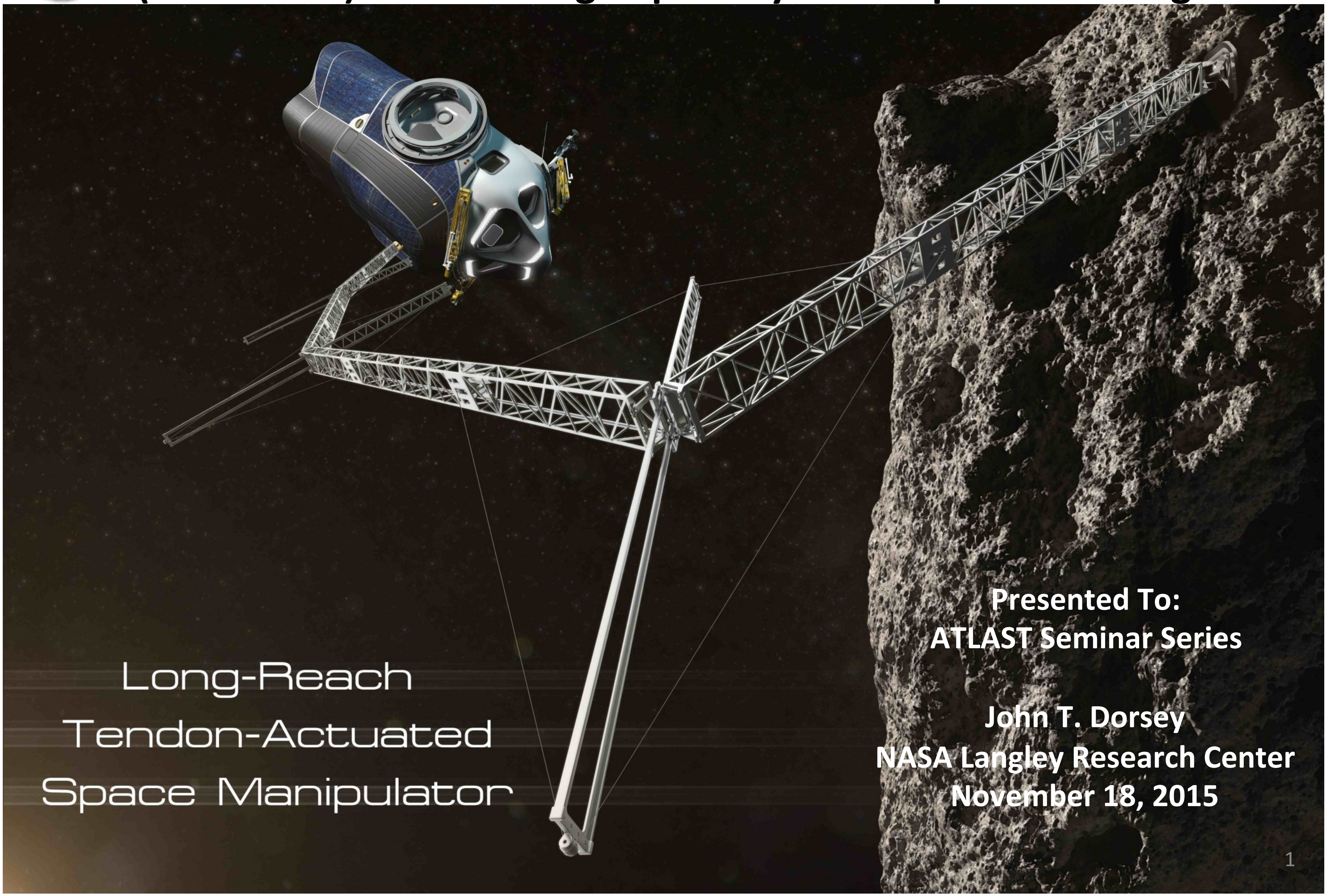
The Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN): An Enabling Capability for In-Space Servicing



Presented To:
ATLAST Seminar Series

John T. Dorsey
NASA Langley Research Center
November 18, 2015

Outline

- Motivation for Technology
- Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN)
  - Description of concept and features
  - Design versatility
- TALISMAN-Based Mission Applications
  - Shuttle Remote Manipulator System (SRMS)
  - Satellite Servicing
  - Asteroid Retrieval Missions
  - Telescope Servicing and Assembly
- Technology Status
- Concluding remarks

Spacecraft and Satellite Servicing: A Critical Capability That Must Be Maintained

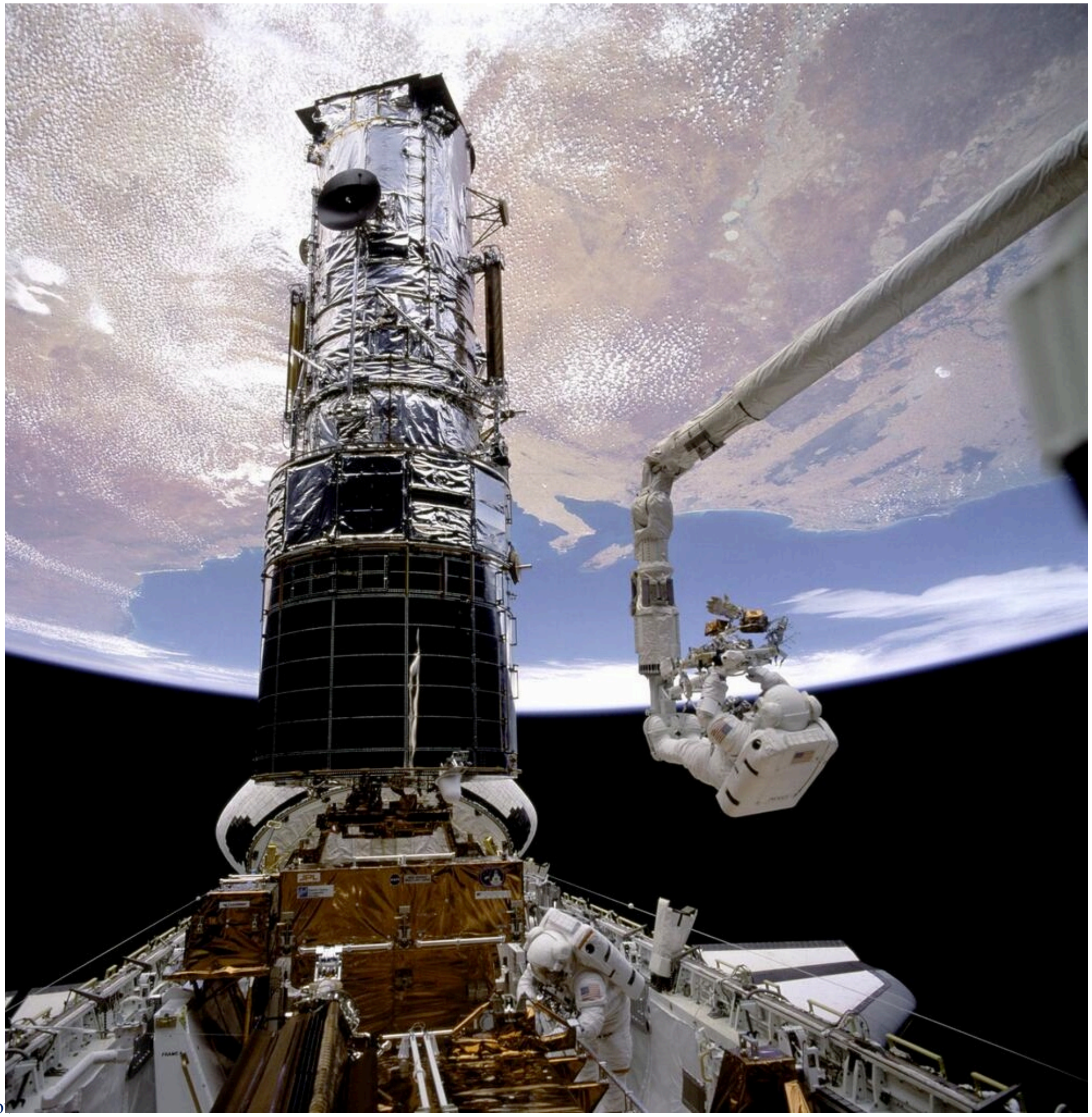
Hubble Servicing Missions: Demonstrated the Importance and value of On-Orbit Servicing:

- **Long Reach Manipulator (SRMS) provided Spacecraft Grappling / Berthing and positioning of astronaut**
- **SRMS launched and based on Space Shuttle**
- **Astronaut positioned on SRMS to perform dexterous operations**

Without Space Shuttle and EVA resources, previous capability within NASA to perform satellite servicing no longer exists.

