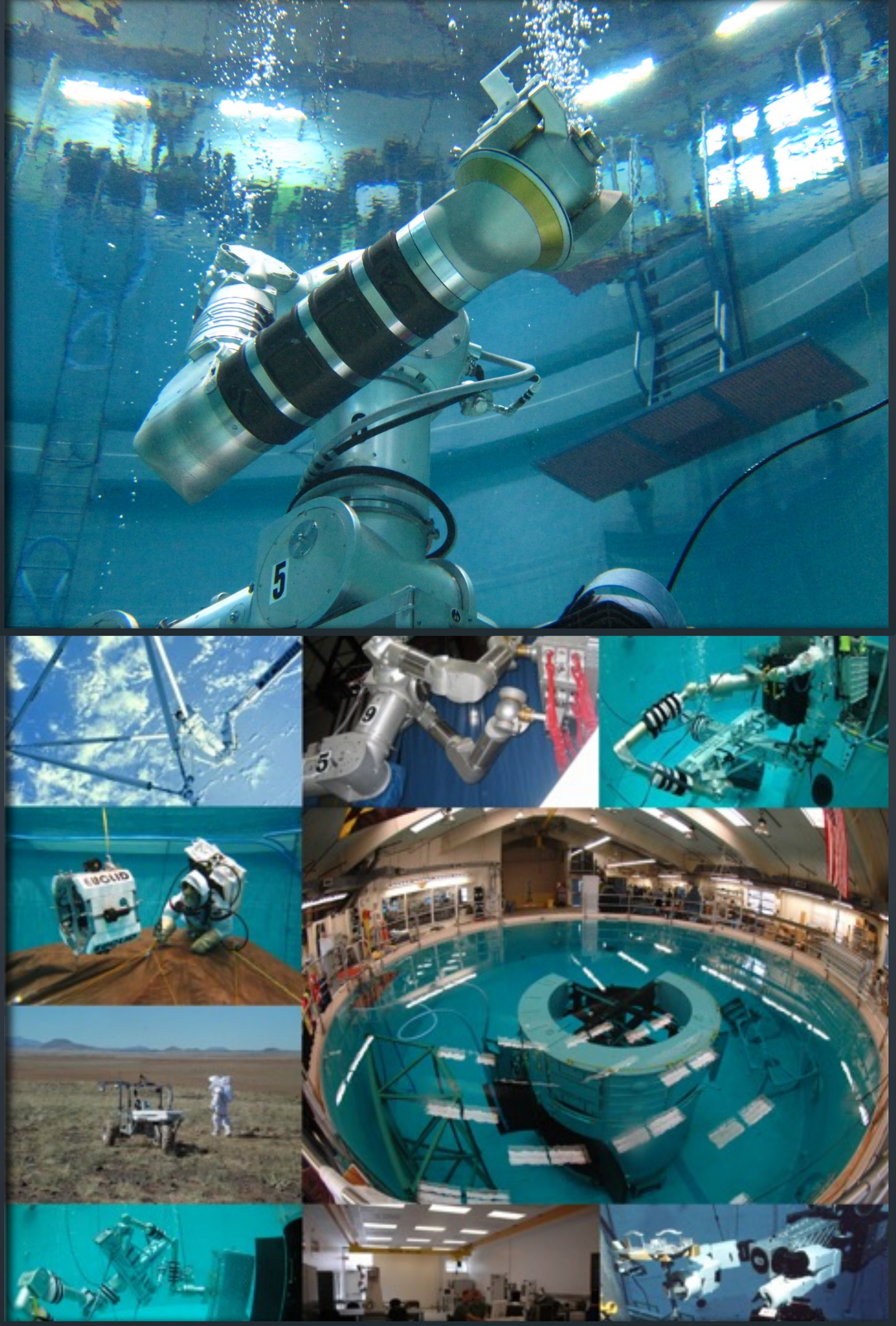

ROBOTIC SERVICING AND CONSTRUCTION IN THE FACE OF UNKNOWN DYNAMICS

Identification of dynamics parameters to aid in robotic servicing and control

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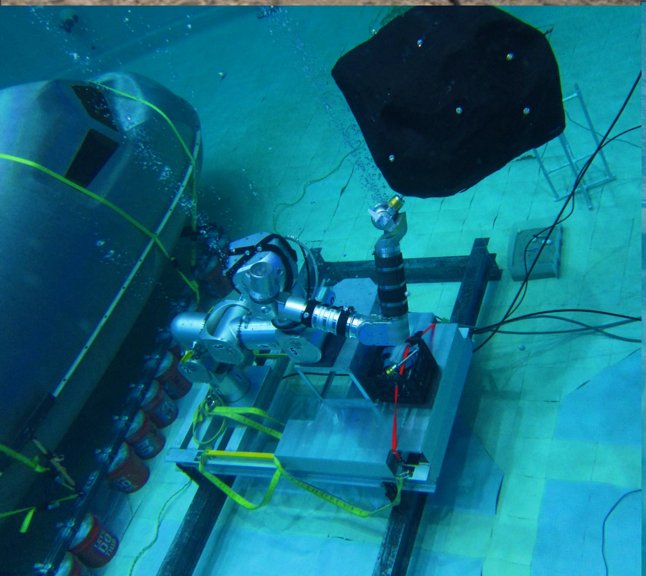
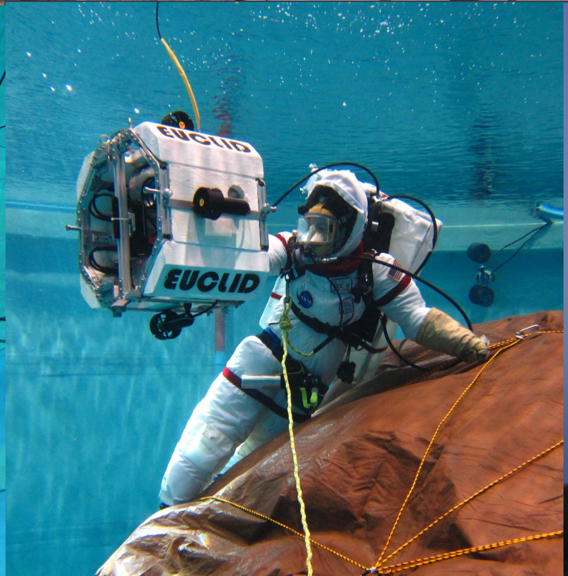
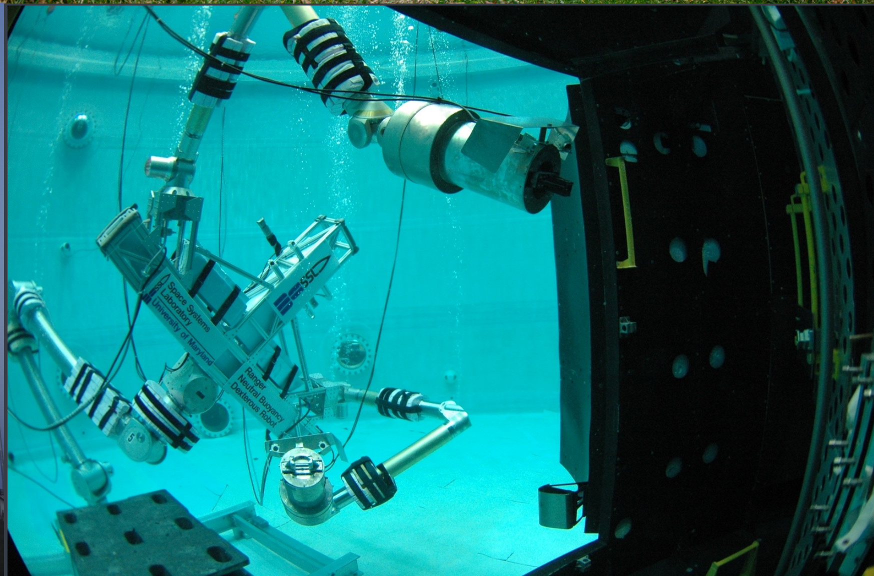
University of Maryland, College Park

SPACE SYSTEMS LABORATORY







DYNAMICS PARAMETER IDENTIFICATION OF PAYLOADS FOR SERVICING AND ONWARDS

Example Applications:

- Orbital debris removal
  - Spent rockets
  - Dead satellites
- Satellite servicing with small spacecraft
  - “Tugboat” maneuvering of satellite
  - Movement and delivery of mission extension packages for satellites
  - End-Of-Life deorbit operations
- Robotic assembly and construction
  - Future, large optic, observatory construction
  - Orbital outposts

