Sample Capture and Orientation Technologies for Potential Mars Sample Return

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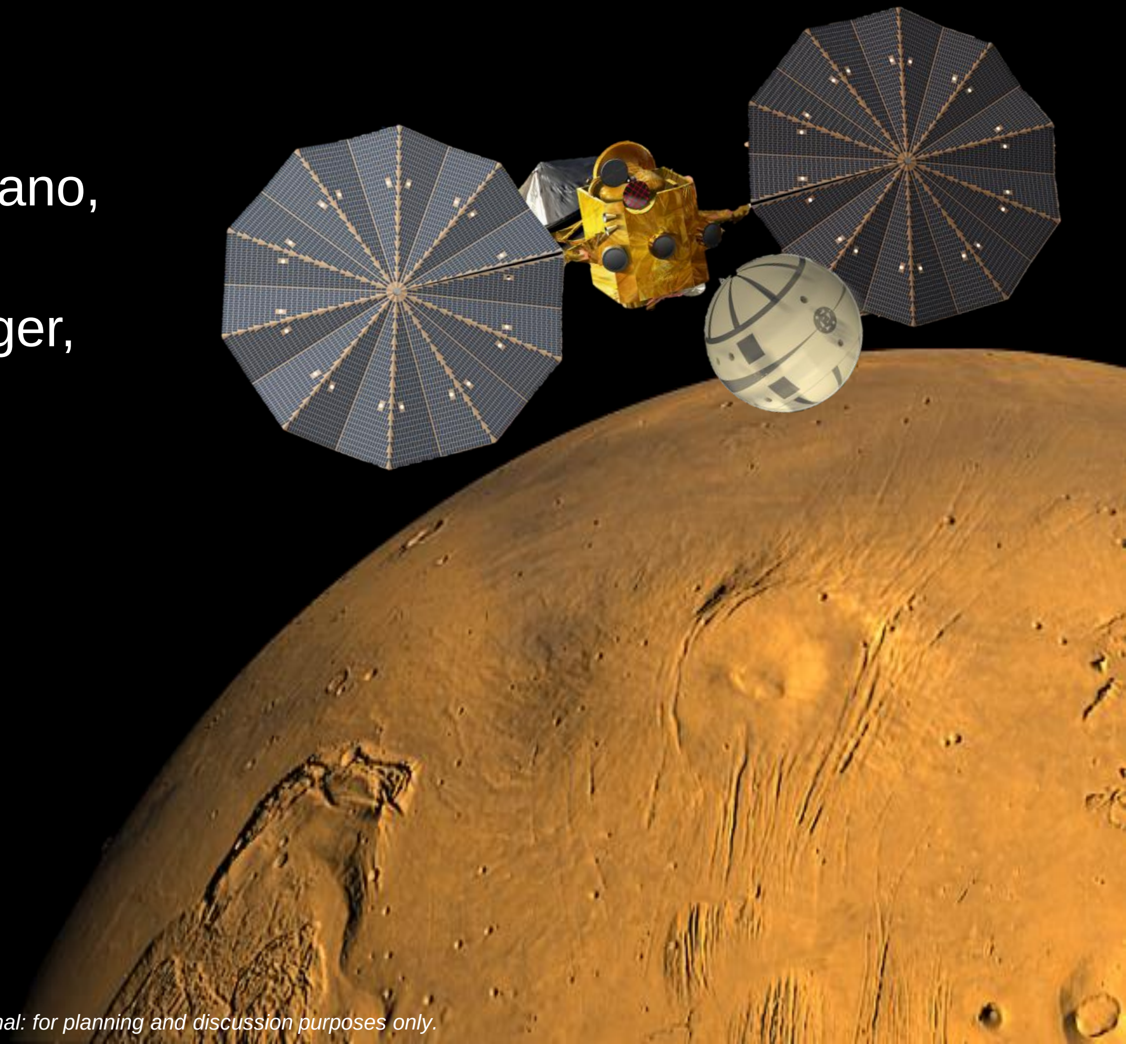

Overview

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- A sample capture and orientation system architecture for a Rendezvous and Orbiting Sample Capture System (ROCS) was developed that provides:
  - On-orbit Orbiting Sample (OS) capture, orientation, and transfer into a containment vessel
  - “Captures before contact” to contain Martian dust and alleviate the need to V&V contact dynamics in zero-g
  - Isolation of the OS from the critical sample containment hardware during capture
  - Modularity with clean functional partitioning, spatial partitioning, and interfaces
- Initial developmental testing was performed
- Plan to develop a full-scale TRL 4 Capture and Orient Module, and eventually test within an integrated end-to-end ROCS prototype

Notional Mars Sample Return Architecture

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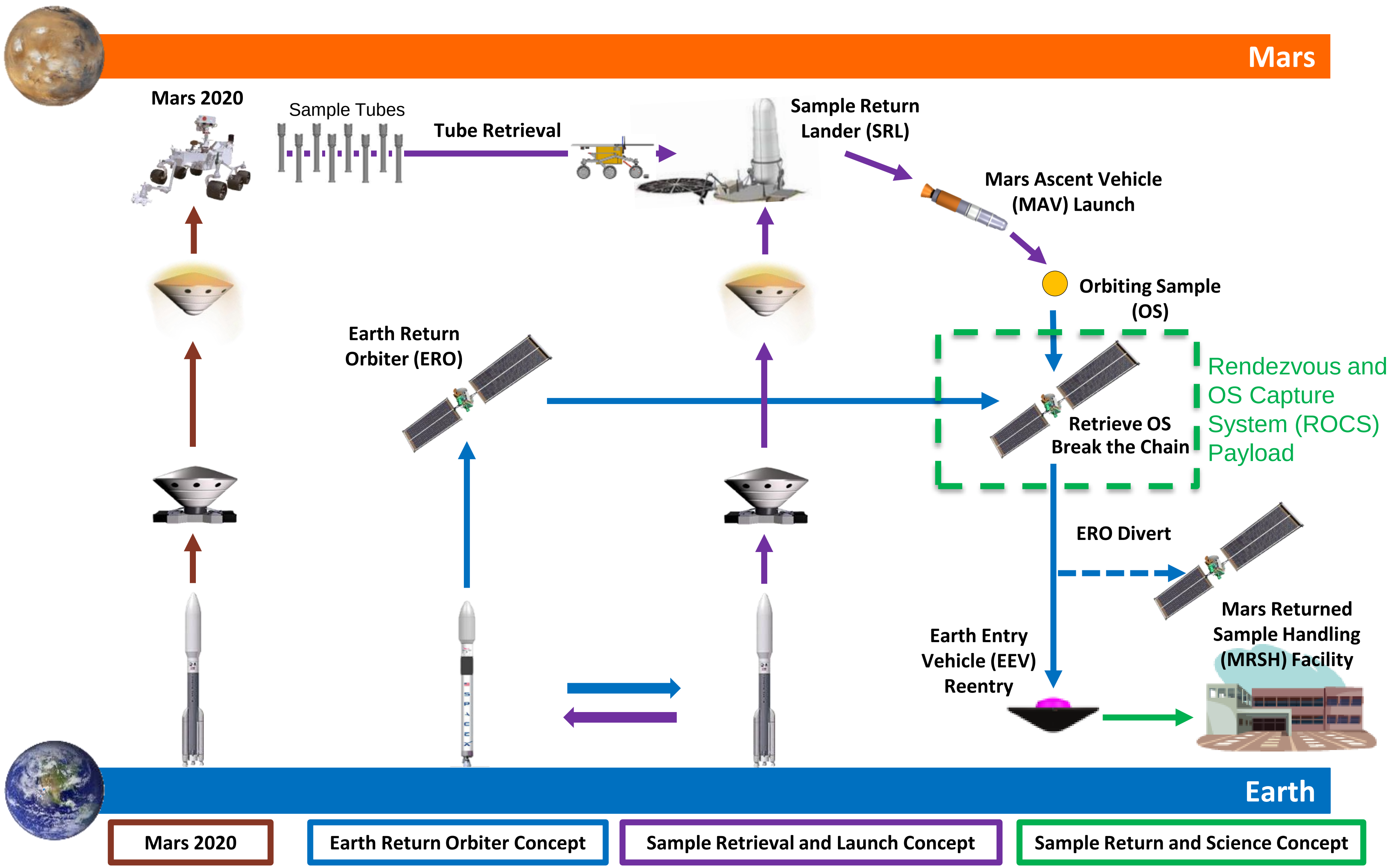
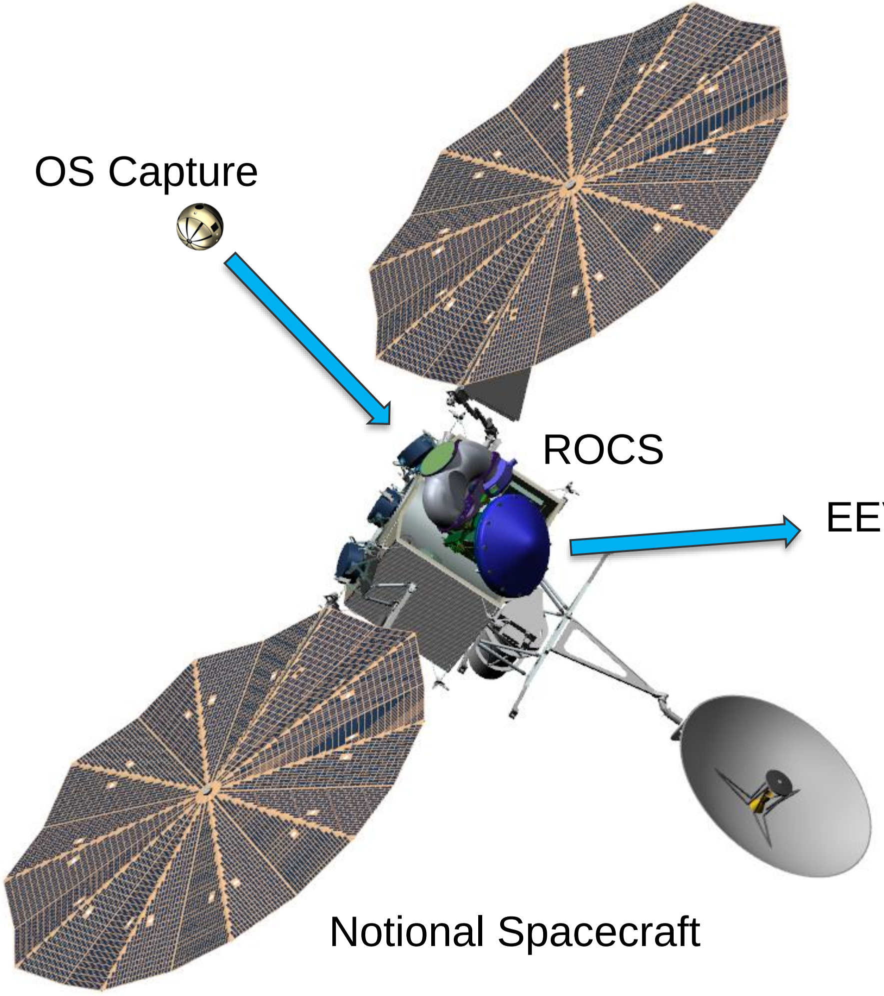
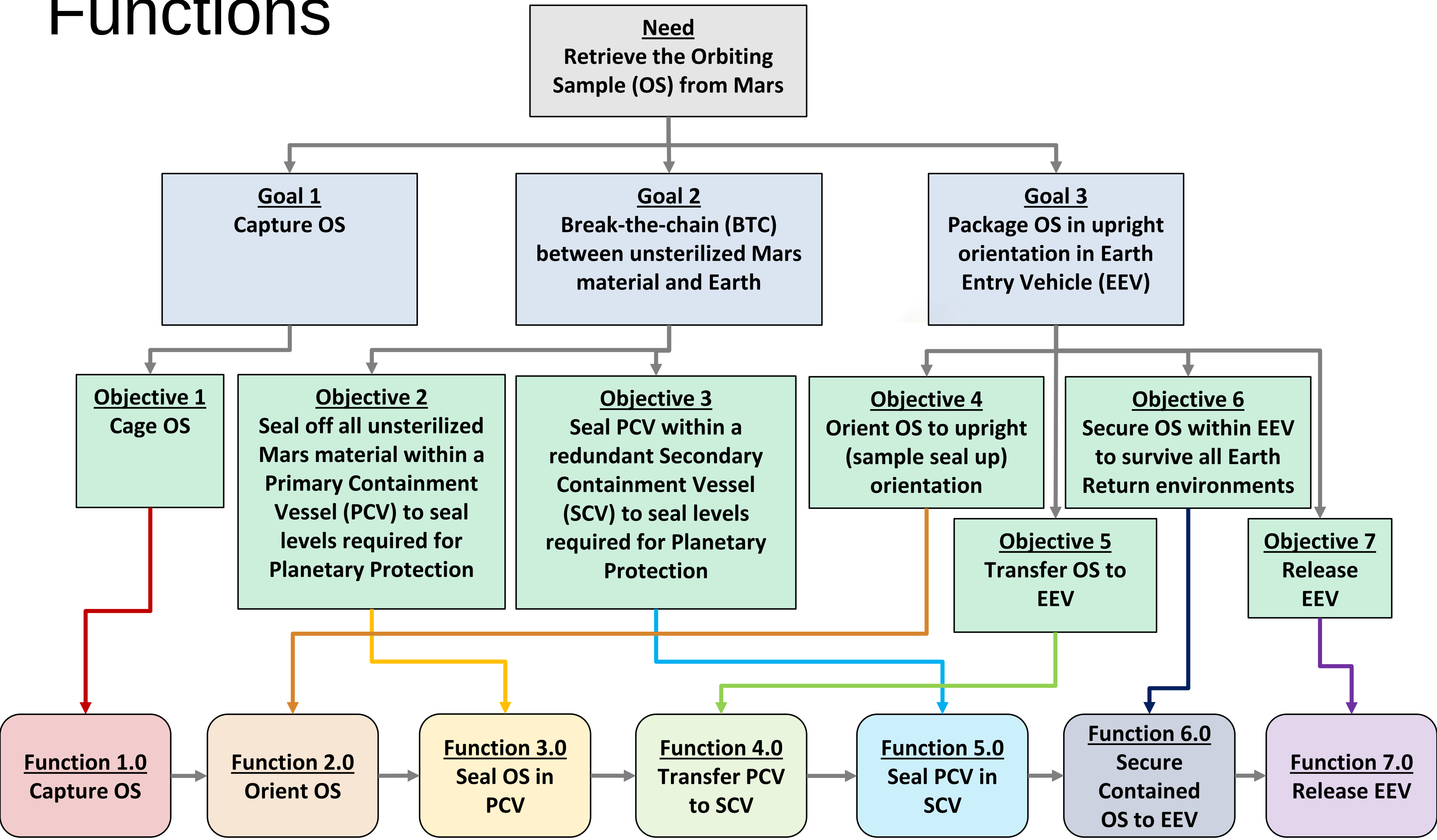