Solution: Robotic Satellite Servicing

- **Long Reach Robotic Manipulator**
- **Dexterous robots & end effectors**



Motivation: Opportunity for Significant Advance in Long Reach Space Manipulators

- **Goal - to improve the state-of-the-art (SOA) in space robotic manipulators by increasing:**
  - **Dexterity**
  - **Reach**
  - **Packaging Efficiency**
  - **Structural Efficiency**
  - **Extend to In-Space Assembly**

- **State of Art: Shuttle and Space Station Remote Manipulator Systems (SRMS & SSRMS)**
  - **Conventional Robotic Architecture**
  - **Massive joints (co-located joint and motor)**
  - **High compliance**

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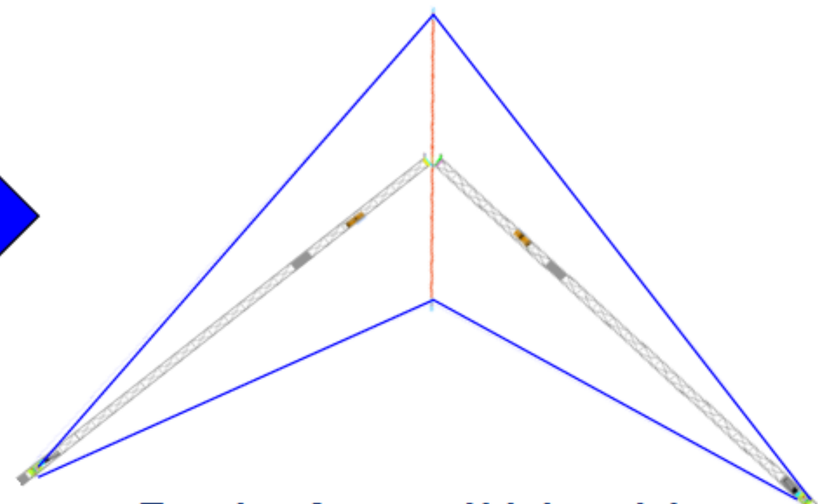
Approach: Guyed Structures For Efficient Spans

Credit: Dog River Bridge, AL NOAA

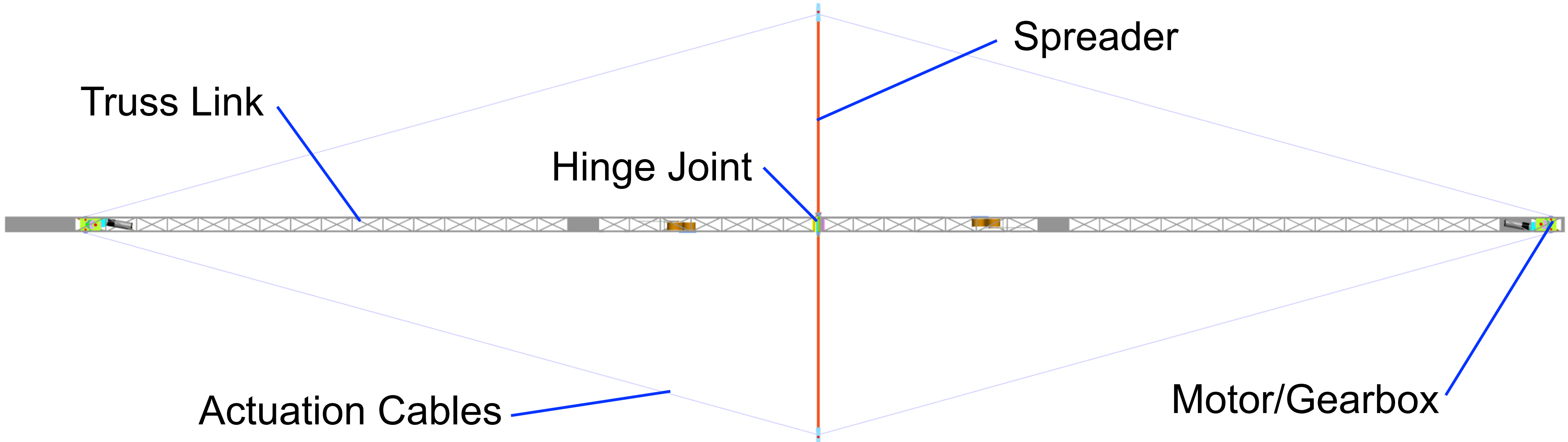
Credit: Photographs in the Carol M. Highsmith Archive,
Library of Congress, Prints and Photographs Division.

SRMS



Tension Actuated Lightweight
In-Space MANipulator (TALISMAN)

New Approach: Tendon Actuated Lightweight In-Space MANipulator (TALISMAN)



<u>What Is New In This Approach?</u>

- **Tendon and spreader architecture: high gear ratio and mechanical advantage, lightweight motor/gearboxes**
- **Tendon architecture: low joint compliance and mass**
- **Tension/compression structural elements: minimize structural mass**
- **Actuation tendons: also provide stiffening for the structure**
- **Lightweight joints: number can be optimized to increase dexterity and/or packaging efficiency**
- **Tendon actuation: full or semi antagonistic control options possible**
- **Design: modular and scalable making it versatile to many applications**

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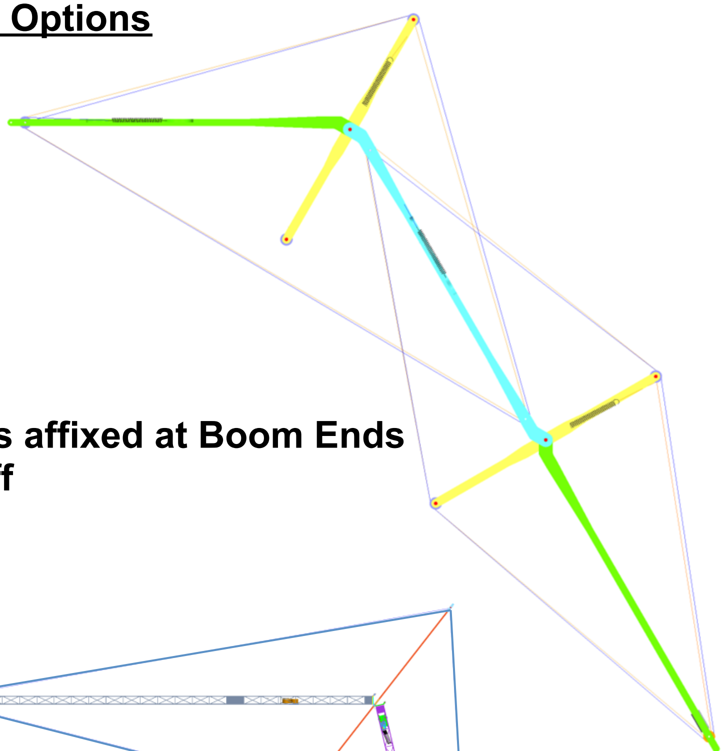
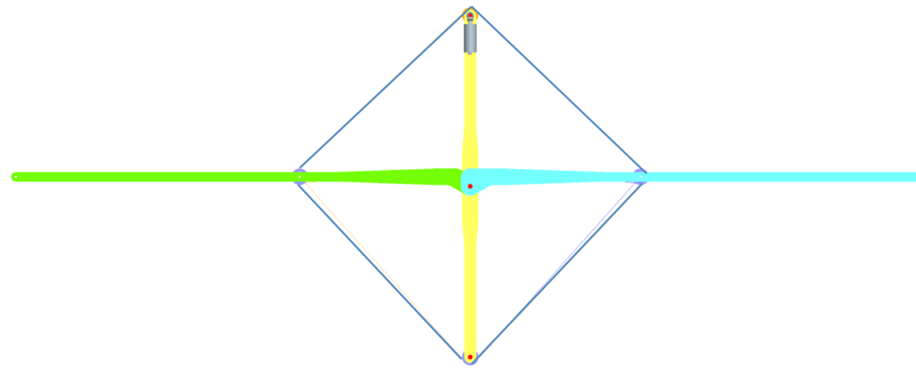
TALISMAN Design Versatility