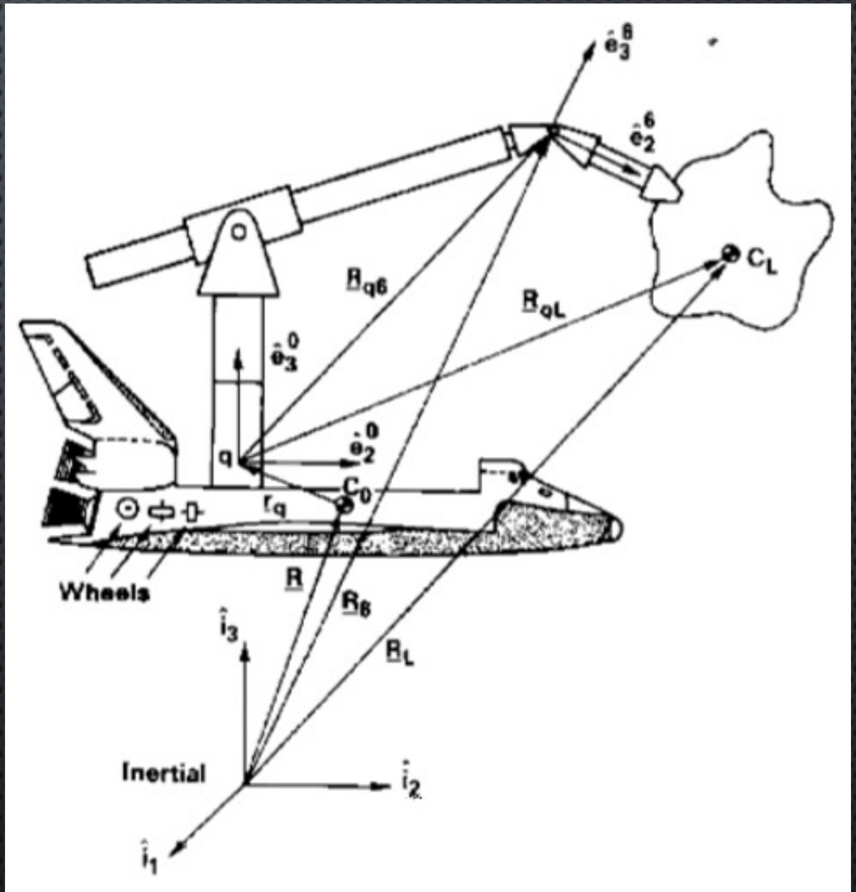
PRIOR WORK

Coupled dynamics of a manipulator and spacecraft system

- Reaction Moment Compensation [1]
- Base Parameters of a Manipulator Dynamic Model [2]
- Generalized Jacobian Matrix [3]

Dynamics parameter identification

- Estimators and Observers [4-6]
- Inverse and Direct Dynamic Models [7-11]
    - Inverse Dynamic Identification Model