Rendezvous and OS Capture System (ROCS) Payload



ROCS Need, Goals, Objectives, Functions



Functional Partitioning

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Capture and Orient Module	Containment Module	Earth Return Module
Technical Challenge (Strategy: Balance technology development efforts; consolidate domains)		
Capture/Orient Mechanisms	Primary/Secondary Seal	EDL
OS State (Strategy: Isolate dynamic interactions)		
Dynamic	Static	Static
Operational Environment (Strategy: Separate environmental requirements)		
Space	Internal	Internal/Space/Earth
Planetary Protection Cleanliness (Strategy: Separate Planetary Protection zones)		
Exposed to Mars Material	Clean	Exposed to Earth

- **Function 1.0** Capture OS →
- **Function 2.0** Orient OS →
- **Function 3.0** Seal OS in PCV →
- **Function 4.0** Transfer PCV to SCV →
- **Function 5.0** Seal PCV in SCV →
- **Function 6.0** Secure Contained OS to EEV →
- **Function 7.0** Release EEV

Capture Technologies

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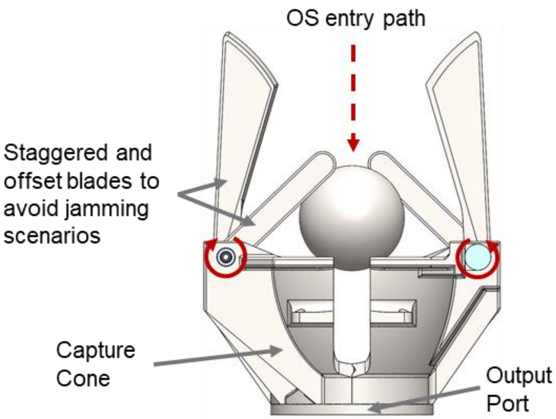
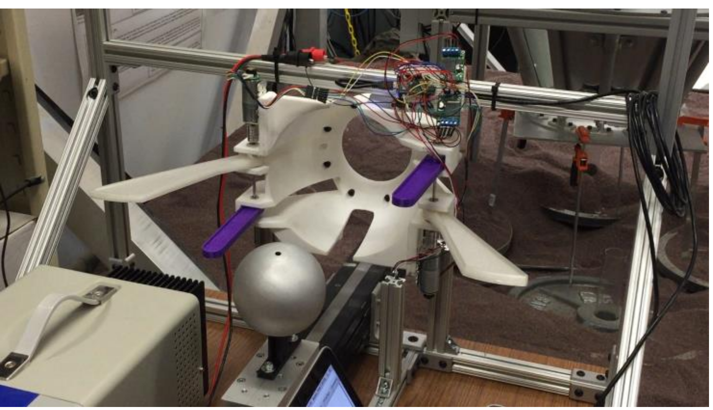
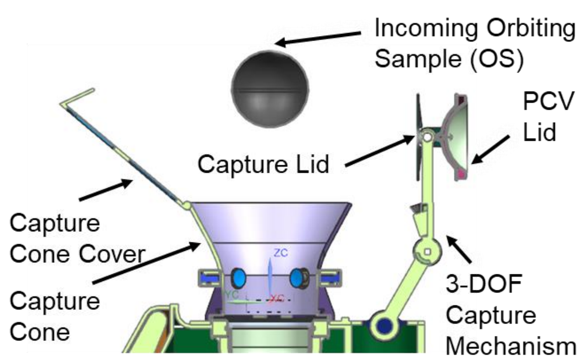
Bladed Capture