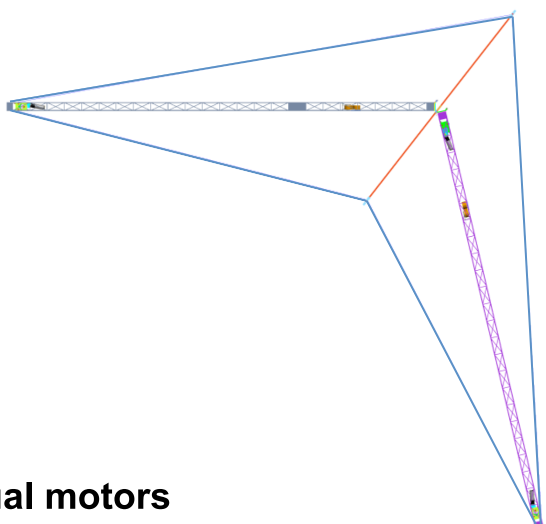
A Few Options



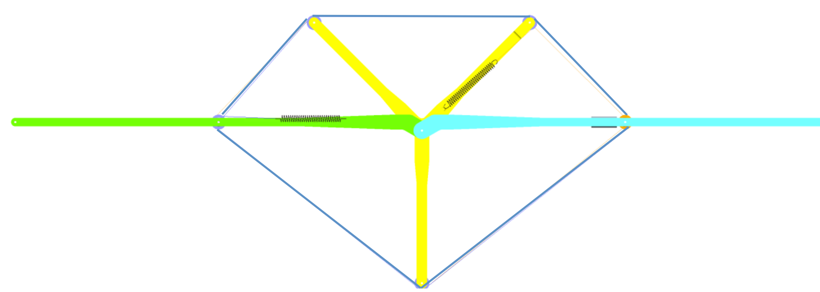
Cables affixed at Boom Ends
Lift Off



Single Motor in spreader,
Cables affixed 1/3 Boom



Dual motors
Cables affixed at Boom Ends
Constrained Lift Off



Single Motor in Arm,
Cables affixed ½ Boom
Multiple spreaders on one side

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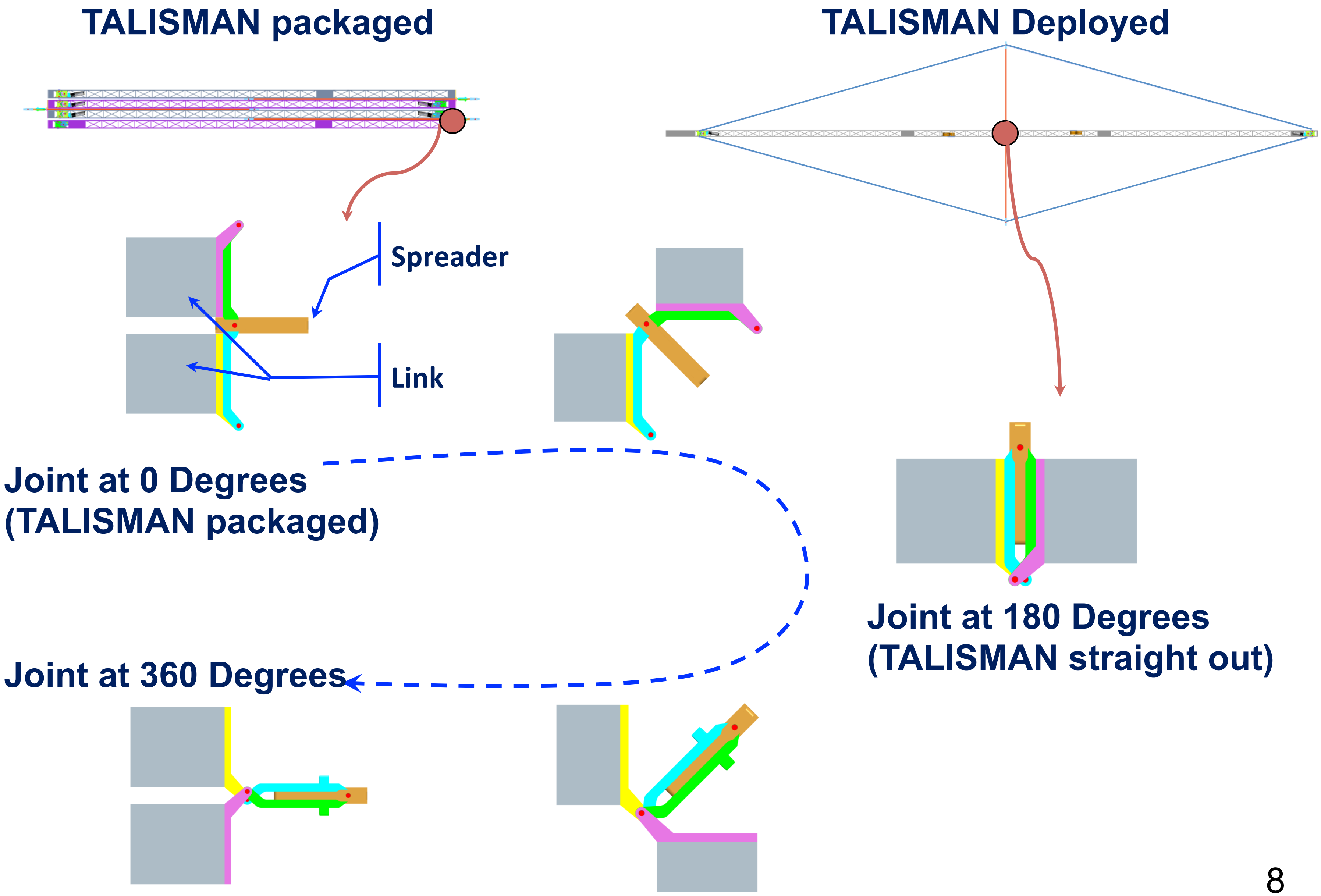
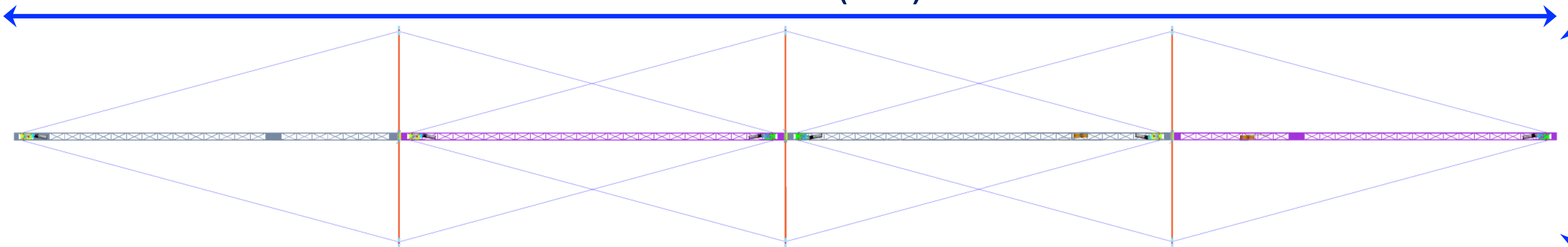
Unique Hinge Joint: Articulation Detail



TALISMAN Compact Packaging: 4 Link Example

Deployed Manipulator

15.24 m (50 ft)

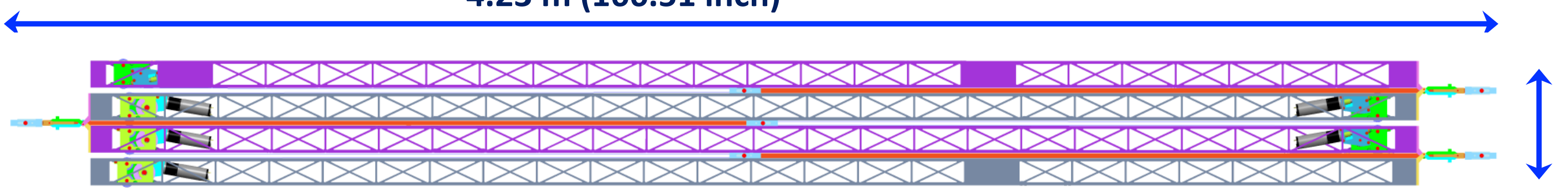


2.06 m (6.6 ft)

Stowed Manipulator

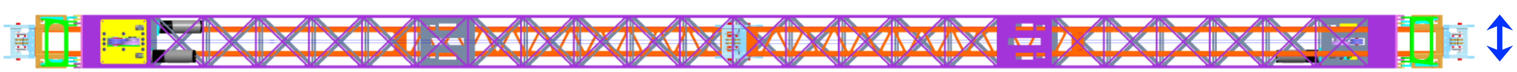
Spreaders Package Between Links

4.23 m (166.51 inch)



0.35 m (14 inch)

Top View



0.1524 m (6 inch)

Side View

End View

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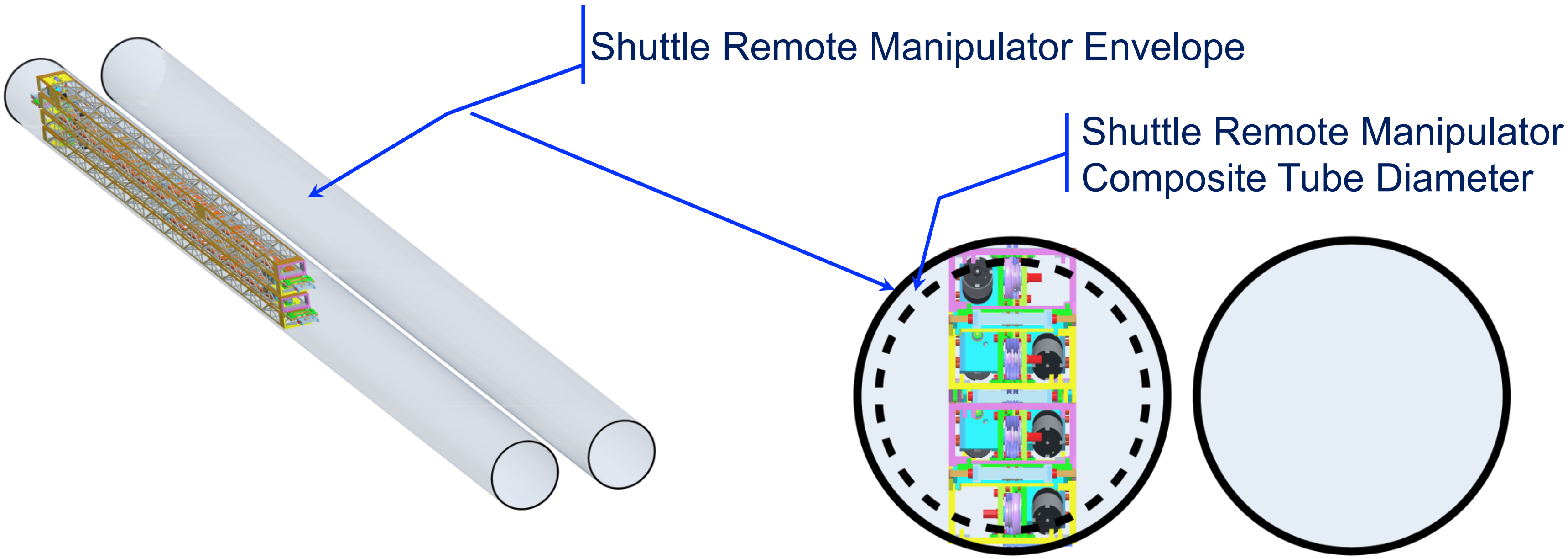
TALISMAN vs. Shuttle Remote Manipulator System



Design Parameter	SRMS	TALISMAN
Total manipulator length	15.3 m (50 ft)	15.3 m (50 ft)
Number of joints in manipulator	6 (2 shoulder, 1 elbow, 3 wrist)	5 (2 base, 3 joints)
Number of links in manipulator	2	4
Tube/Link System Mass [kg]	46 kg (101.4 lbf)	7.03 kg (15.5 lbf)
Manipulator Mass	410 kg (904 lbf)	36.1 kg (79.6 lbf)
Packaged Volume	1.74 m^3 (61.4 ft^3)	0.23 m^3 (8 ft^3)

Talisman compared to SRMS: < 1/10th mass and < 1/7th the volume
(Talisman does not include an end-effector)

Spacecraft and Satellite Servicing: Maintaining A Critical Capability Using Robotics