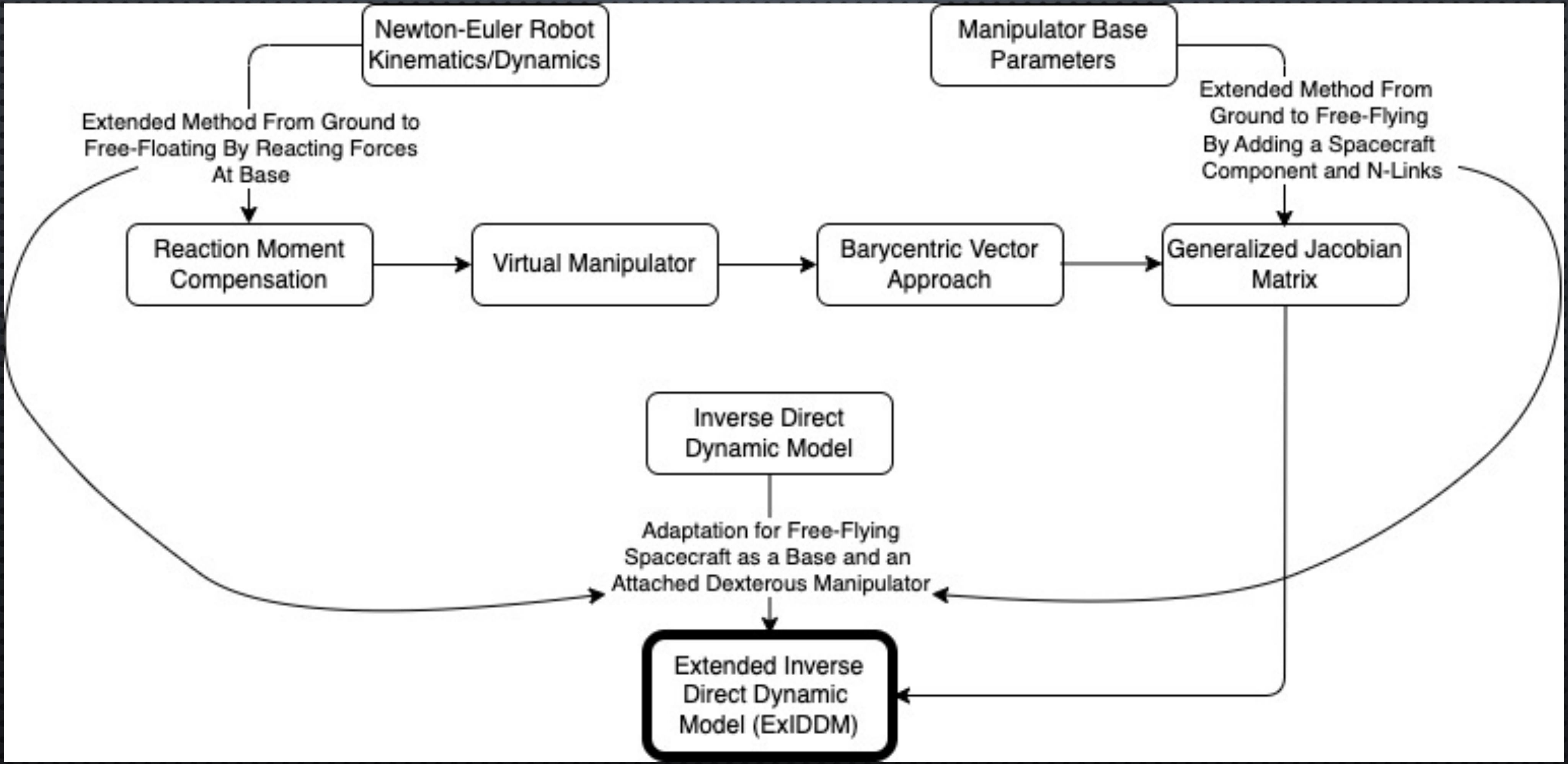


Satellite-mounted robot showing reaction wheels and inertial coordinate frames [1]

LIMITATIONS OF PRIOR WORK

- Much of the work is for free-floating systems limiting the ability to translate
- Assumption that accurate estimates of dynamics parameters for the grappled payload are known a priori for coupled dynamics models
- Existing dynamics parameter identification methods assume the manipulator is rigidly attached to the ground
  - Or they completely ignore identification altogether [12]