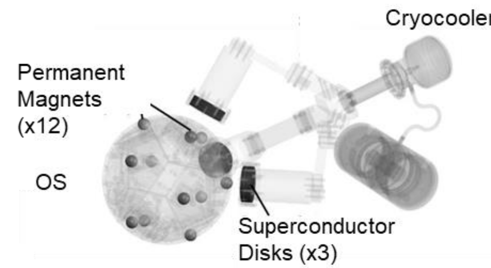




Capture Arm



Flux Pinning



Orient Technologies

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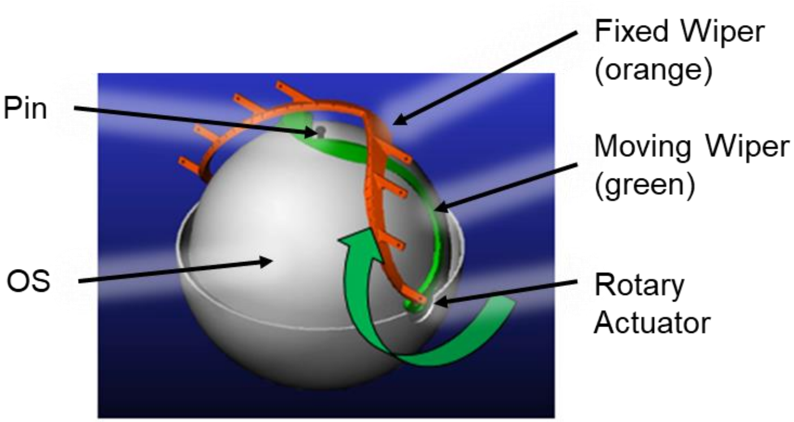
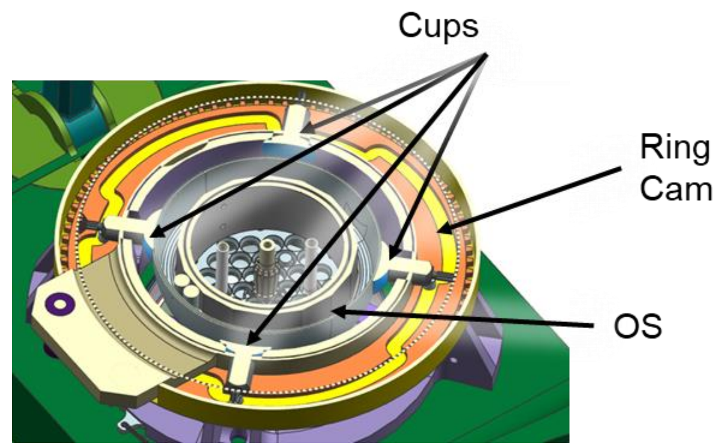
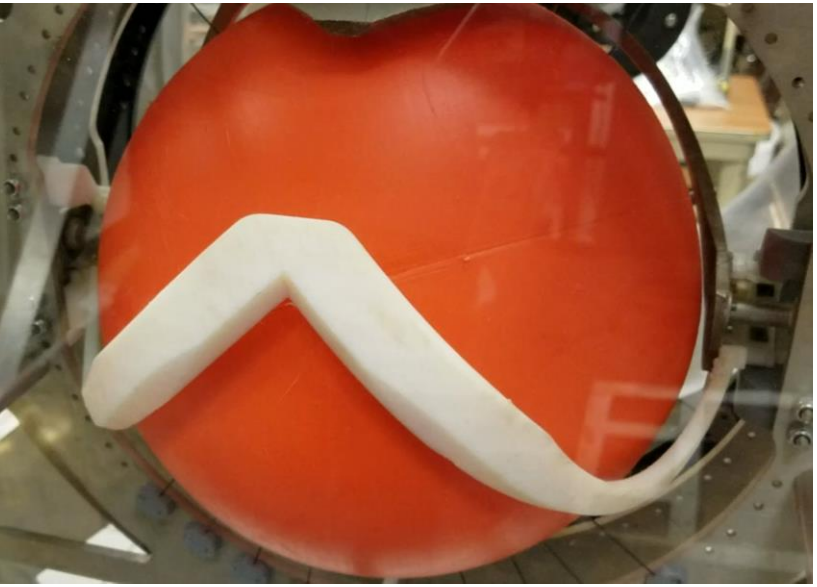
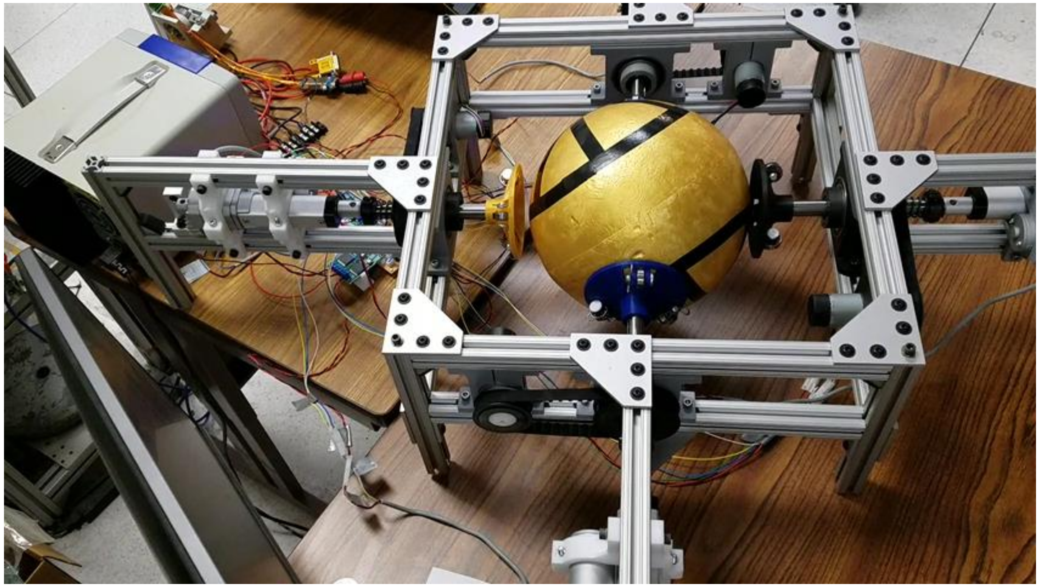
Wiper Mechanism



Motorized Cups







Capture and Orient Module Architecture

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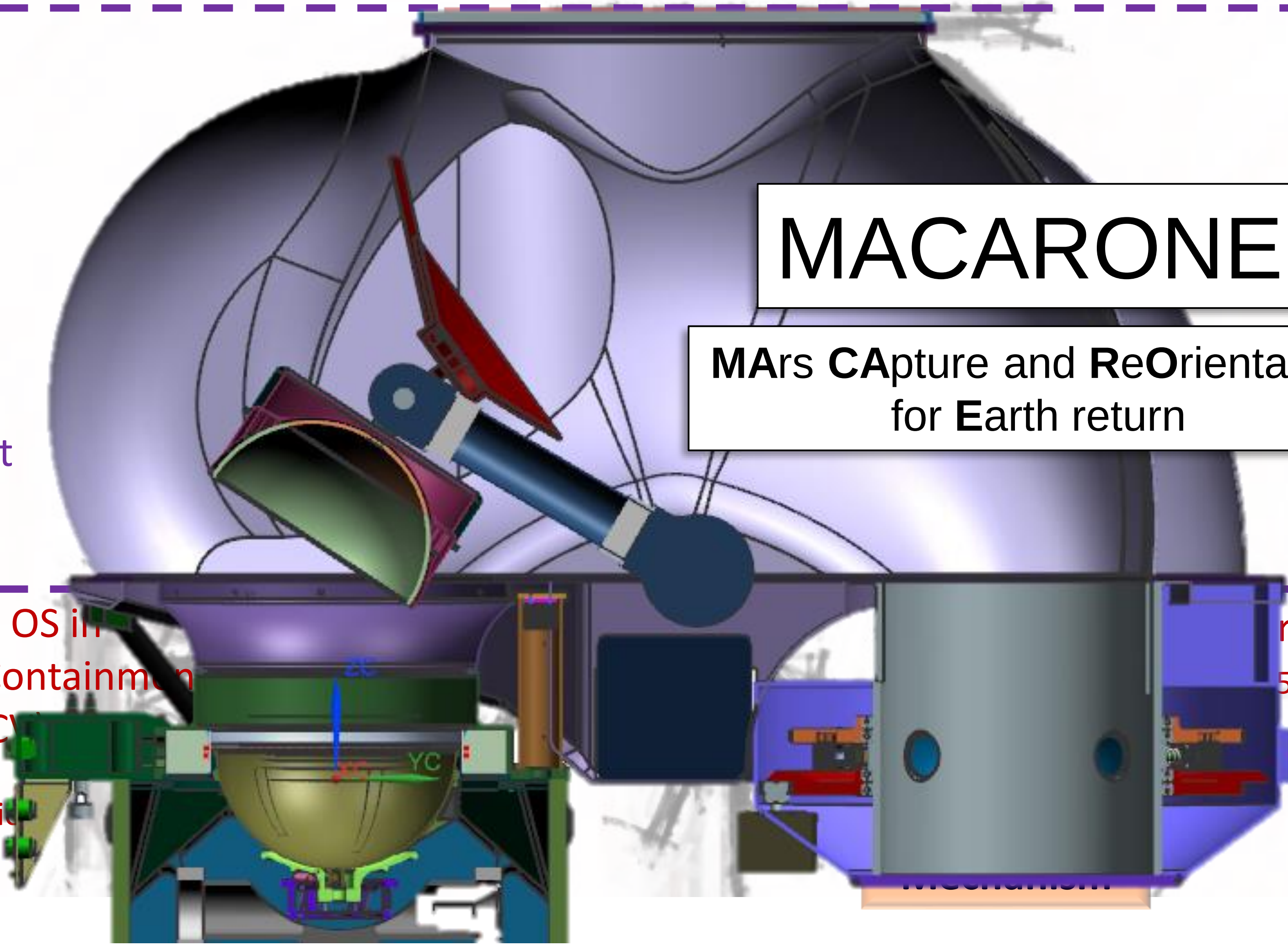
1 Capture OS

- Ø28 cm
- 12 kg
- 10 cm/s

Capture Plane

Capture and Orient Module



MACARONE

MArs **CA**pture and **R**e**O**rientatio**N** for **E**arth return

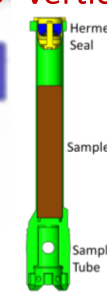
Capture and Orient Module to Containment Module Interface Plane

3 Assemble OS in Primary Containmen Vessel (PC

- 300 N load
- 1 mm precisi

rient OS

5° vertical



Predecisional: for planning and discussion purposes only.

Capture and Orient CONOPS

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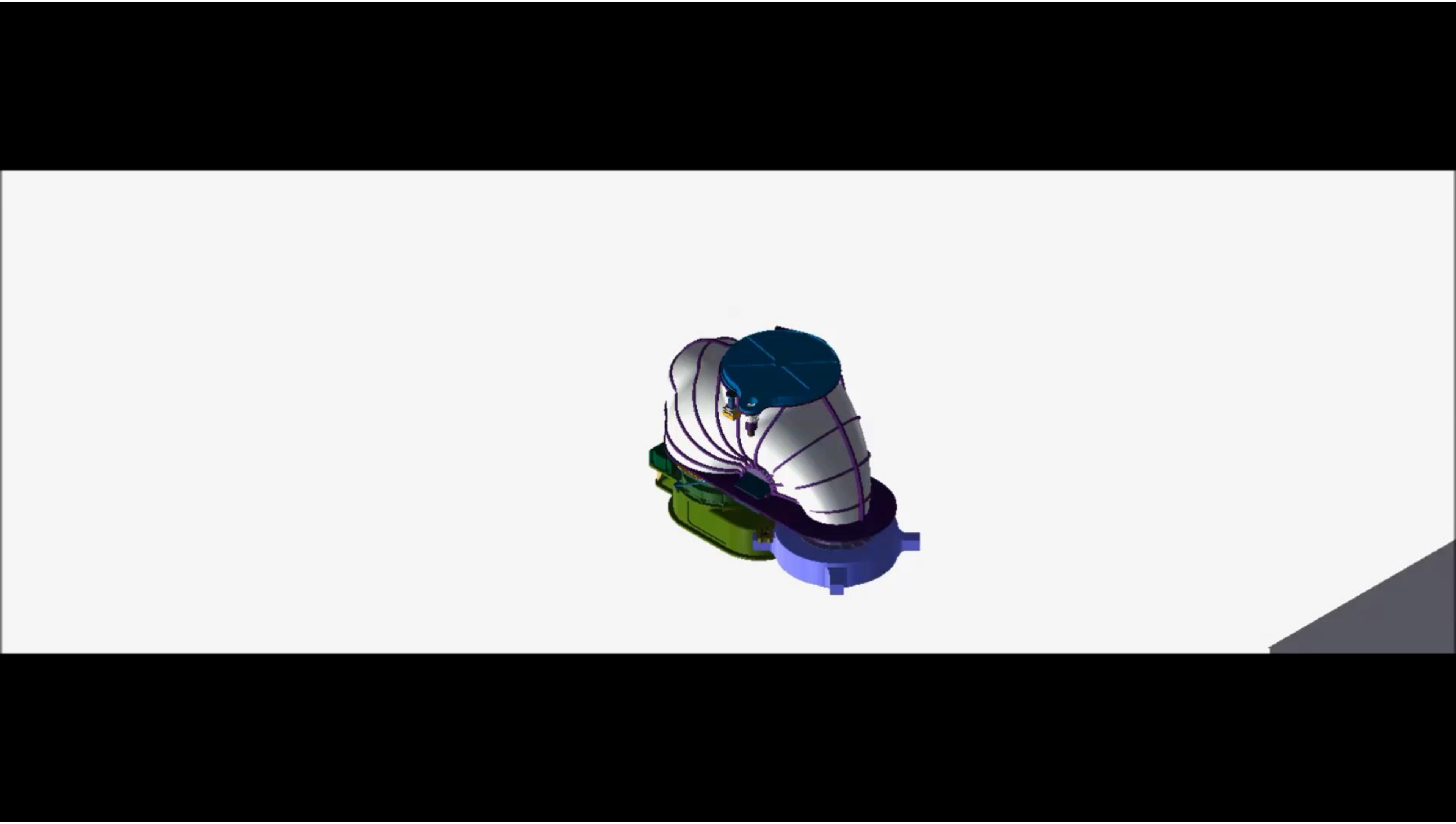