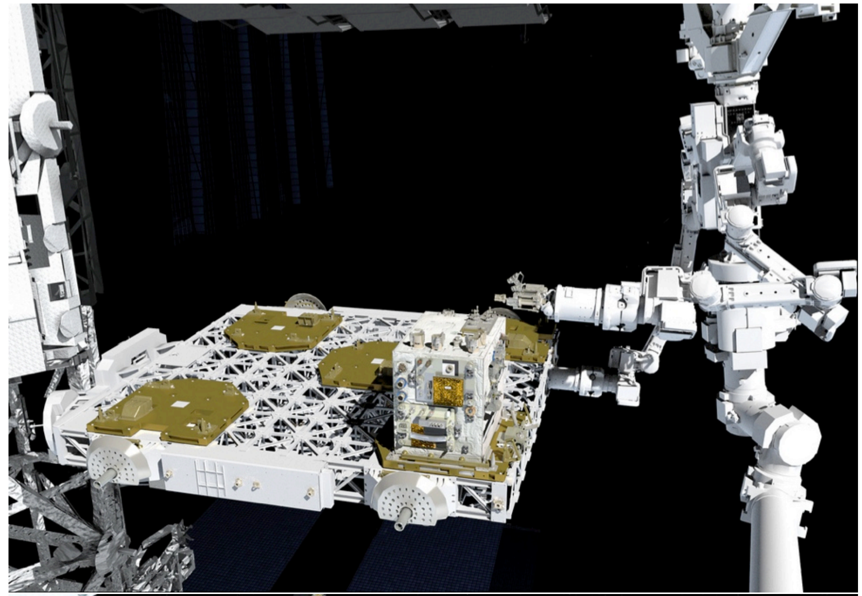
A Combination of GSFC/LaRC Technologies Provides all of the Capabilities Necessary for a Complete Robotic Servicing System:

- **GSFC:** Servicing tools and end effectors
- **GSFC:** Servicing operations and planning
- **GSFC:** Dexterous Servicing Manipulators (DEXTRE/FREND)
- **GSFC:** Servicing Spacecraft
- **GSFC:** Dual Manipulator Control Technology

- **LaRC:** Tendon Actuated Lightweight In-Space MANipulator (TALISMAN): Grapple, position and stabilize satellite.
- **LaRC:** TALISMAN to position and stabilize GSFC servicing manipulators
- **LaRC:** Advanced control strategies to enable grappling/berthing of uncooperative targets

- **LaRC Satellite Servicing Video**

- ***These Same Capabilities Enable Robotic In-Space Assembly***



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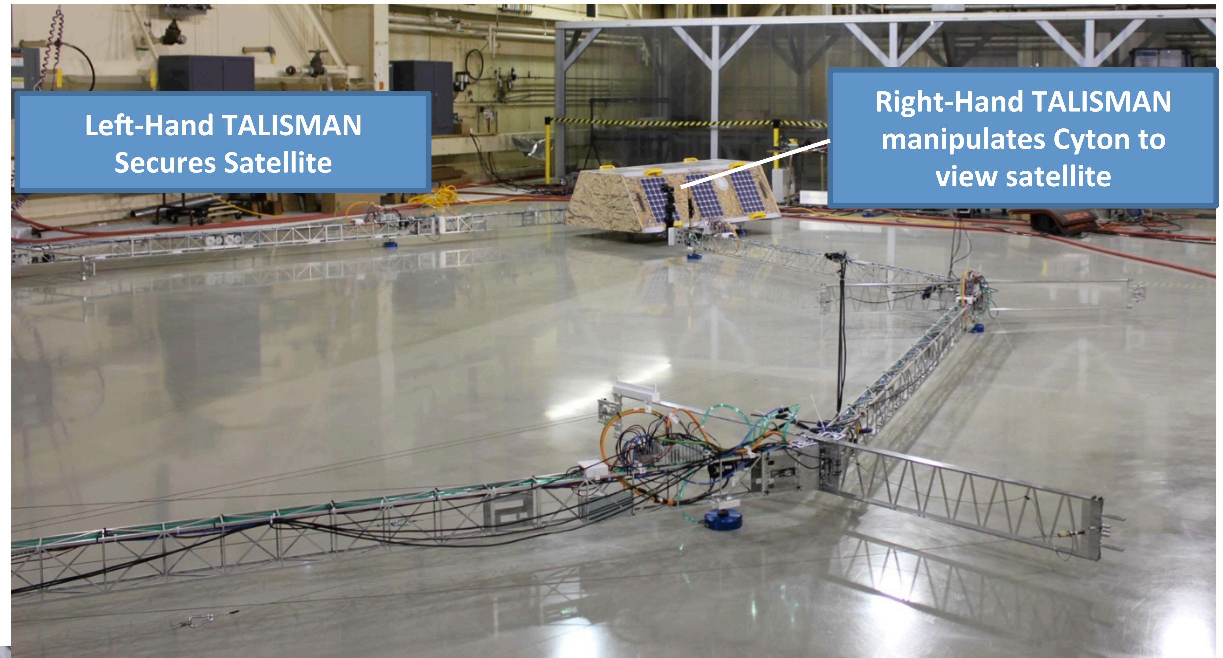
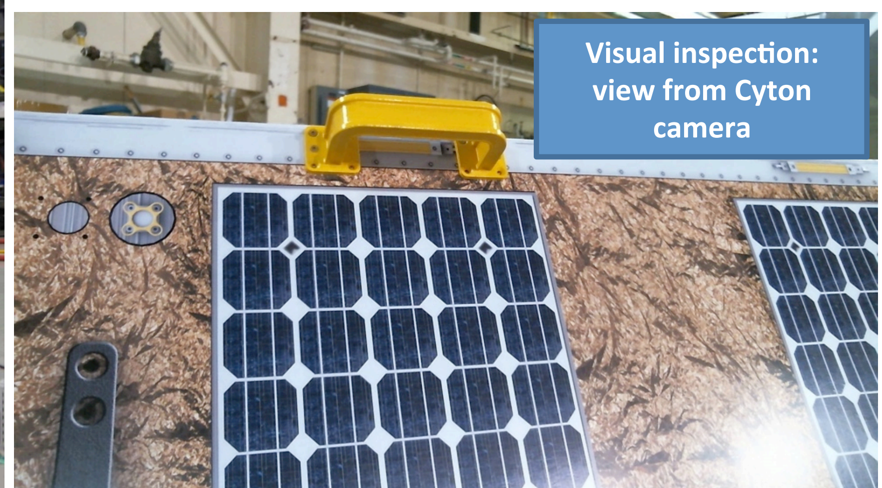
Satellite Servicing Demonstration Using Two TALISMANs

TALISMAN manipulates Cyton 1500 dexterous manipulator and demonstrates satellite inspection capability





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Manipulator-Based Asteroid Redirect Mission (ARM) Capture System Concepts

- The TALISMAN provides a capability for general-purpose and long-reach manipulation.
- Versatile TALISMAN technology can be directly applied to both Mission Concepts A and B.
- TALISMAN design easily modified (reach and dexterity for example) to accommodate changes in mission requirements.
- Long reach and dexterity of TALISMAN can accommodate uncertainty in asteroid/boulder size and shape.
- Multiple lightweight TALISMANs provide system redundancy to decrease risk.
- With a suite of tools/end-effectors, TALISMAN can perform multiple functions, such as
  - Grabbing small asteroid to de-spin
  - Deploying a capture bag
  - Acquire multiple boulders or loose material off of larger asteroid
  - Acquire boulders or material from multiple sites
  - Serve as locomotion (walking legs) on asteroid surface
  - Align asteroid/boulder center-of-gravity with spacecraft thrust axis
  - Secure asteroid/boulder against spacecraft for return trip
  - Serve as astronaut positioning arms
- Versatile TALISMAN technology can be directly applied to other missions such as satellite servicing and repair, Mars spacecraft assembly, large space telescope assembly, spacecraft berthing, etc.

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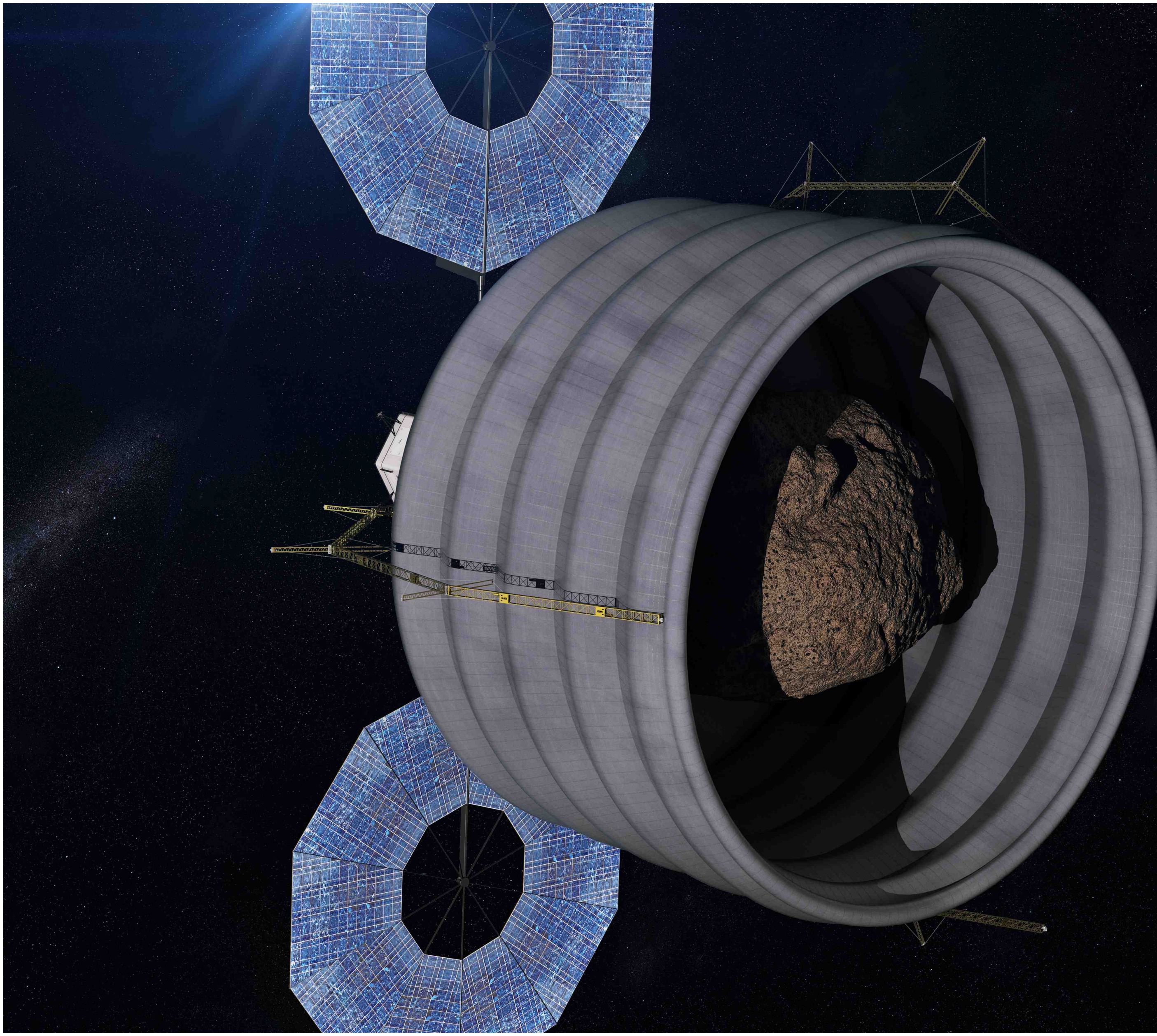
ARM Concept A TALISMAN-Based Capture System: Capture a Whole Small Asteroid