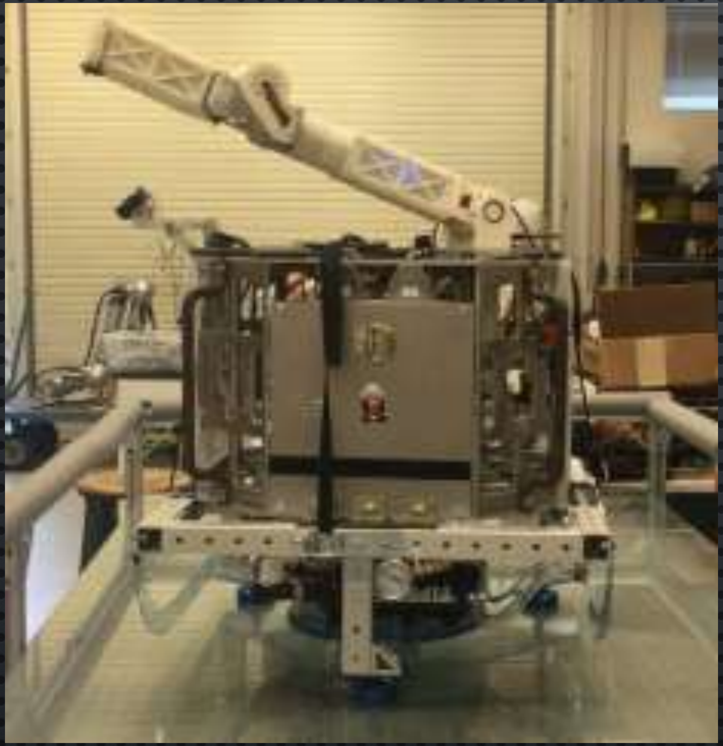
INSPIRATION FOR A SOLUTION



CONTRIBUTIONS

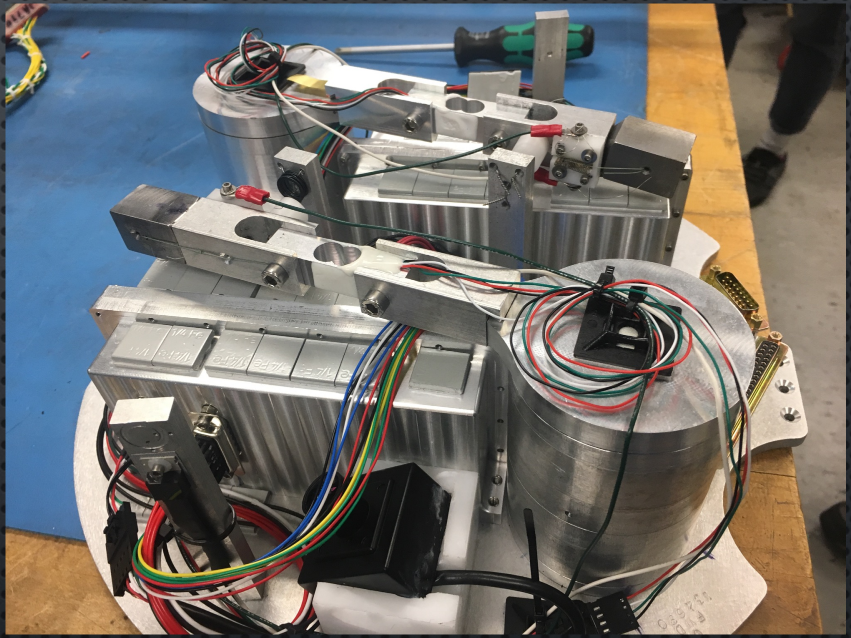
- Theoretical method to extend the Inverse Direct Dynamics Model (IDDM) to include a robotic manipulator and a free-floating spacecraft
- Experimental results for calculation of the base inertial parameters of a payload attached to a spacecraft based robotic manipulator using the Extended Inverse Direct Dynamics Model (ExIDDM)
- Demonstration of the ExIDDM methods following the same calculation methods as the IDDM, e.g. the Inverse Dynamics Identification Model (IDIM)