Capture and Orient Module Development Testing

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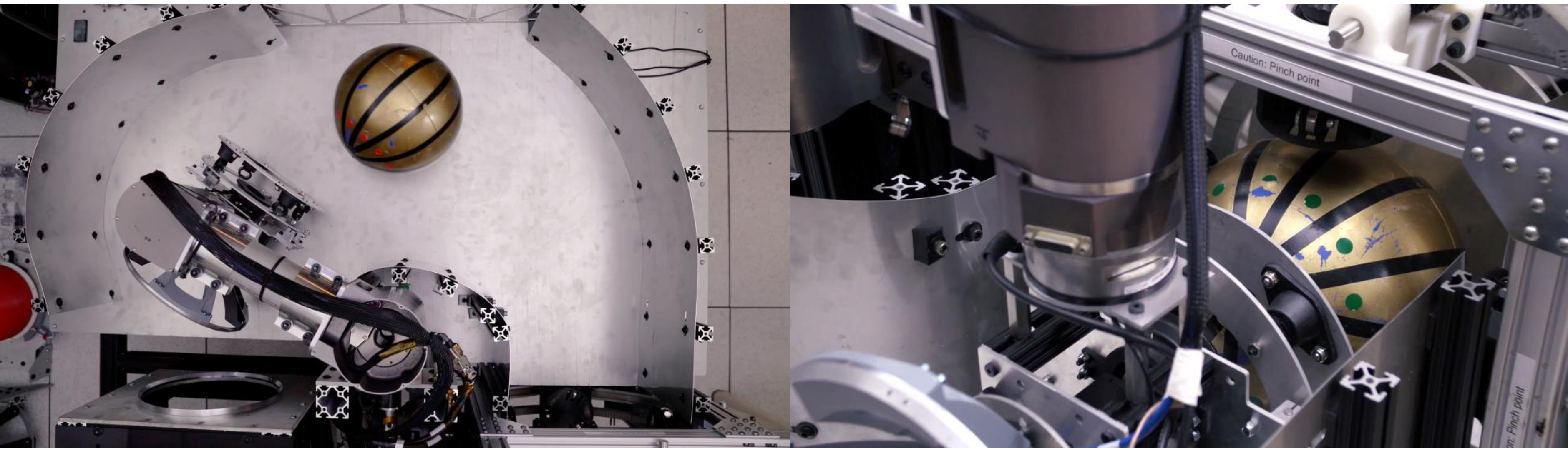
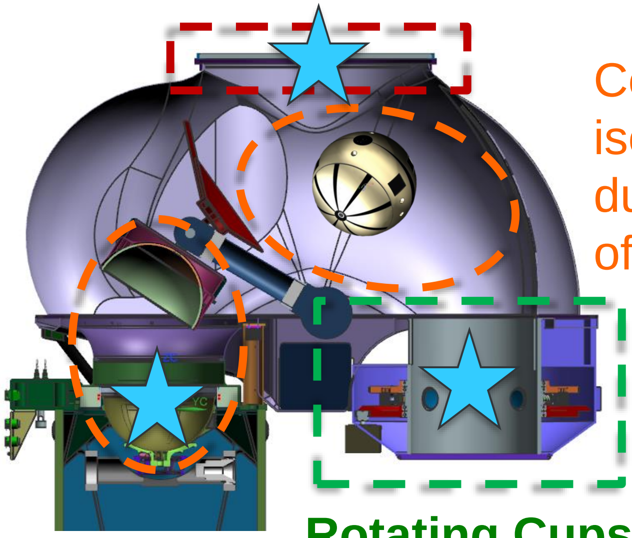


Benefits

“Capture before Contact” Capture Lid

- Containment of OS and dust prior to first contact reduces spacecraft contamination risk
- Eliminates the need to simulate contact dynamics for V&V analysis and testing
- Separates time-dependent capture function from other time-independent functions



Containment hardware isolated from OS contact during capture, reducing risk of damage from impact

Subsystem modularity with clean functional partitioning, spatial partitioning, and interfaces allows for development flexibility and technology flexibility

Rotating Cups Orientation Device

- No physical OS modification required
- Cups stow within structure to avoid contact with OS during capture
- Deterministic, quasi-static operation, testable in 1 G

Integrated ROCS Concept

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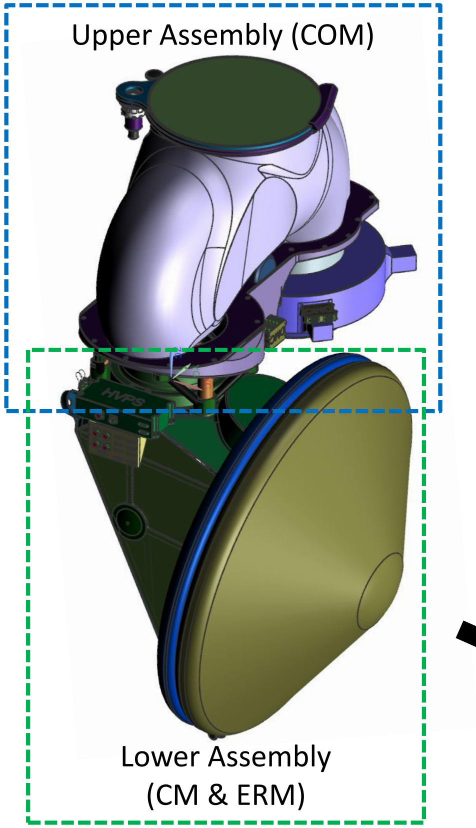
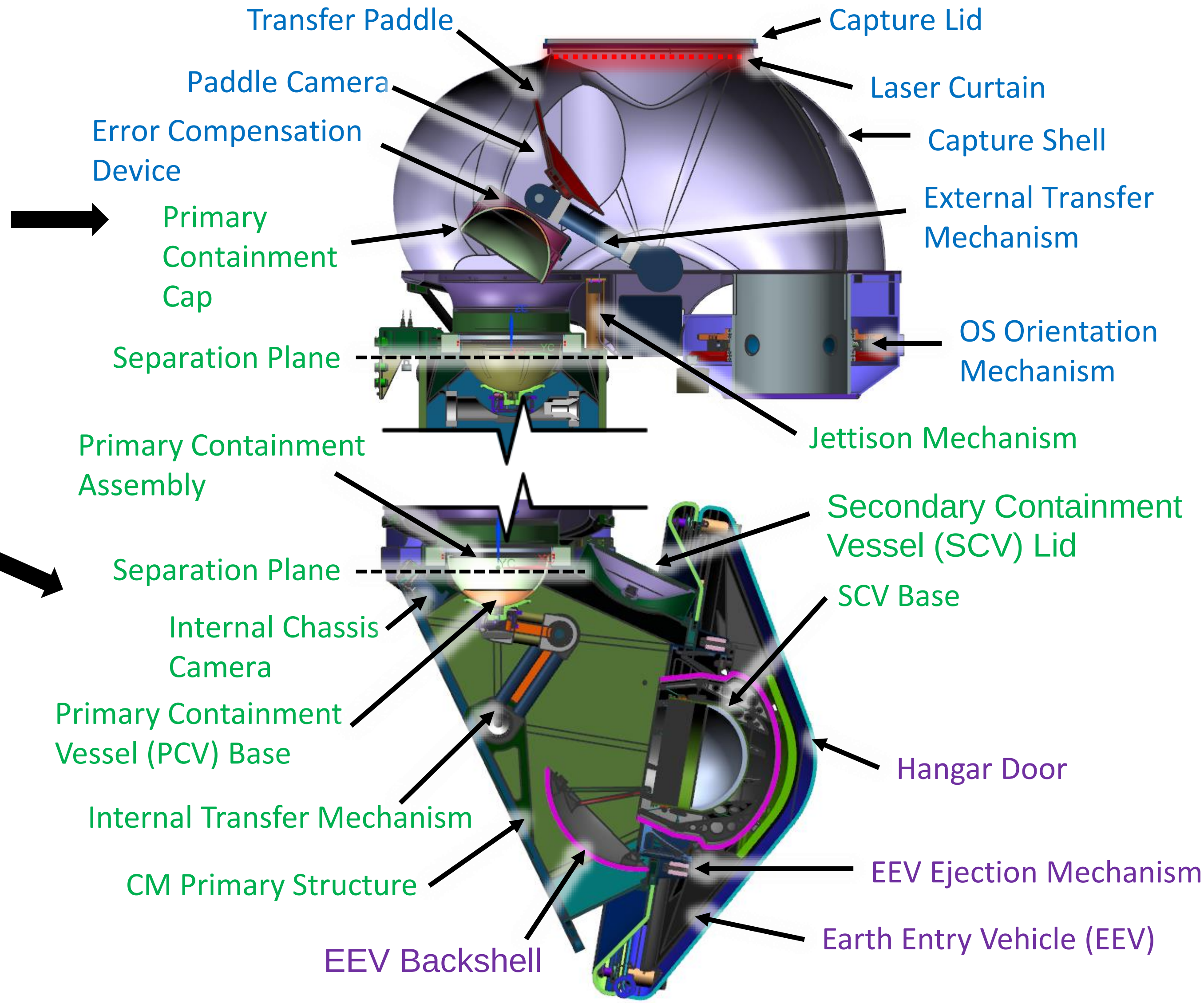