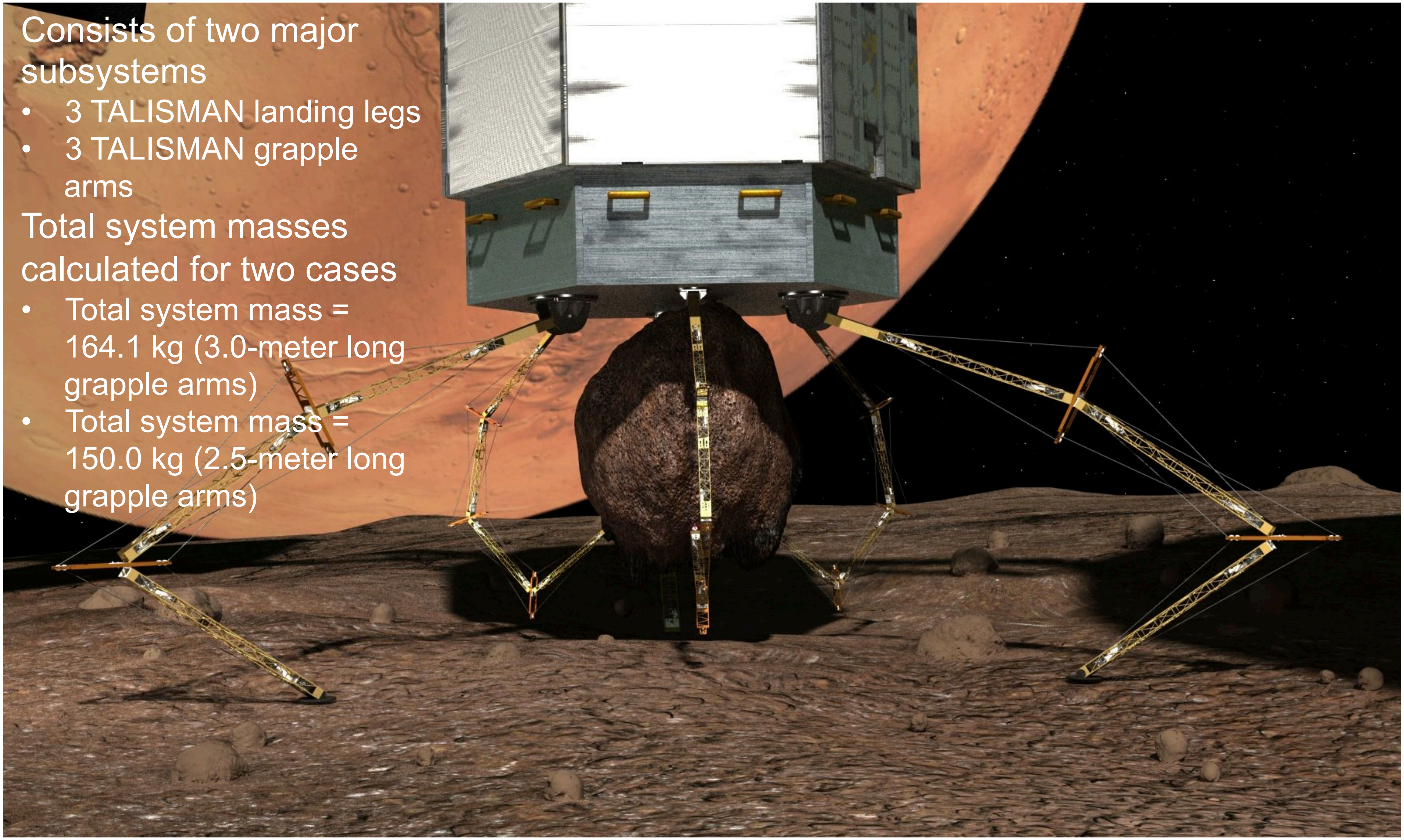
Consists of two major subsystems

- Set of 3 TALISMANS with end effectors
- Simple lightweight enclosure bag (EB)

Total system masses calculated for two cases

- 16-meter long TALISMANs: total mass = 256.5 kg
- 20-meter long TALISMANs: total mass = 293.3 kg

ARM Concept B TALISMAN-Based Capture System: Retrieve Single Boulder From Large Asteroid



Consists of two major subsystems

- 3 TALISMAN landing legs
- 3 TALISMAN grapple arms

Total system masses calculated for two cases

- Total system mass = 164.1 kg (3.0-meter long grapple arms)
- Total system mass = 150.0 kg (2.5-meter long grapple arms)

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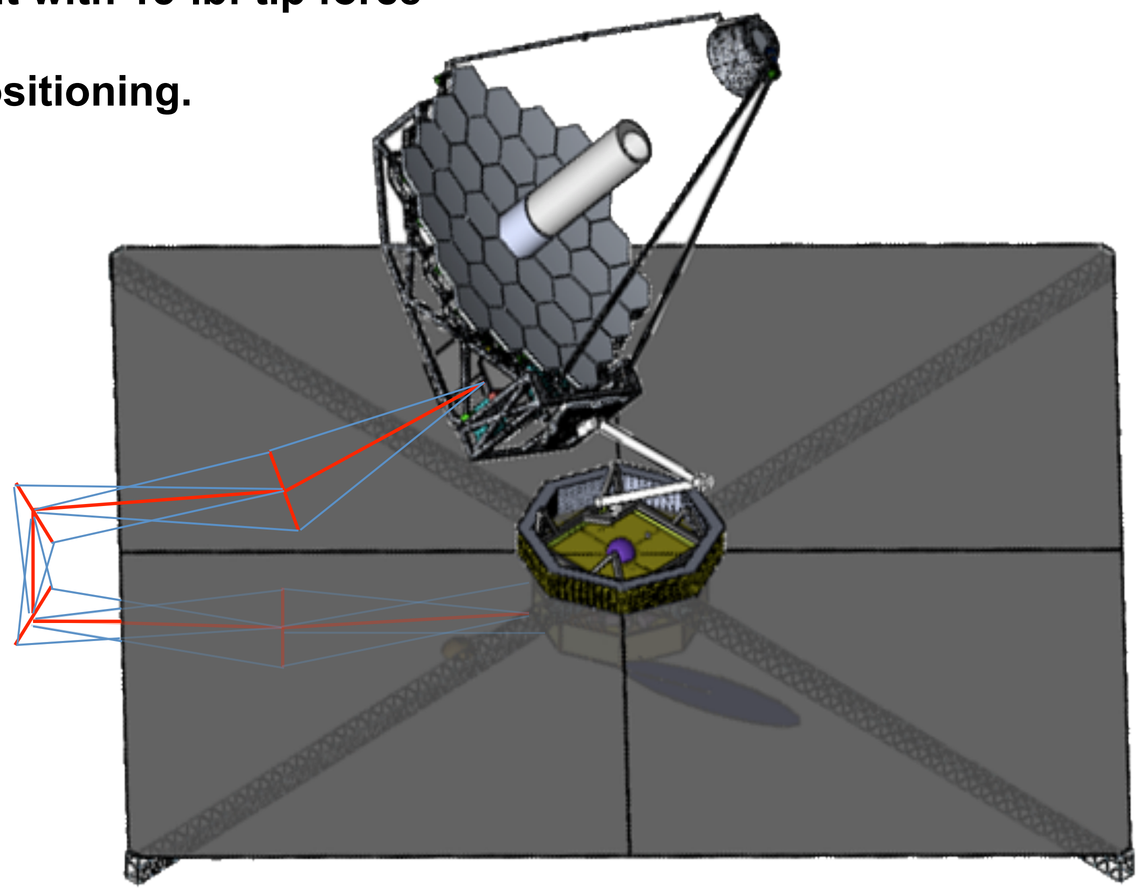
ATLAST Telescope Servicing Design Cases