EXPERIMENTAL VERIFICATION



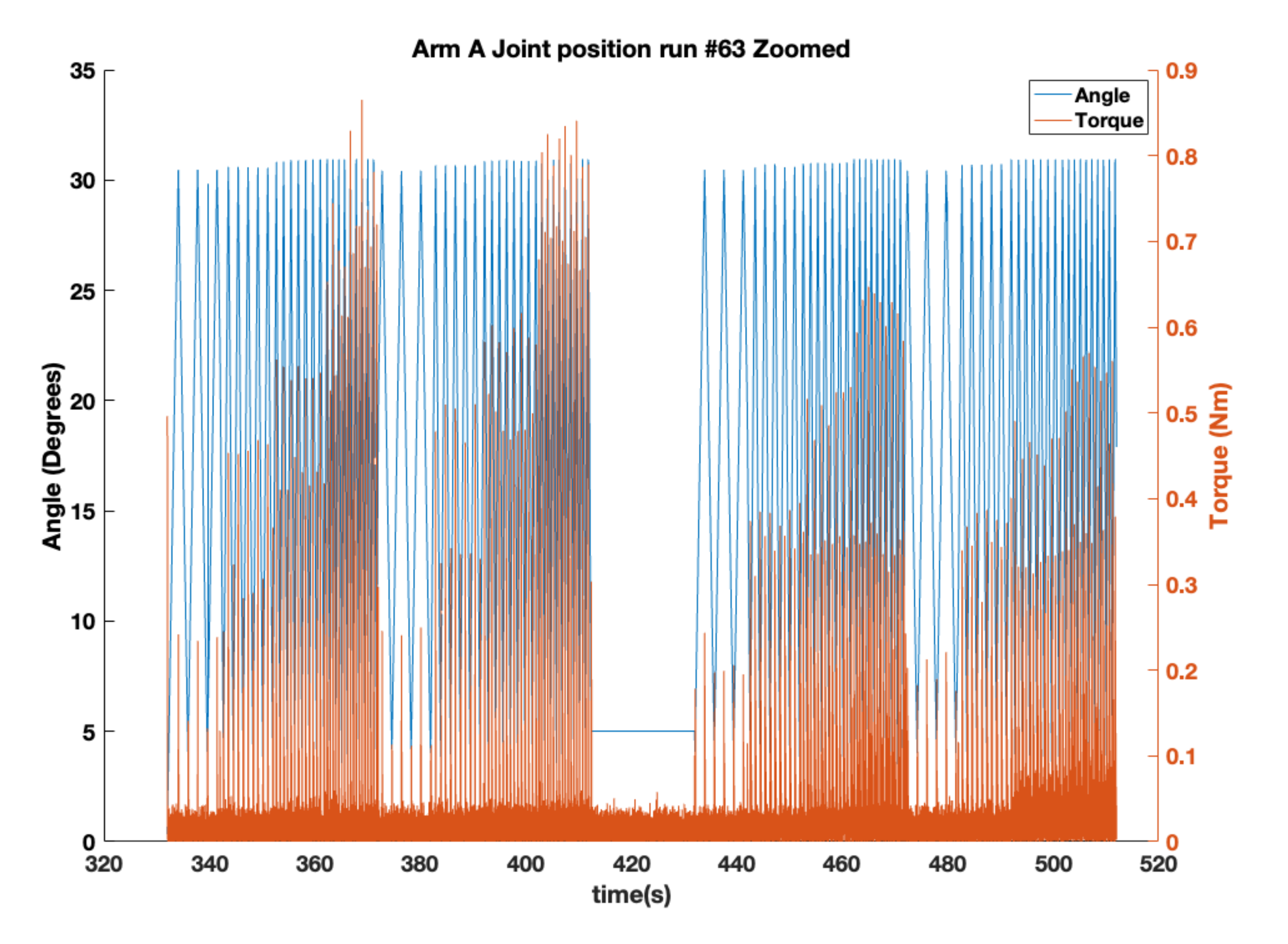
Air Bearing Table

Parabolic Flight



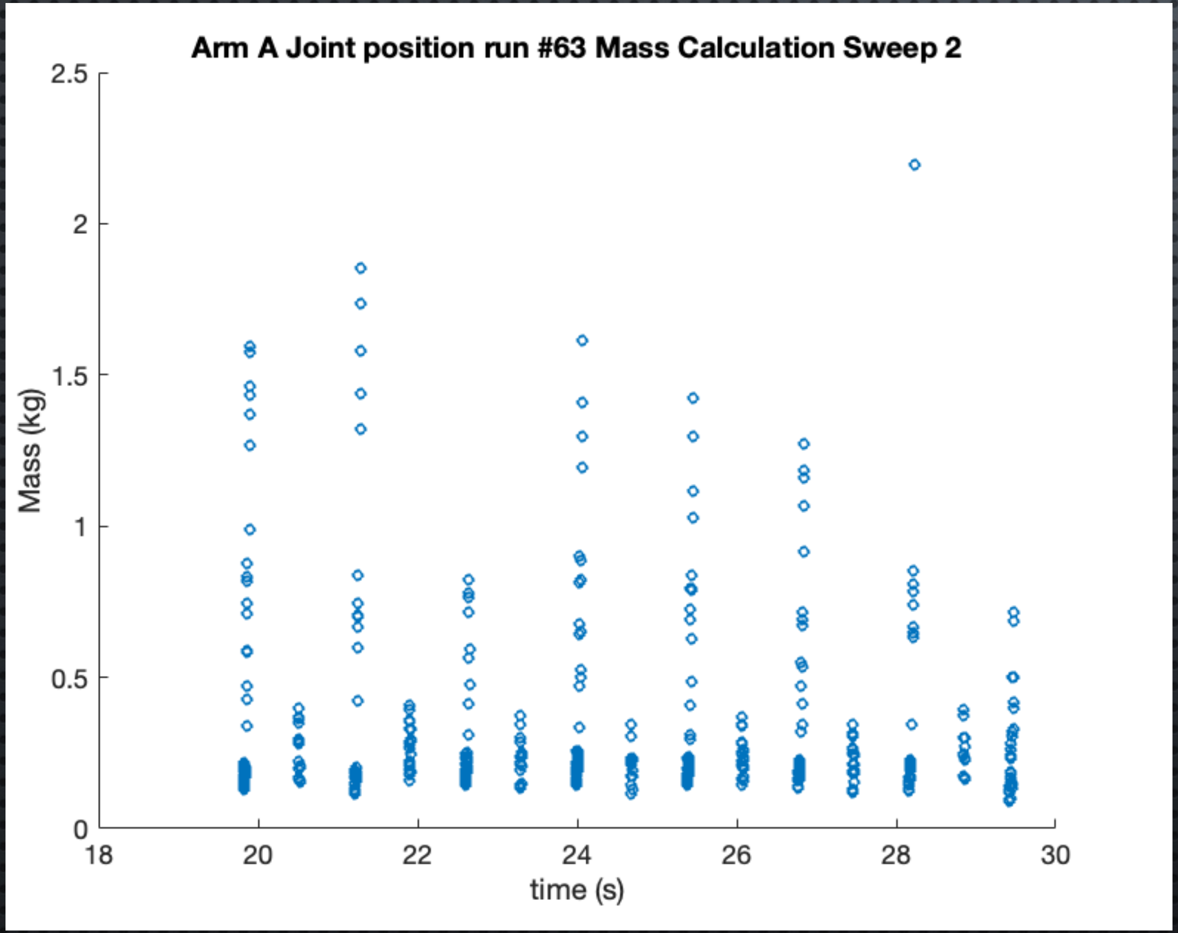
Suborbital Rocket Flight

ROCKSAT-X SUBORBITAL ROCKET



The robot DIVO sweep motions and payload cutdown

SUBORBITAL EXPERIMENT RESULTS