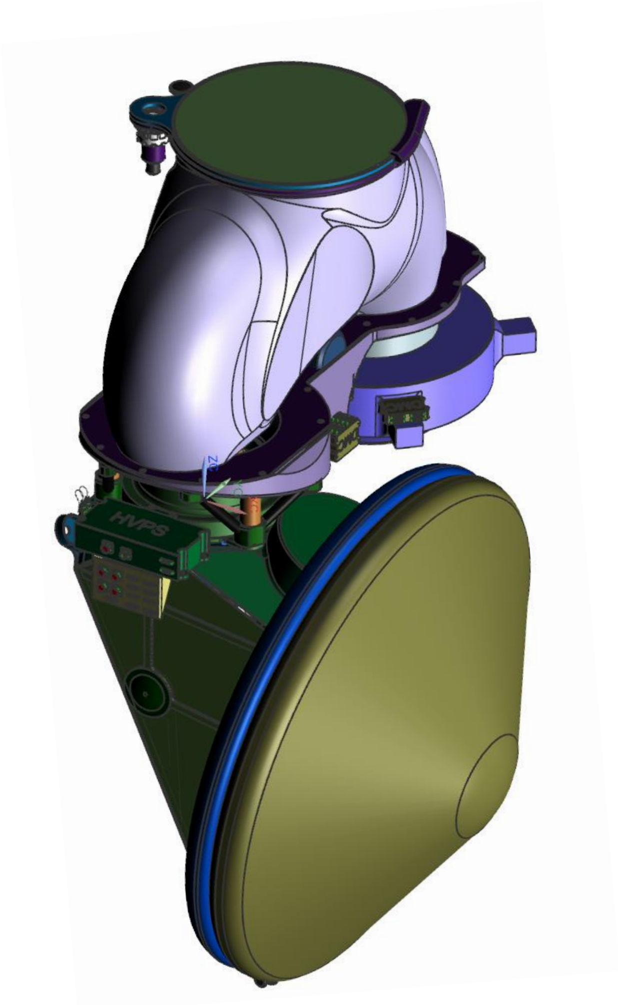
ROCS Elements

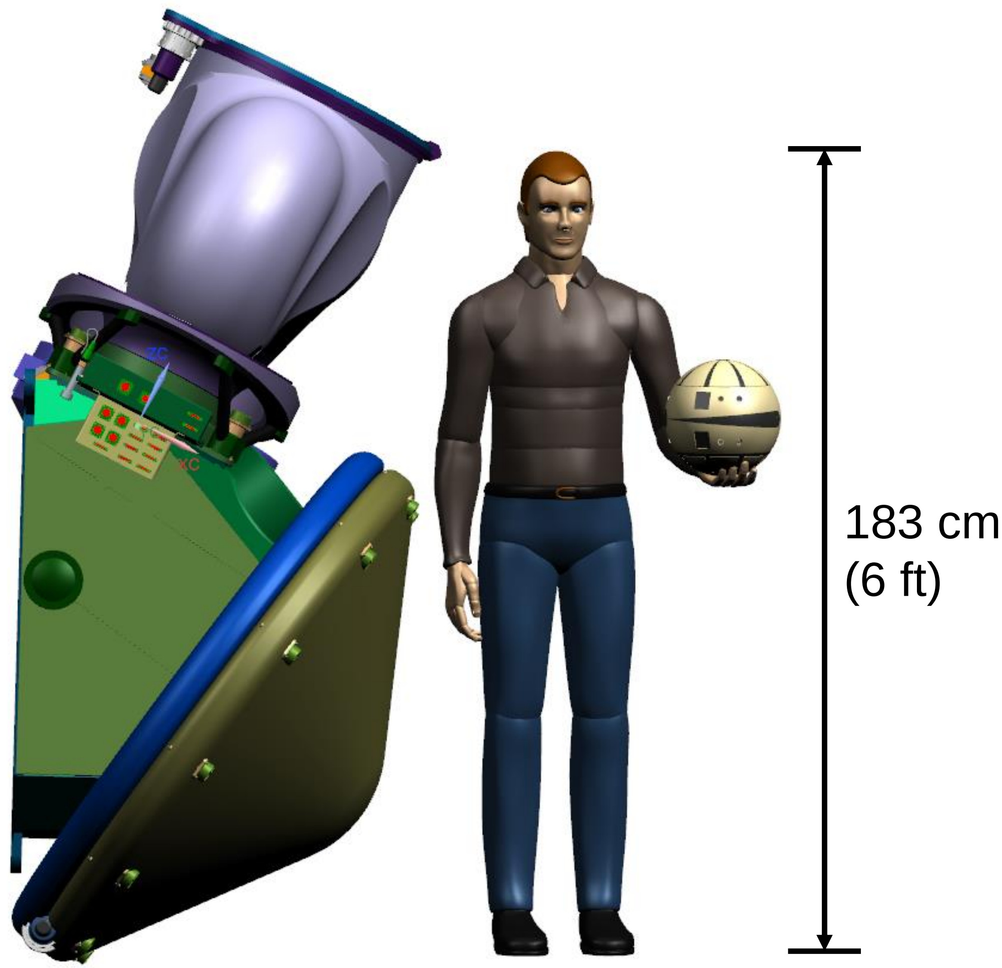
Capture & Orient Module (COM)

Containment Module (CM)

Earth Return Module (ERM)

Integrated ROCS Concept

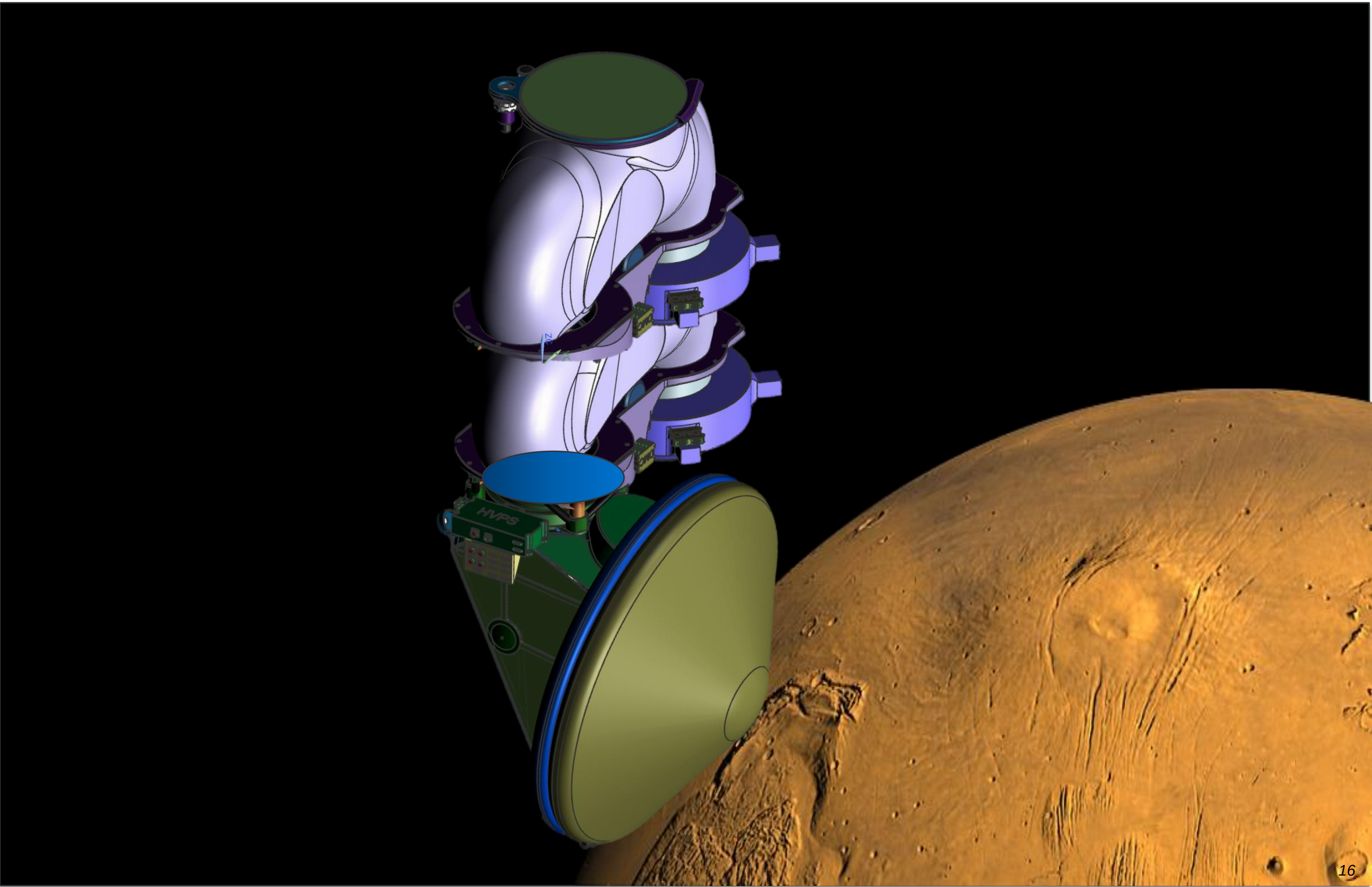




“Wizard”