26 m and 47 m, 5-link TALISMANs

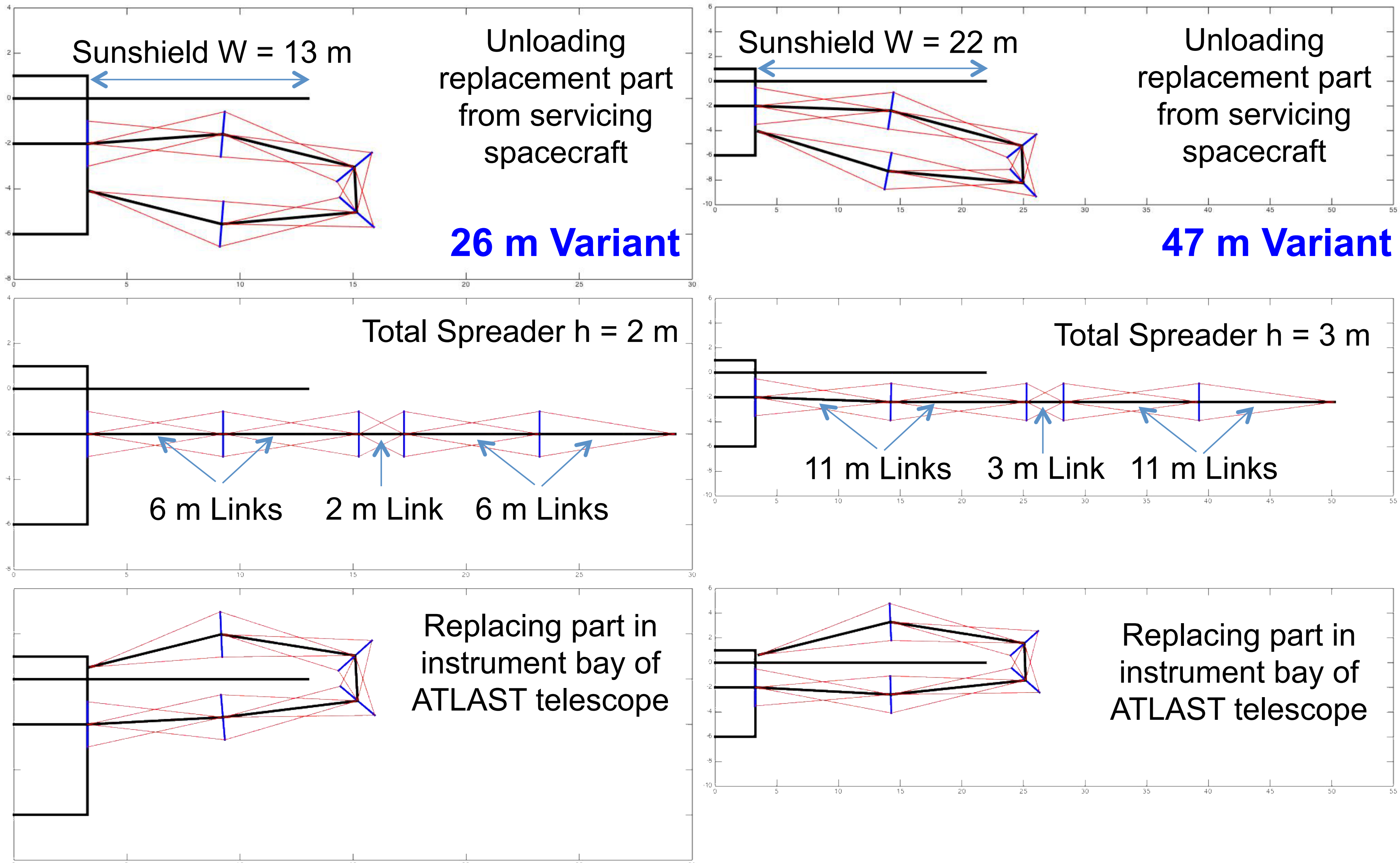
- Designed to reach around the sunshields of completed ATLAST space telescopes (9.2 m and 15.5 m, respectively) for servicing tasks
- 1% in-plane tip deflection limit with 15-lbf tip force capability.
- Smaller mid-link for easier positioning.

ATLAST Telescope
D = 9.2 m or 15.5 m



TALISMAN
Servicing Arm

Telescope Assembly and Servicing Design Cases: Resulting 26 m and 47 m 5-Link TALISMANs



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Satellite Servicing and Telescope Assembly Design Cases Structural and System Mass

		Mission A		Satellite Servicing ATLAST Mission			
		16m (52.5ft)		26m 5-Link		47m 5-Link	
	Material -->	Composite		Composite		Composite	
	# of LINKS -->	4-Links		5-Links		5-Links	
Component	**Sub-Comp**	**(Kg)**	***(Lbs)***	**(Kg)**	***(Lbs)***	**(Kg)**	***(Lbs)***
Structure	Truss Arms	5.7259	*12.62*	18.0295	39.7483	32.35533	71.3313
	Spreaders	2.6294	*5.797*	7.7066	16.9902	11.41228	25.1598
	Cables	3.4087	*7.515*	1.54918	3.41536	2.920491	6.43859
	TOTAL STRUCTURE:	**11.764**	***25.94***	**27.2853**	***60.154***	**46.6881**	***102.93***
Joints	Arm Hinges	1.7962	*3.96*	4.78993	10.56	4.789932	10.56
	Base Rotary	1.9867	*4.38*	3.97347	8.76	3.973466	8.76
Springs / Pulleys / Mount	~	4.7899	*10.56*	11.9748	26.4	11.97483	26.4
Motors	~	13.269	*29.25*	27.7191	61.1102	50.10763	110.469
Gearbox	~	7.1679	*15.8*	14.9739	33.0118	27.06819	59.6752
Control Boxes	~	0.5394	*1.189*	0.67313	1.484	0.673131	1.484
Wiring and Cables	~	5.0406	*11.11*	8.19002	18.0559	14.80503	32.6395
Sensors	4-angle per joint	0.4423	*0.975*	0.57833	1.275	0.57833	1.275
	1-tension per joint	0.2631	*0.58*	0.32885	0.725	0.328854	0.725
Cameras	~	0.6622	*1.46*	0.66224	1.46	0.662244	1.46
Robotic Quick Change	~	2.268	*5*	4.53592	10	4.53592	10
	TOTAL OTHER:	**38.225**	***84.27***	**78.3997**	***172.84***	**119.4976**	***263.45***
SUBTOTAL		49.989	*110.2*	105.685	*233*	166.1857	*366.38*
Growth Factor	30%	14.997	*33.06*	31.7055	*69.899*	49.8557	*109.91*
TOTAL:		**64.986**	***143.3***	**137.39**	***302.89***	**216.0413**	***476.29***

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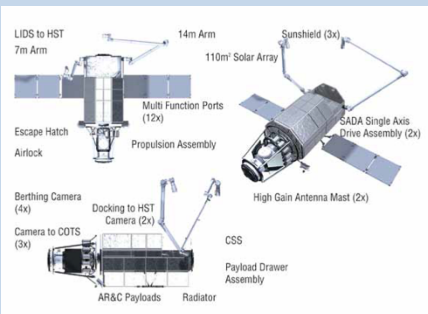
GSFC Satellite Servicing Study Project Report, October 2010: Notional Missions and Robotics Needs

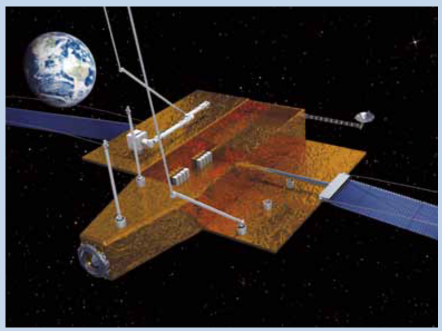
Mission 3
Robotic & Human Servicing of Satellite in LEO



Dexterous Robots:
1 at 7 m reach

Long Reach Manipulators:
1 at 14 m reach
- Berth/deploy Dragon SC
- EVA positioning

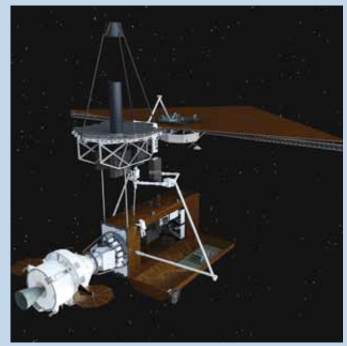
Mission 4
Assembly of 30-m Space Telescope (TMST) at EML1



Dexterous Robots:
2 at 6 m reach

Long Reach Manipulators:
2 at 20 m reach
- Positioning 6 m Dexterous Manipulators

Mission 5
Servicing the 9.2-m Advanced Technology Large Aperture Space Telescope (ATLAST) with Robots and Humans in HEO



Dexterous Robots:
2 at 2 m reach

Long Reach Manipulators:
2 at 20 m reach
- Berthing
- EVA positioning
- Large mass manipulation
- Dexterous manipulator positioning

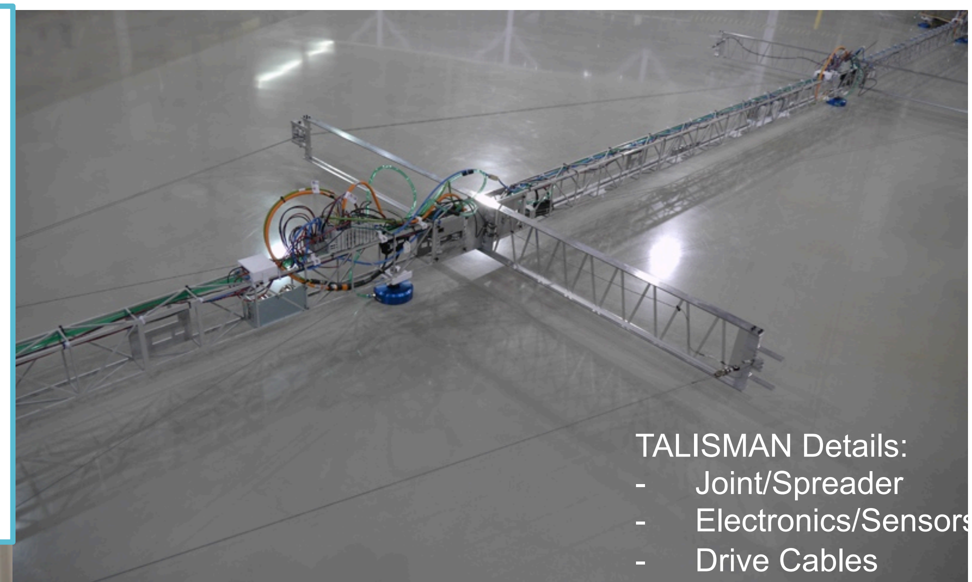
Mission 6
Assembly of the 15.5-m ATLAST Observatory at SEL2 with Humans and Robots