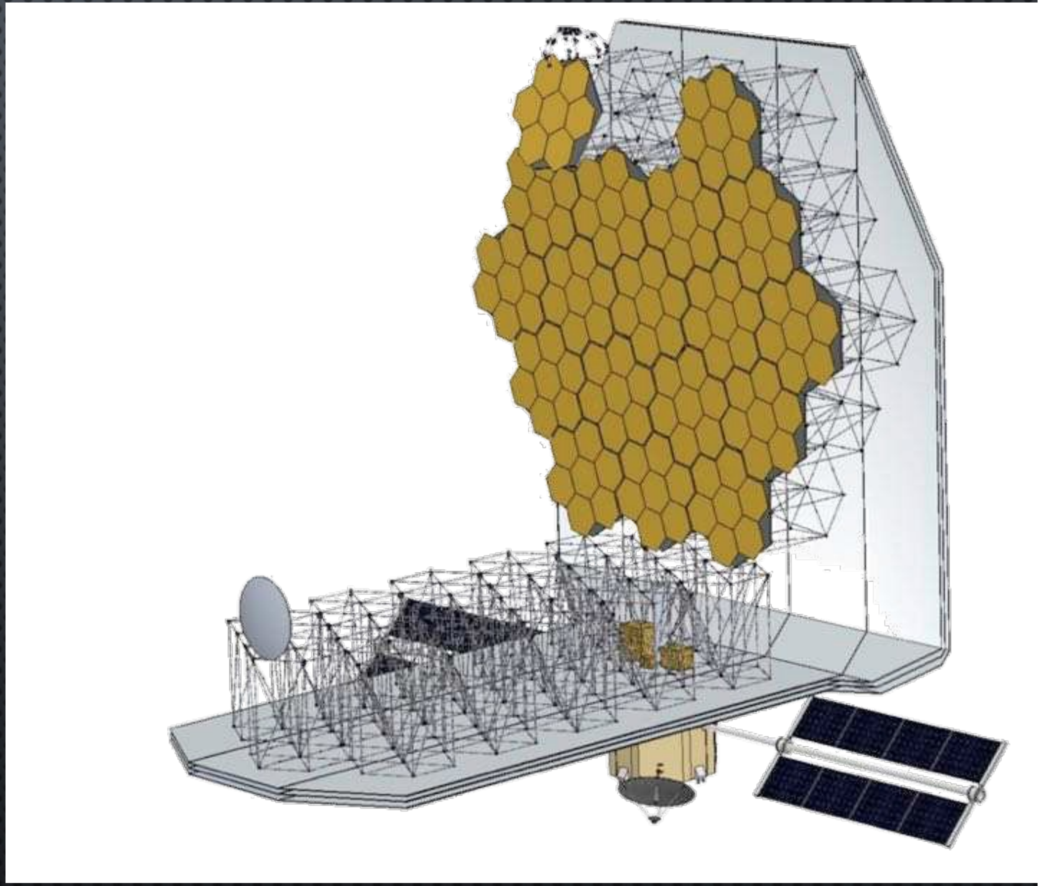
RockSat-X: $m_4 + m_5$ converging pre-ejection of the tip mass

Parameter	Expected Value	Identified Value	Difference	Error
m_4 (Arm)	233.1 g	244.5 g	11.4 g	4.89%
$m_4 + m_5$	299.4 g	296.0 g	3.4 g	1.14%
m_5	66.3 g	51.5 g	14.8 g	22.3%