ROCS CONOPS

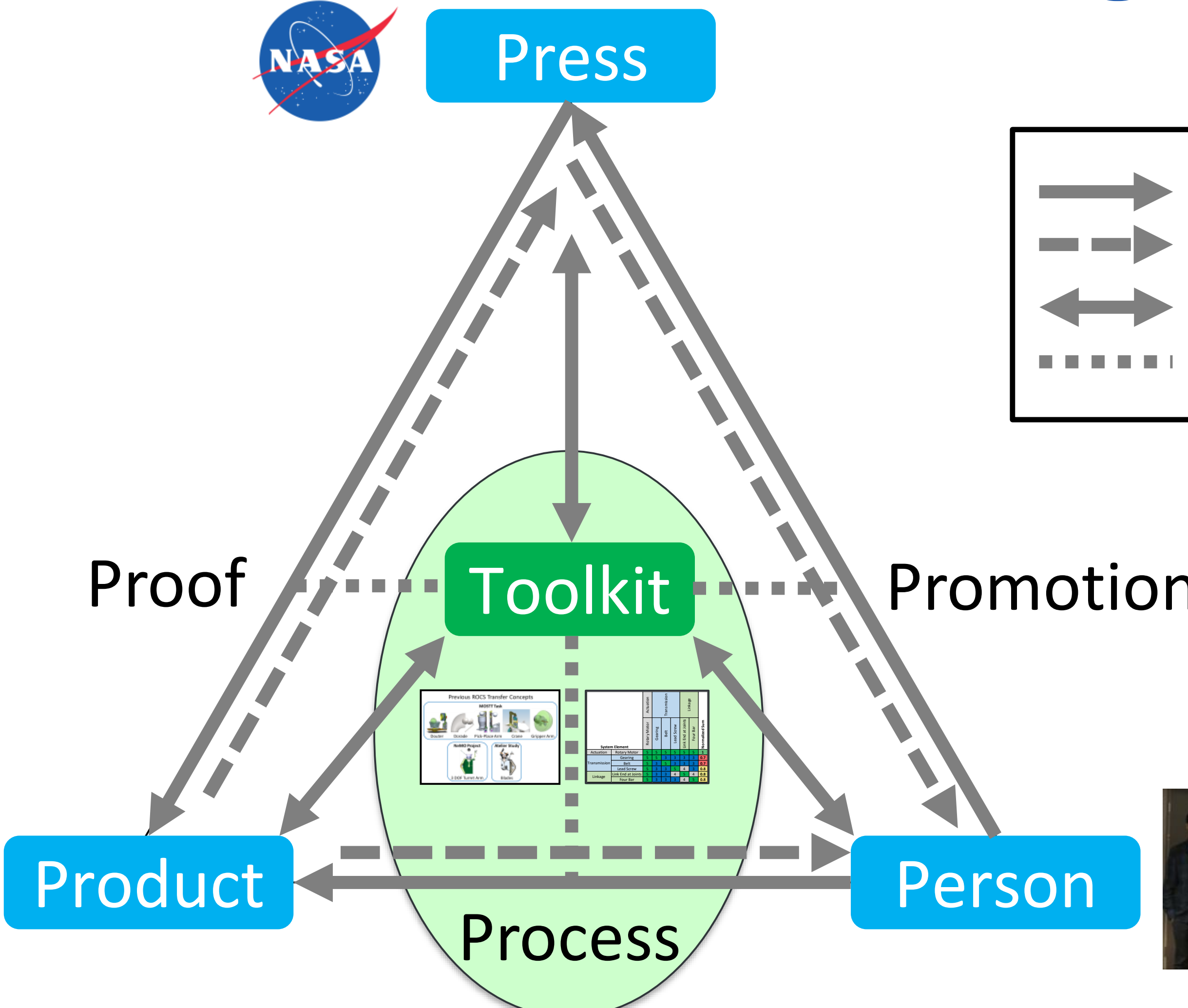
Jettison at Mars

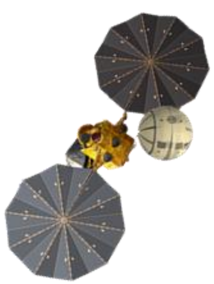


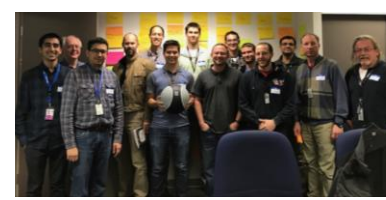
Future Work

- Develop a full-scale TRL 4 (breadboard validation in a laboratory environment) prototype of the Capture and Orient Module
  - Autonomous behaviors
  - Sensing and telemetry
  - Full-size 28 cm OS with realistic surface characteristics
- Integrate the Capture and Orient Module with a Containment Module and Earth Return Module to perform full ROCS end-to-end system testing

6 P's Development Framework







Younse, P., J. Strahle, M. Dolci, P. Ohta, K. Lalla, R. Adajian, "Systems Architecting using Bloom's Taxonomy to Promote Creative Engineering Synthesis," *2018 IEEE Aerospace Conference*, Big Sky, MT, Mar. 3-10, 2018.

Summary

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Acknowledgements

Jet Propulsion Laboratory
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Questions?

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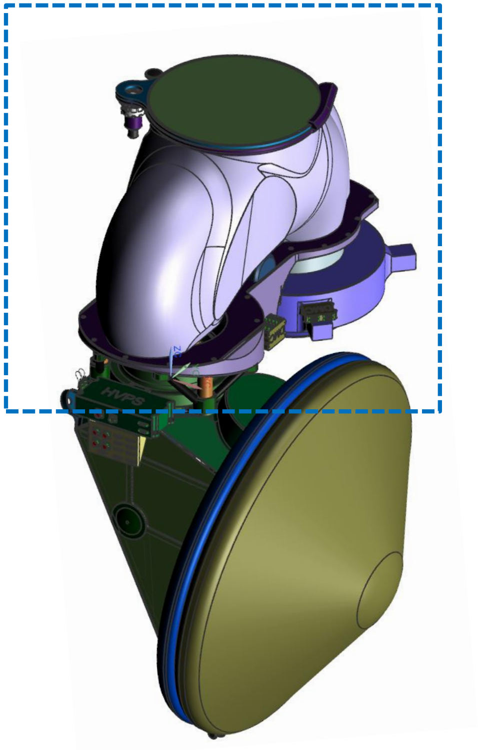

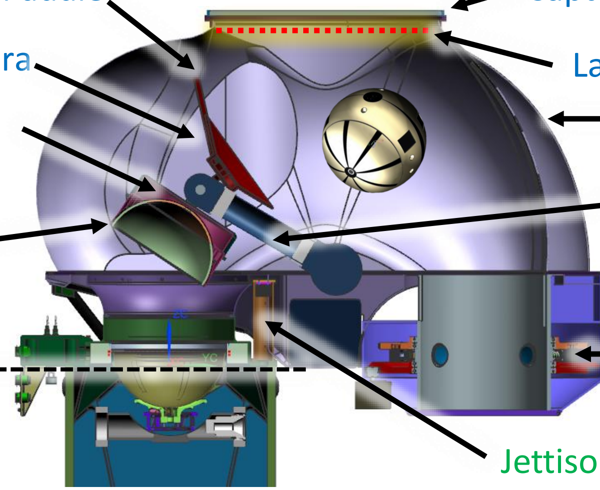

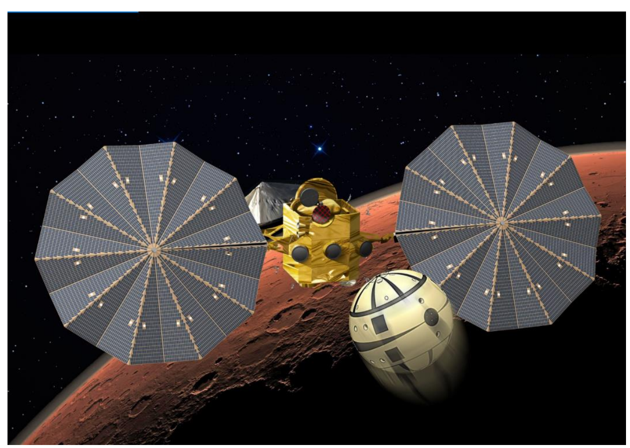

Backup

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A Systems Architecting Methodology Using Bloom's Taxonomy to Promote Creative Engineering Synthesis

Paulo Younse, Jackson W. Strahle, Karan Lalla, Marco Dolci, Preston Ohta, Rama Adajian

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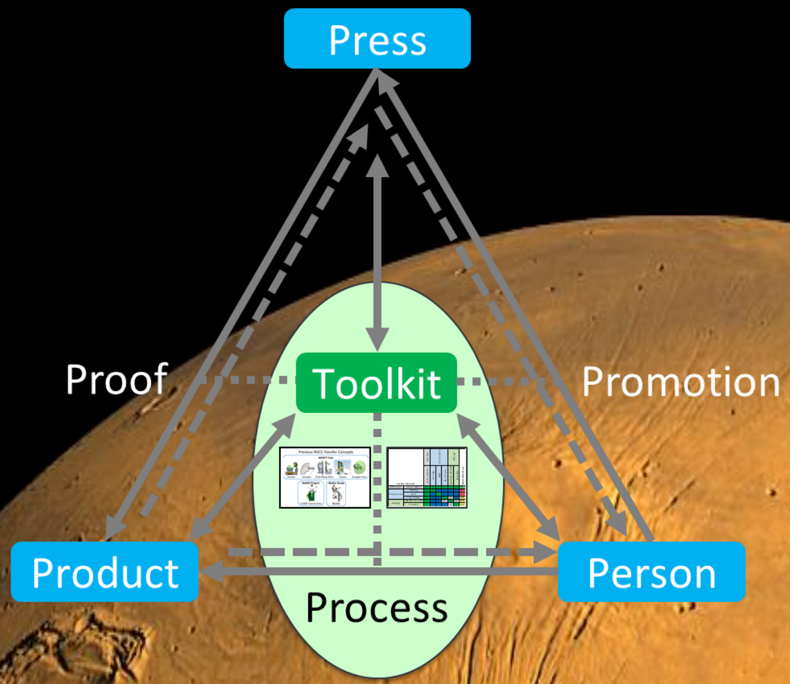

Overview

- A systems architecting methodology was developed to synthesize complex systems requiring high levels of creativity and expertise
- Methodology was derived from:
  - Creativity processes from cognitive psychology
  - Principles of learning from educational psychology
  - Engineering tools from systems engineering
- Bloom's Taxonomy was used a framework to develop learning objectives and activities associated with the tools in the methodology to develop expertise
- The methodology provides a mechanism to develop deeper system knowledge and capture complex information
- The methodology is currently being applied to develop elements of a Mars Sample Return Capture and Orient Module concept

Architecting Complex Systems

- Modern engineering systems are rapidly becoming increasingly complex due to the development of new emerging technologies and the integration of elements that span multiple knowledge domains.
- Architecting new and effective complex systems requires both a high level of creativity and a deep knowledge expertise stemming from multiple domains.

Mars Sample Return Example

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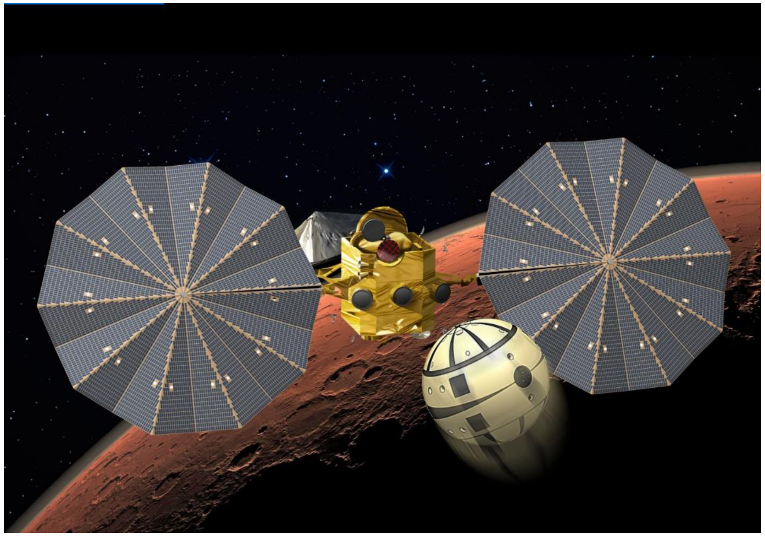
- Rendezvous and Orbiting Sample Capture System (ROCS) designed to retrieve a samples from Mars
- Capture and Orient Module concept to enable spacecraft-based, on-orbit capture, orientation, and transfer of a Mars Orbiting Sample (OS) container into a containment vessel as part of a potential Mars Sample Return campaign