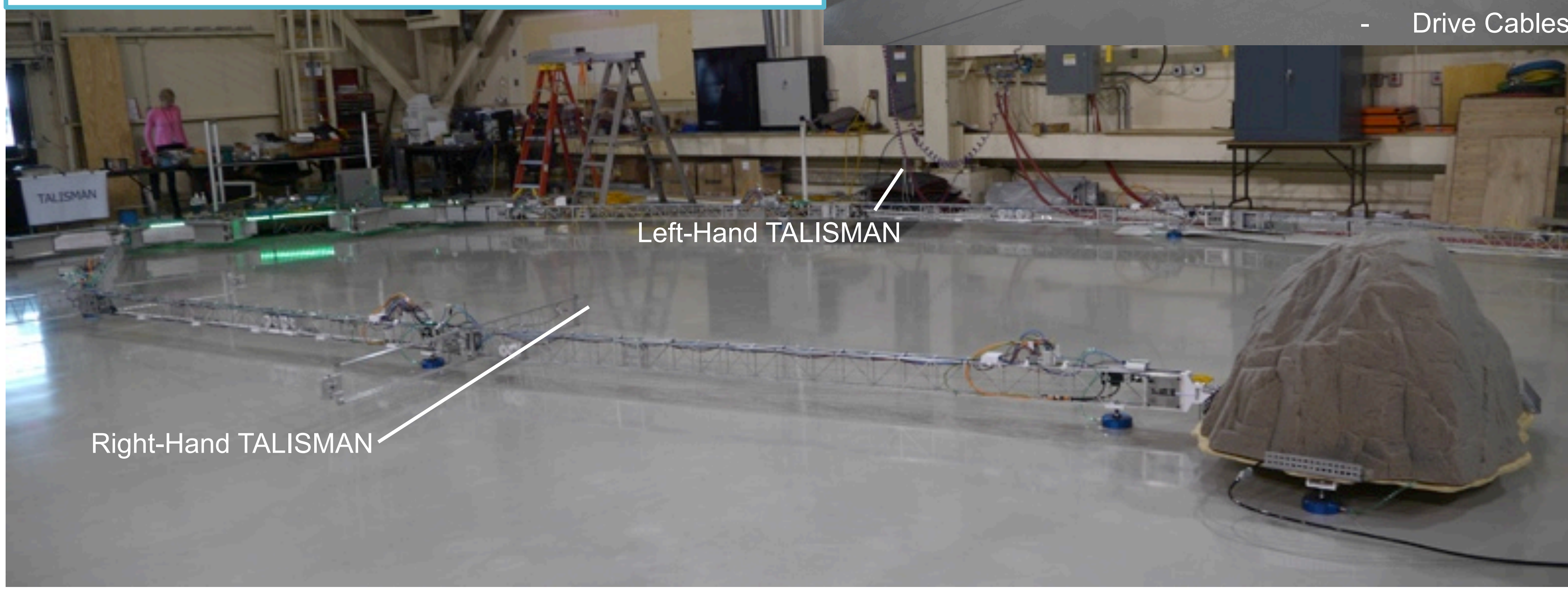
Dexterous Robots:
2 at 2 m reach

Long Reach Manipulators:
2 at 20 m reach
- Berthing
- Large-scale assembly

Technology Status: TALISMAN System

Two 3-Link (3 DOF) TALISMAN Operational
- 1st Generation Active-Passive Actuation
- 1st Generation Truss Links
- 2nd Generation Hinge Joints/Spreaders
- 1st Generation Sensor Suite (Angle/Tension)
- 1st Generation Electronics
- 1st Generation Control Software System
- Cyton 1500 Dexterous Manipulator (Serves as End Effector)





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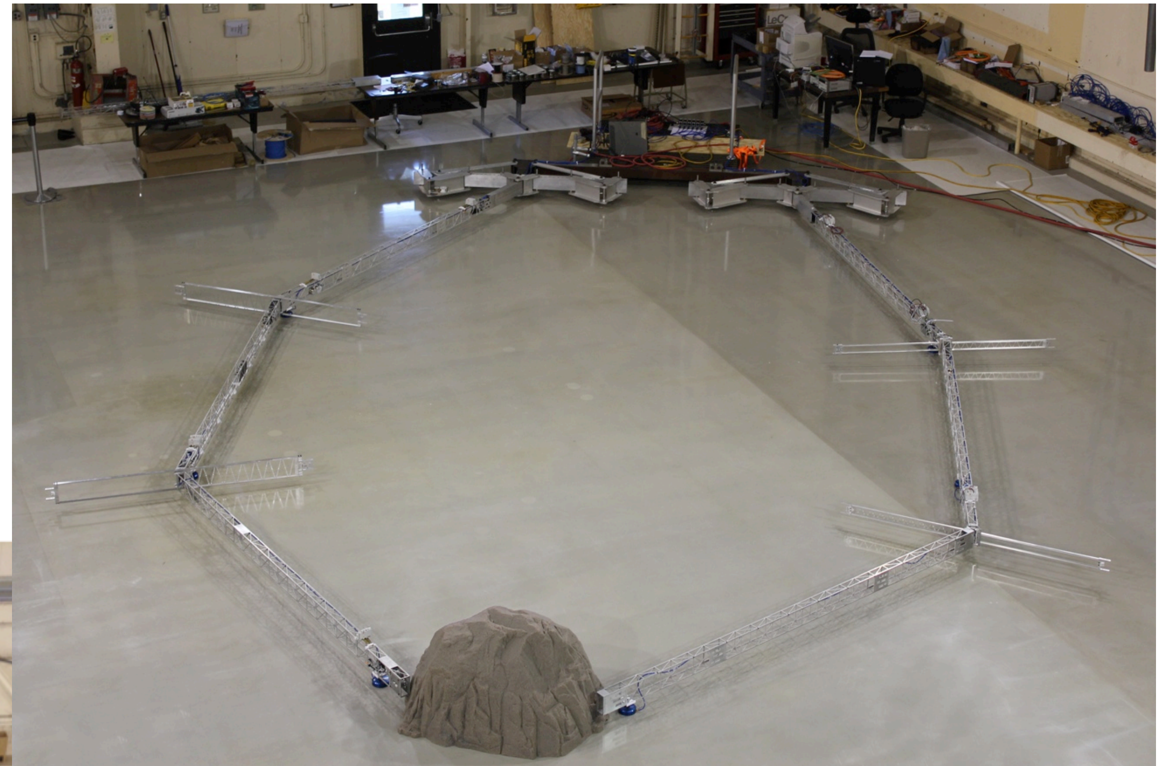
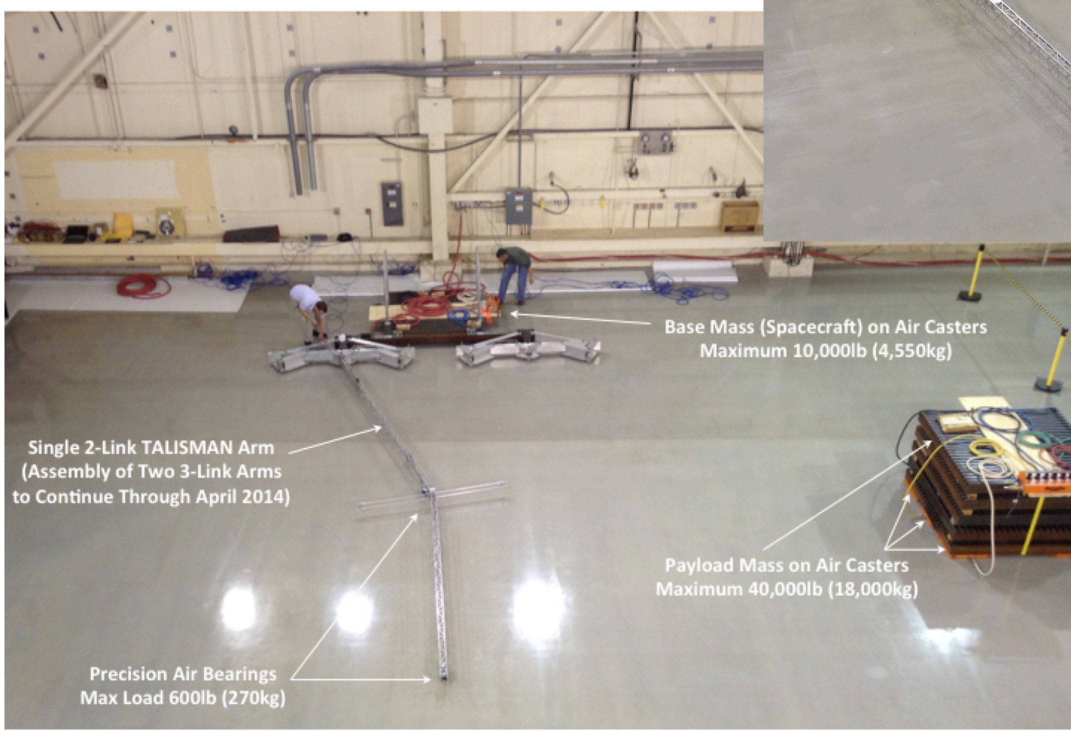
Technology Status: Flat Floor Facility

Zero-G Simulation Facility

- Simulate 0-g Operations in 2D
- Flat Floor with ~54 ft by 88 ft unobstructed area (~4800 ft^2)
- High bay
- Air bearings and air supply system
- Variety of weights to simulate spacecraft, payload, etc. masses
- Asteroid and Satellite Mockups