RockSat-X Payload: Identified Parameter Values

APPLICATION TO OBSERVATORIES

- In Space Assembly of large aperture observatories
- "Tugboat" operations for moving cargo from transfer craft to assembly staging areas
- Adaptability to unknown payloads
  - Identification of manifest errors
- Repair of observatories in-situ
  - Larger apertures have higher probability of MMOD strikes increasing need for serviceability
  - Valuable at Sun-Earth L2 where manned missions are unlikely
  - Damaged systems will have changed intrinsic characteristics



iSA Study 20m Telescope Reference Concept [13]

FINAL REMARKS

- Developed the Extended Inverse Direct Dynamic Model for Dynamics Parameter Identification.
  - Verified via experiments with air bearing table, parabolic flight, and suborbital sounding rockets
  - Applications for robotics servicing, construction, and depot management
  - Successfully defended Spring 2024
- Currently working as a Postdoctoral researcher at UMD
  - Working on the NASA LuSTR program developing and testing technologies for reusable gecko skin-based adhesives to remove lunar dust from space suits and lunar infrastructure
  - Looking for future full-time employment opportunities within the servicing community

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BACKUP SLIDES

EXTENDED INVERSE DIRECT DYNAMICS MODEL

$$\boldsymbol{M}(\boldsymbol{\chi}, q)\ddot{q} + \boldsymbol{C}(\boldsymbol{\chi}, q, \dot{q})\dot{q} + \cancel{\boldsymbol{g}(\boldsymbol{\chi}, q)} + \boldsymbol{\zeta}(\boldsymbol{\chi}, \dot{q}) = \boldsymbol{\tau}_{idm}$$

$$\boldsymbol{\chi}_{Ex} = [\boldsymbol{\chi}_0^\top \ \boldsymbol{\chi}_1^\top \ \boldsymbol{\chi}_2^\top \cdots \boldsymbol{\chi}_n^\top \ \boldsymbol{\chi}_{n+1}^\top]^\top$$

$\boldsymbol{M}(\boldsymbol{\chi}, q)\ddot{q} \in \mathbb{R}^{(n+2)\times(n+2)}$ = Generalized inertia matrix for the system containing inertial parameters for all components

$\boldsymbol{Y}_{\boldsymbol{\chi}}(\ddot{q}, \dot{q}, q) \in \mathbb{R}^{(n+2)\times p}$ = Jacobian matrix with respect to $\boldsymbol{\chi}$

$\boldsymbol{\tau}_{idm} \in \mathbb{R}^{n+2}$ = Input torque vector for the system

$\boldsymbol{\chi} \in \mathbb{R}^{n+2}$ = Inertial parameters vector for the system

$$\boldsymbol{\chi}_j = [XX_j, XY_j, XZ_j, YY_j, YZ_j, ZZ_j, MX_j, MY_j, MZ_j, M_j, Ia_j, Fv_j, Fc_j]^\top$$

$$\boldsymbol{L}_j = [XX_j, XY_j, XZ_j, YY_j, YZ_j, ZZ_j]^\top$$

$$\dot{P} = \begin{bmatrix} \dot{p}_n \\ \omega_n \end{bmatrix} = \bar{\boldsymbol{J}}(\phi)\dot{\phi} + \dot{\boldsymbol{P}}_0 \text{ (From GJM)}$$

$$\frac{\partial \boldsymbol{\tau}_{idm}}{\partial \boldsymbol{\chi}} = \boldsymbol{Y}_{\boldsymbol{\chi}}(\ddot{q}, \dot{q}, q) + \dot{\boldsymbol{P}}_0$$

$\boldsymbol{Y}_{\boldsymbol{\chi}}(\ddot{q}, \dot{q}, q) \in \mathbb{R}^{(n+2)\times p}$ = Jacobian matrix with respect to $\boldsymbol{\chi}$

$\boldsymbol{\tau}_{idm} \in \mathbb{R}^{n+2}$ = Input torque vector for the system

$\boldsymbol{\chi} \in \mathbb{R}^{n+2}$ = Inertial parameters matrix for the system

$\dot{\boldsymbol{P}}_0 = (\boldsymbol{v}_G^\top, \boldsymbol{\omega}_G^\top)^\top$ = is the initial translational and rotational movement of the base satellite

${}^A\dot{\boldsymbol{r}}_0 + {}^A\dot{A}_0{}^0\boldsymbol{b}_0$ = is the rotation and translation of the base satellite in the GJM

$\boldsymbol{\chi}_j$ = Inertial parameters of the j^{th} system element

$\boldsymbol{L}_j$ = The inertia tensor parameters for the j^{th} link