	b_i [m]	0.191	0.191	0.191	0.168
	I_i [kg m^2]	0.034	0.034	0.034	0.034

Kinematic Manipulability analysis



Fixed-base workspace analysis

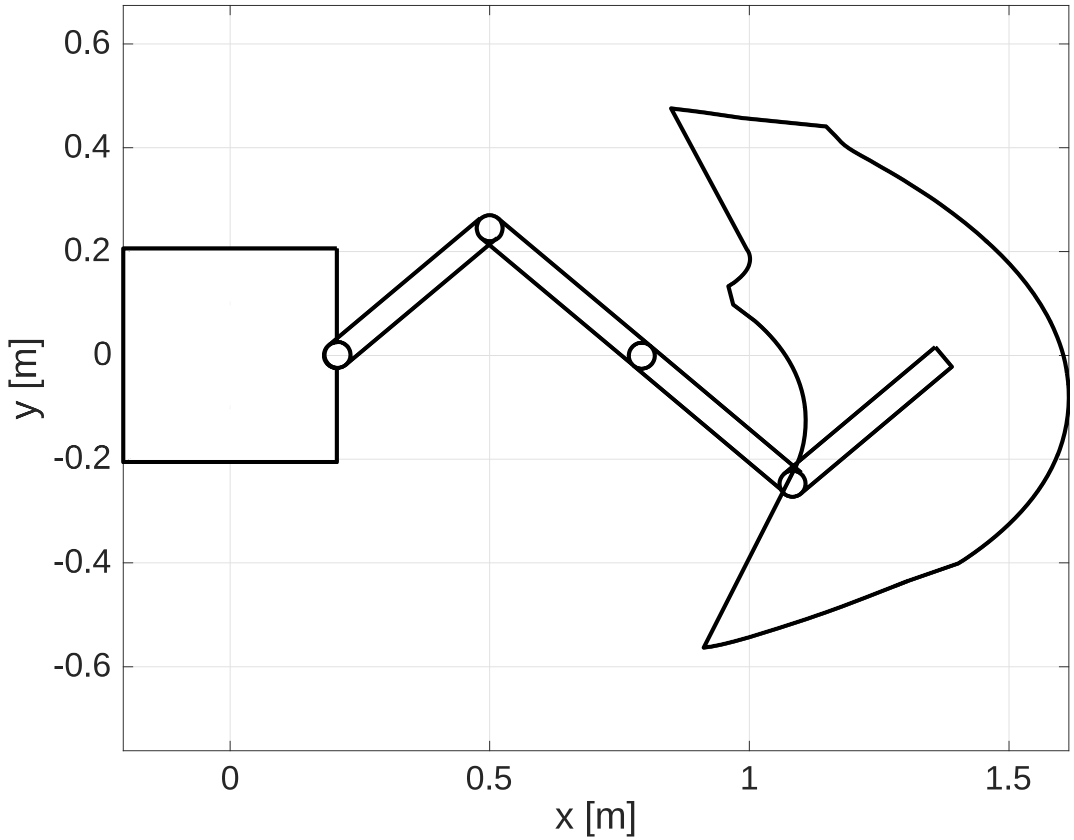
- Area that can be reached with a fixed-base.
- Kinematic manipulability measure is proportional to the ellipse area.



Floating-base workspace analysis

Straight-Path Workspace

- Move the end-effector in a straight path until a dynamic singularity or a joint limit is encountered.



Maximum reachable workspace → Radius of 1.3 m

Conclusions

1) A four link modular robotic arm has been design, assembled and commissioned to be used in the NPS-FSS T/B.