Creative System Architecting

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- Creativity
  - Mental Activity
    - **Cognitive Psychology**: Branch of psychology concerned with the scientific study of the mind (Goldstein, 2015)
  - Expertise
    - **Educational Psychology**: Branch of psychology concerned with how we think and learn, and how to address learning needs of students (Long et al., 2011)
- System Architecting
  - Engineering Tools
    - **Systems Engineering:** Branch of engineering concerned with engineering complex systems, where a system is a set of interrelated elements working together toward a common objective (Kossiakoff et al., 2011)

Creativity

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- Sociocultural definition (Sawyer, 2009)
  - “Creativity is the generation of a **product** that is **judged** to be **novel** and also to be appropriate, useful, or **valuable** by a suitably knowledgeable social **group**.”
- Creativity framework (Rhodes, 1961)
  - Product
  - Person
  - Process
  - Press

6 P’s Creativity Framework

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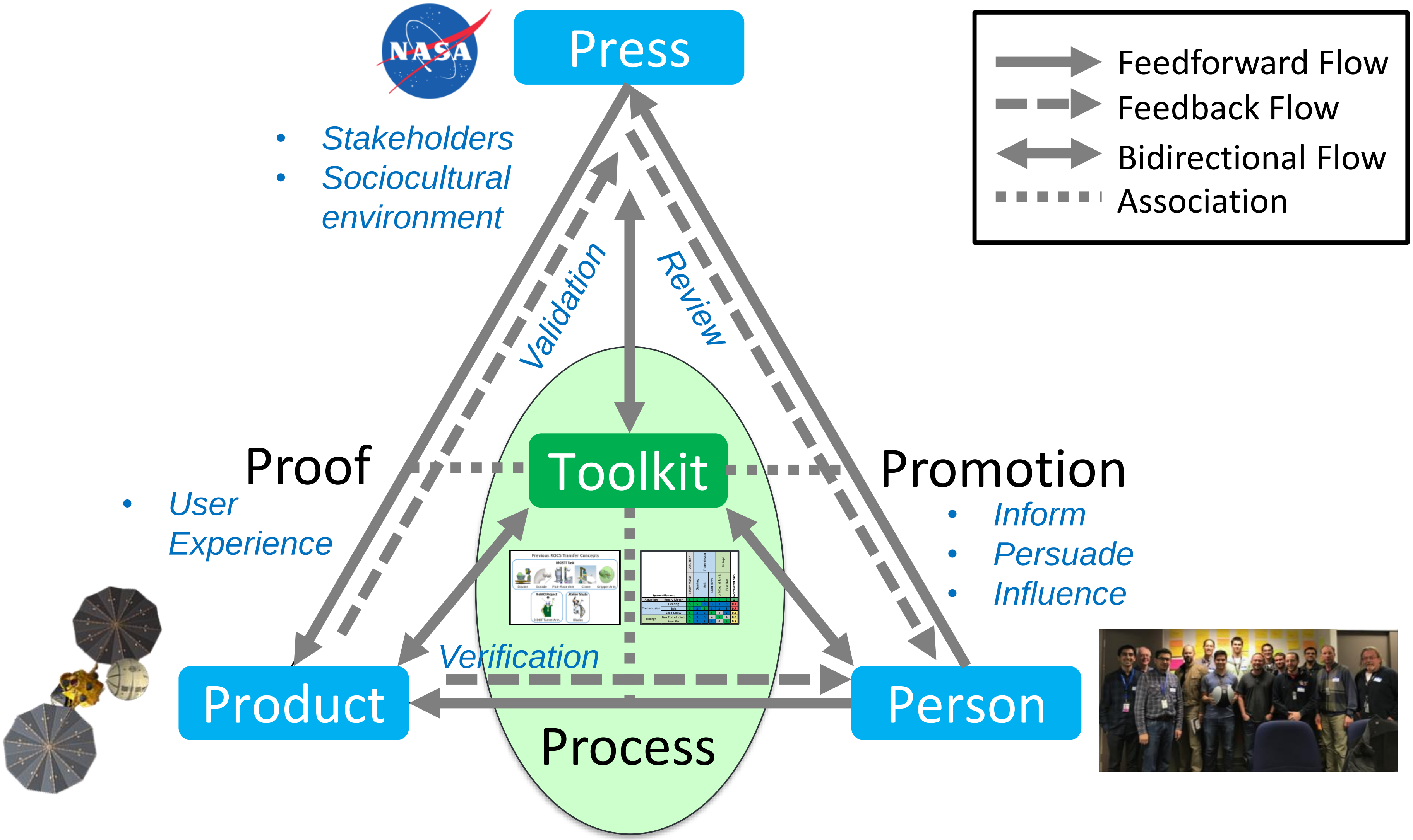

Creative Process

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- Eight stage process (Sawyer, 2009)
  - Find and formulate the problem
  - Acquire knowledge relevant to the problem
  - Gather a broad range of potentially related information
  - Take time off for incubation
  - Generate a large variety of ideas
  - Combine ideas in unexpected ways
  - Select the best ideas
  - Externalize the idea using materials and representations

Problem Solving Blocks

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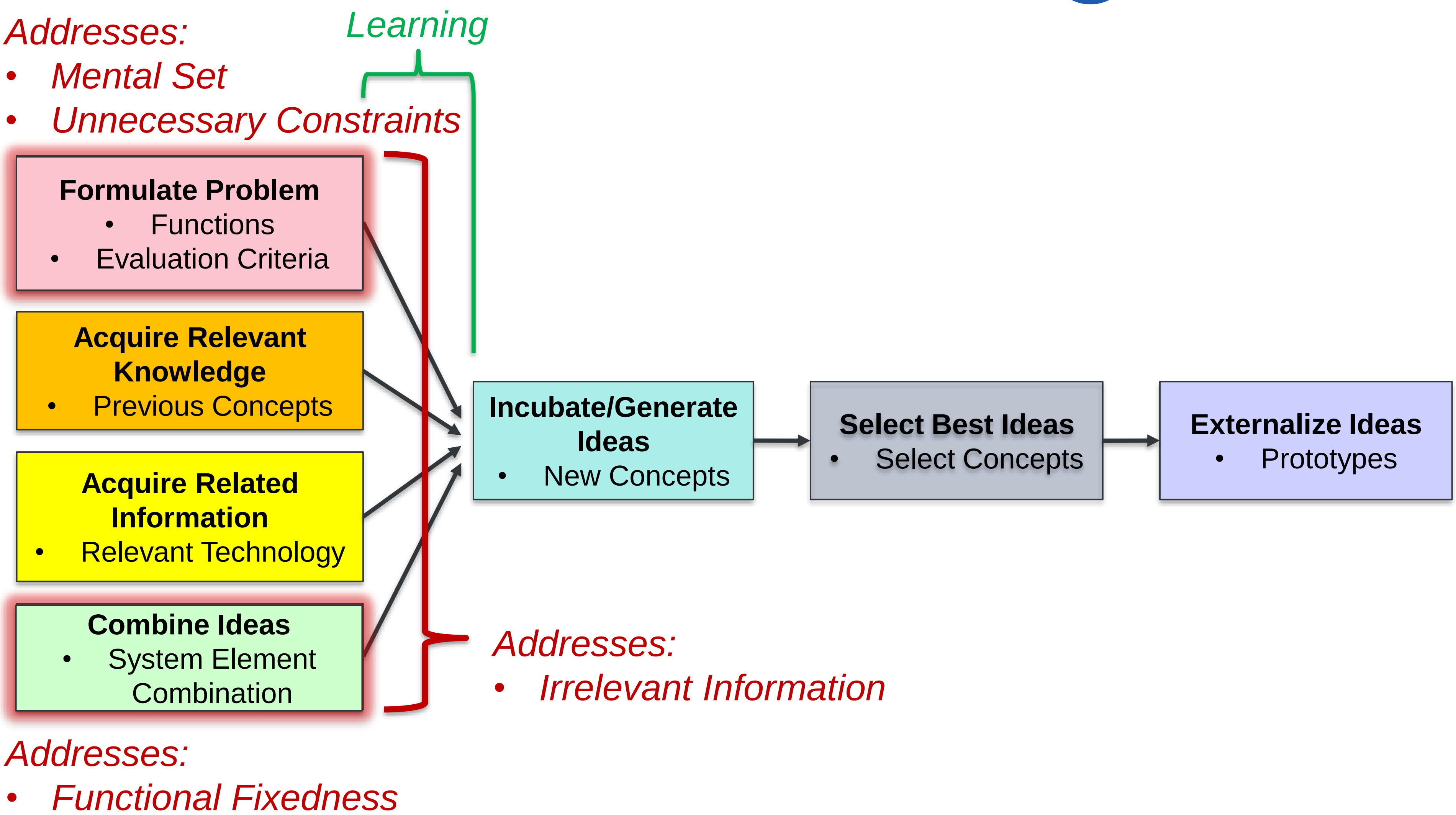
- Common psychological barrier to problem solving (Weiten, 2017)
  - Irrelevant information
  - Functional fixedness
  - Mental set
  - Unnecessary constraints

Creative Process

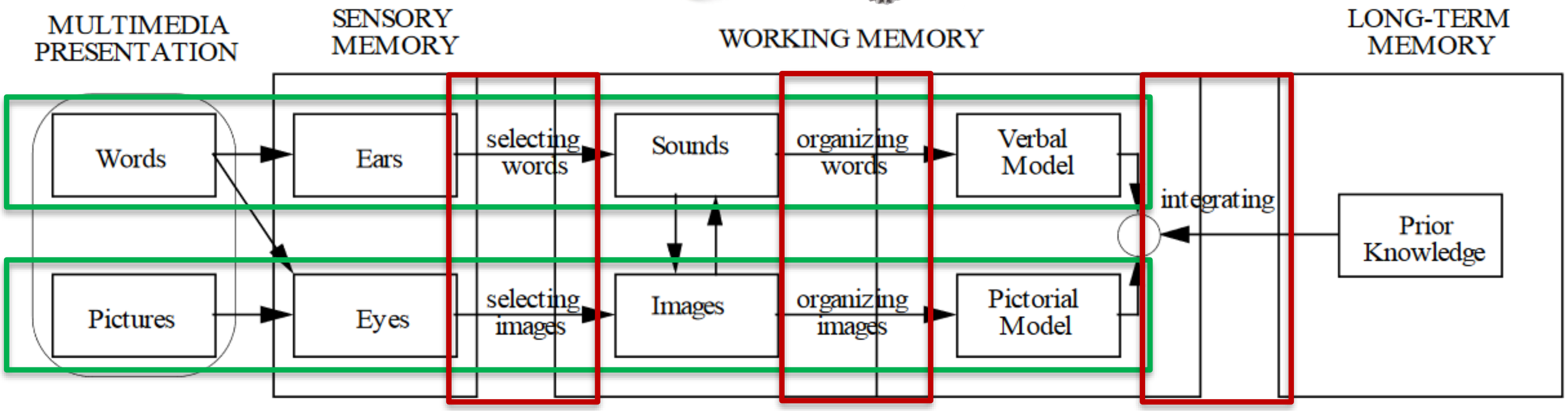


Principles of Learning

- Research-based principles from the science of learning to help build transferable knowledge (Mayer, 2014)
  - Dual Channels Principle
  - Limited Capacity Principle
  - Active Processing