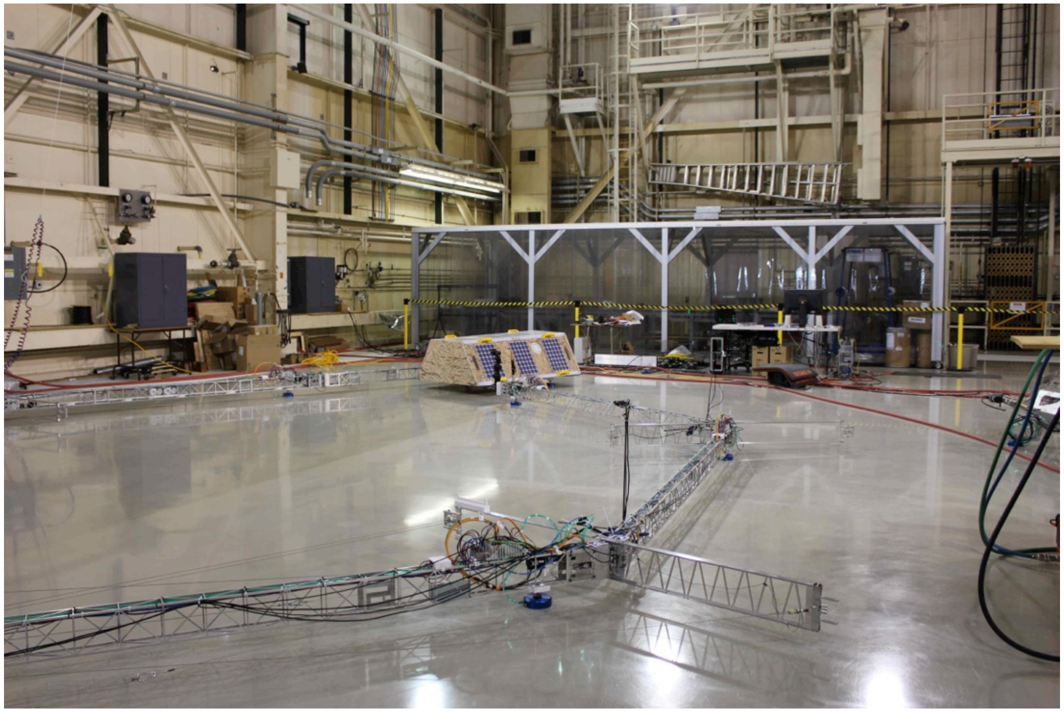




Technology Status: Analysis and Simulation Capabilities

Analysis Capabilities

- Geometric and Configuration Optimization
  - Number and Length of Links
  - Number of DOF/Dexterity
  - Pose Optimization (To Minimize Internal Loads)
  - Clearance and Collision Avoidance
- Static Structural Sizing
- Mass Estimation
- Coupled Rigid-Body Kinematics/Flexible Body Dynamics
  - Dynamic Response Characteristics
  - Optimize Operational Scenarios
  - Dynamic Effects on Static Sizing
- Plant Model: Control System Design



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TALISMAN Intellectual Property/Awards

Patents or NTRs:

- United States Patent, Doggett et al.: **Tension Stiffened and Tendon Actuated Manipulator**
  - Patent No.: US 9,168,6569, B2.
  - Date of Patent: Oct. 27, 2015.
- Case No. LAR-18160-2, Divisional Application Title: **Tension Stiffened and Tendon Actuated Manipulator and a Hinge For Use Therein**
  - Divisional Patent Application Being Prepared
- Case No. LAR-18708-1, Application Title: **Significant enhancements to TALISMAN** (previously identified in disclosure: LAR 18160-1).
  - Was evaluated by the LaRC Innovation Assessment Panel (IAP) and was recommended to be considered for possible NASA patent prosecution.
  - LaRC plan is to patent the invention and pursue licensing opportunities.
- Invention Disclosure for "**Offset Differential Capstan Drive**" submitted to LaRC.

Major Award:

- The "Compact Long-Reach Robotic Arm" (aka TALISMAN) is the winner of the Tech Briefs Create the Future DESIGN CONTEST 2015 in the category of Machinery/Automation/Robotics; see http://contest.techbriefs.com/2015/winners and http://contest.techbriefs.com/2015/entries/machinery-automation-robotics/5679 .

TALISMAN References

Conferences/Publications:

- Doggett, William R.; Dorsey, John T.; Jones, Thomas C.; and King, Bruce D.: Development of a Tendon-Actuated Lightweight In-Space Manipulator (TALISMAN). Presented at the 42nd Aerospace Mechanisms Symposium, NASA Goddard Space Flight Center, Greenbelt, MD, May 14 – 16, 2014.
- Dorsey, John T.; Doggett, William R.; Jones, Thomas C.; and King, Bruce D.: Application of a Long-Reach Manipulator Concept to Asteroid Redirect Missions. Presented at the AIAA SciTech 2015 Conference, January 5 – 9, 2015, Kissimmee, FL. Available as AIAA-2015-0225.
- Five papers written and presented in special TALISMAN Session at the AIAA Space 2015 Conference (8.31 9.2, 2015, Pasadena, CA):
  - Doggett, William R.; Dorsey, John T.; Jones, Thomas C.; Lodding, Kenneth N.; Ganoe, George G.; Mercer, Charles D; and King, Bruce D.: Improvements to the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN). Presented at the AIAA Space 2015 Conference, August 31 – September 2, 2015, Pasadena, CA. Available as AIAA-2015-4682.
  - Jones, Thomas C.; Dorsey, John T.; and Doggett, William R.: Structural Sizing Methodology for the Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) System. Presented at the AIAA Space 2015 Conference, August 31 – September 2, 2015, Pasadena, CA. Available as AIAA-2015-4627.
  - Komendera, Erik E.; Doggett, William R.; Dorsey, John T.; Debus, Thomas J.; Holub, Kris; and Dougherty, Sean P.: Control System Design Implementation and Preliminary Demonstration for a Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN). Presented at the AIAA Space 2015 Conference, August 31 – September 2, 2015, Pasadena, CA. Available as AIAA-2015-4628.
  - Altenbuchner, Cornelia: Flexible Multi-body Dynamic Modeling of a Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN). Presented at the AIAA Space 2015 Conference, August 31 – September 2, 2015, Pasadena, CA. Available as AIAA-2015-4629.
  - Altenbuchner, Cornelia: Dynamic Response Characteristics of a Robotic Manipulator-Based Capture System Performing the Asteroid Redirect Mission. Presented at the AIAA Space 2015 Conference, August 31 – September 2, 2015, Pasadena, CA. Available as AIAA-2015-4630.

Concluding Remarks

- **New Concept For Long-Reach Space Manipulators: Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN) Invented That Overcomes Many Limitations of the State-of-the-Art Technology.**
- **TALISMAN Concept Versatility Illustrated in Applications to:**
  - **Shuttle Remote Manipulator System (SRMS) Replacement**
  - **Satellite Servicing**
  - **Asteroid Redirect Mission (ARM)**
  - **ATLAST Servicing.**
- **TALISMAN Technology Developed for First-Generation System and Operational Scenarios Demonstrated in Simulated Zero-g Environment.**
- **Large Suite of Analytical Tools Developed to Design, Size, and Assess TALISMAN Architectures and Operations.**

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Backup Information

Tendon-Actuated Lightweight In-Space MANipulator (TALISMAN)

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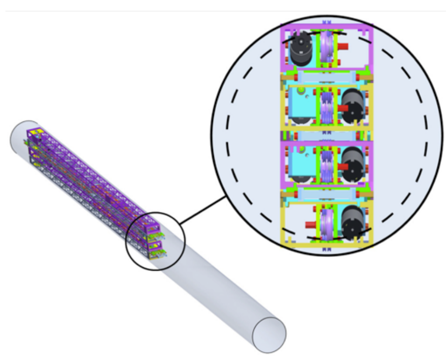
Background

NASA mission and exploration architecture studies show that devices for maneuvering and precisely placing payloads are critical for efficient space operations involving reusable assets or in-space assembly and construction. New missions and applications such as: asteroid retrieval and redirection, asteroid mining, satellite servicing, small payload delivery to space stations and large space observatory assembly can all benefit from having long reach manipulators.

A New Approach

The robotic architecture of state-of-the-art space manipulators, represented by the Shuttle Remote Manipulator System (SRMS), inherently limits their capabilities to extend reach, reduce mass, apply force and package efficiently. TALISMAN uses a new and innovative robotic architecture that incorporates a combination of lightweight truss links, a novel hinge joint, tendon-articulation and passive tension stiffening to achieve revolutionary performance. A TALISMAN with performance similar to the SRMS has 1/10th of the mass and packages in 1/7th of the volume when compared to the SRMS. The TALISMAN architecture allows its reach to be scaled over a large range; from 10 to over 300 meters. In addition, the dexterity can be easily adjusted without significantly impacting manipulator mass because the joints are very lightweight.

TALISMAN and SRMS Performance Comparison



Design Parameter	SRMS	TALISMAN
Total manipulator reach	15.3 m (50 ft)	15.3 m (50 ft)
Manipulator Mass	410 kg (904 lbf)	36.1 kg (79.6 lbf)
Packaged volume	1.74 m^3 (61.4 ft^3)	0.23 m^3 (8 ft^3)
Degrees of Freedom (DOF)	6 total: 2 at base, 1 elbow, 3 wrist	5 total: base rotation, 4 hinges

A first-generation full-scale TALISMAN prototype, designed for satellite servicing, has been fabricated and is currently undergoing operational testing. This application is focusing on achieving: high dexterity, a large reach envelope, applying and reacting large tip forces, being able to deploy and restow multiple times, while packaging compactly for launch.

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TALISMAN operational testing at NASA Langley Research Center Flat Floor, June 2014

Key Features

- Uses tendon actuation, which can be semi or fully antagonistic, with major components being the links, spreaders, and lightweight cables, motors, gearboxes
- Increased joint stiffness due to tendon architecture
- Lightweight joints enable the number of joints to be optimized to achieve desired packaging, efficiency, range-of-motion, dexterity, etc.
- Potential to increase manipulator stiffness using passive tension elements (very lightweight)
- Versatility; many different cable/motor/control options can be implemented
- Modularity; links and joints are easy to scale for different applications, can combine links and joints as needed for packaging, dexterity, etc. to achieve operational needs
- Novel hinge joint allows full 360-degree rotation between adjacent links, improving dexterity and range of motion
- Uses lightweight truss structures for links.