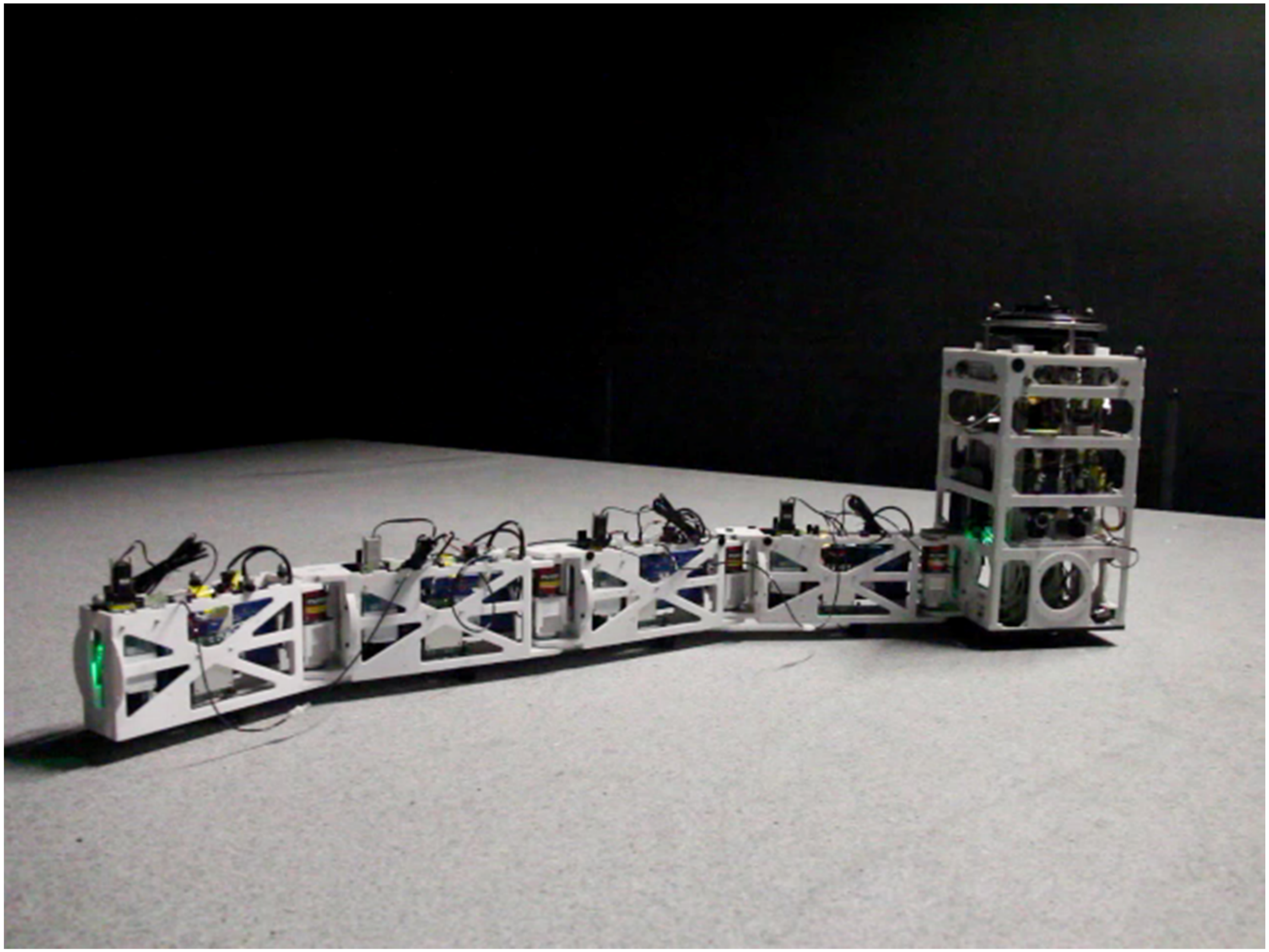
2) Modular design allows for quick re-configuration and incremental upgrades.

3) Kinematic and dynamic calibration performed.

4) New approach to dynamic calibration by observing the base-reaction has been proposed and tested.

Modular Manipulator in action

Video:



Thank you for your attention.

Questions?

Design and parameter identification by laboratory experiments of a prototype modular robotic arm for orbiting spacecraft applications

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