3-5 chunks of information

"Gripper Arm"



Cognitive Theory of Multimedia Learning (Mayer, 2014)

Bloom’s Taxonomy (Original)

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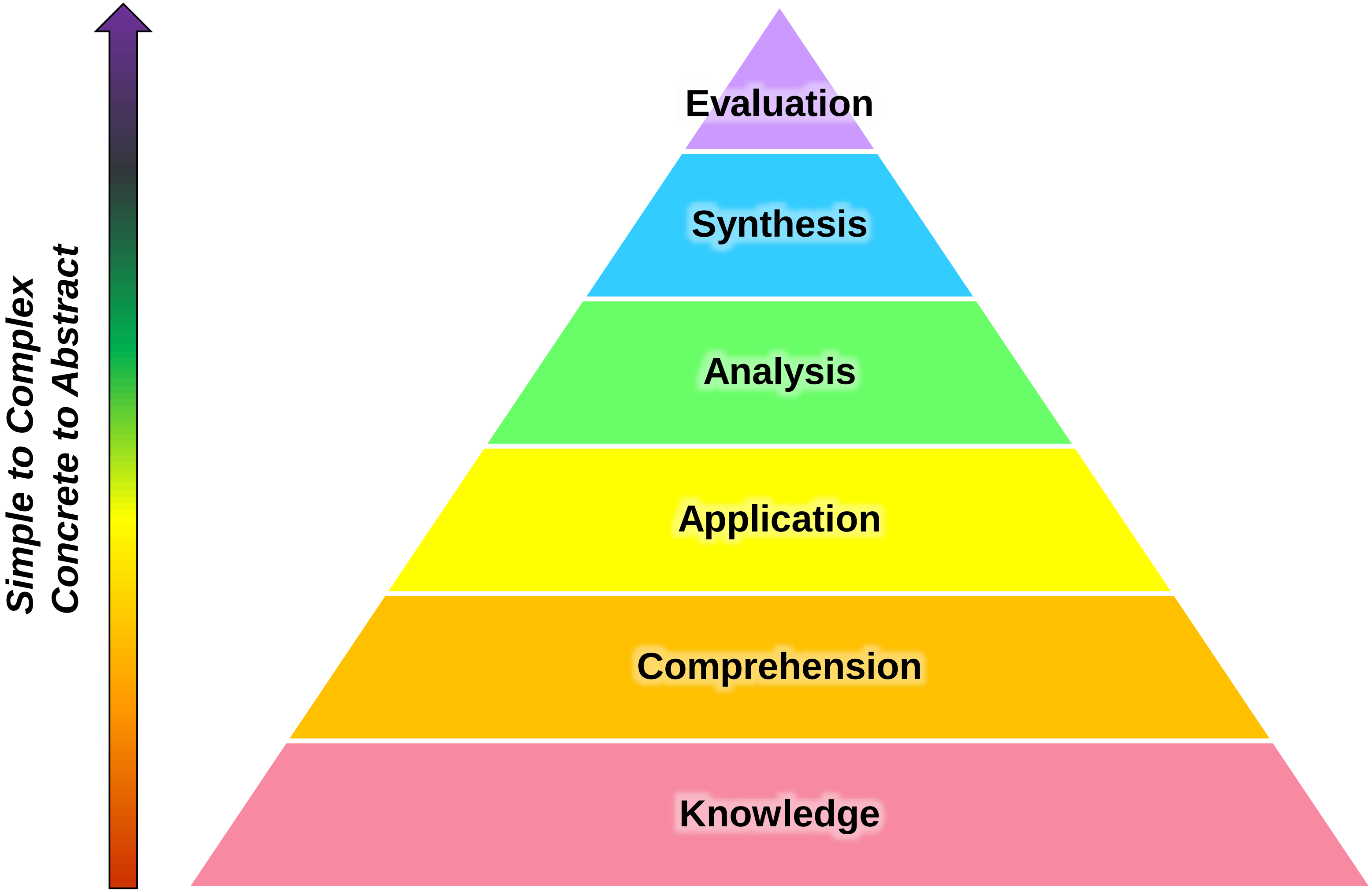

(Bloom, 1956)

Bloom’s Taxonomy (Revised)

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- Revised Bloom’s (Anderson et al., 2001)

Simple to Complex

Concrete to Abstract

					Cognitive Process																		
					1 Remember		2 Understand							3 Apply		4 Analyze			5 Evaluate		6 Create		
					1.1	1.2	2.1	2.2	2.3	2.4	2.5	2.6	2.7	3.1	3.2	4.1	4.2	4.3	5.1	5.2	6.1	6.2	6.3
					Recognizing	Recalling	In...eting	...nplifying	...ssifying	...mmarizing	Inferring	Comparing	Explaining	Executing	Implementing	Differentiating	Organizing	Attributing	Checking	Critiquing	Generating	Planning	Producing
Knowledge	A	Factual	A.A	Terminology	x																		
			A.B	Specific Details/Elements	x									x							x	x	x
	B	Conceptual	B.A	Classifications/Categories																			
			B.B	Principles/Generalizations			x	x															
			B.C	Theories/Models/Structures												x	x	x			x		
	C	Procedural	C.A	Subject-specific Skills/Algorithms																			
			C.B	Subject-specific Techniques/Methods																			
			C.C	Criteria for Procedure Use																			
	D	Metacognitive	D.A	Strategies																			
			D.B	Cognitive Tasks																			
			D.C	Self-knowledge																			

Deeper Learning + Higher Performance

Learning Objective = Cognitive Process + Knowledge

Systems Engineering Tools

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Morphological Matrix

Internal Process	Instrument	Car	Train	Jet Aircraft	Propeller Aircraft	Helicopter	Airship	Glider	Boat	Submarine	Jet Boat	Hydrofoil
Lifting	Wheels	X	X									
	Propeller					X						
	Wings			X	X			X				X
	Closed hull						X			X		
	Open hull								X		X	
Propelling	Wheels	X	X									
	Propeller				X	X	X		X	X		X
	Jet			X							X	
	Gravity							X				
Guiding	Wheels	X										
	Propeller					X						
	Rudder			X	X		X	X	X	X	X	X
	"Ground"		X									

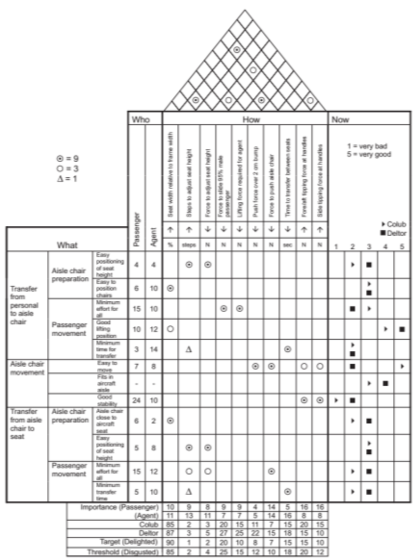
(Crawley et al., 2016)

Design Structure Matrix

Parts List	Cover	Impeller	Housing	Motor	Motor Shaft
Cover	X	Close to	Touch		Aligned with
Impeller	Close to	X	Surrounds		Touch/ is encircled by
Housing	Touch	Within	X	Touch	Is encircled by/aligned
Motor			Touch	X	Within/touches
Motor Shaft	Aligned with	Touch/ encircles	Encircles/ aligned	Surrounds/ touches	X

(Crawley et al., 2016)

House of Quality Diagram



(Ullman, 2016)

Decision Matrix

Issue: Choose a MER wheel configuration		Baseline	Cantilevered Beam	Hub Switchbacks	Spiral Flexures	Multipiece
Mass efficiency	35	Datum	0	0	1	?
Manufacturability	10		0	−1	−1	?
Available internal wheel volume	20		1	1	1	?
Stiffness	35		1	1	1	?
	Total		2	1	2	?
	Weighted total		55	45	80	?

(Ullman, 2016)

Methodology

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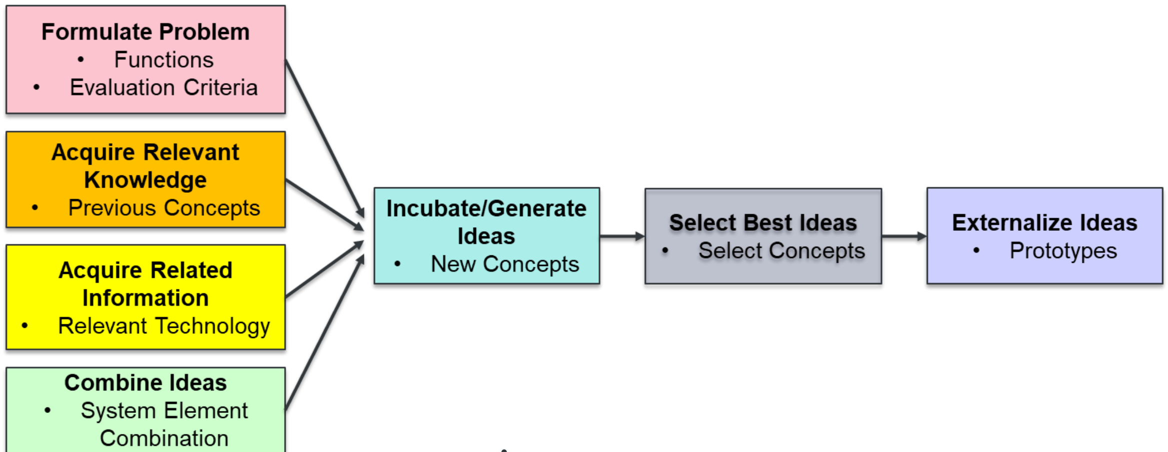
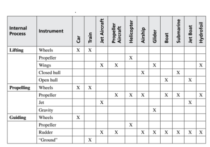
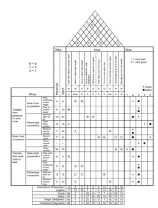
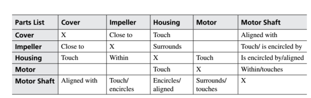
Creative Process to Generate Creative Ideas

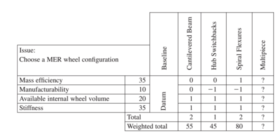


Tools to Carry out Creative Process Stages

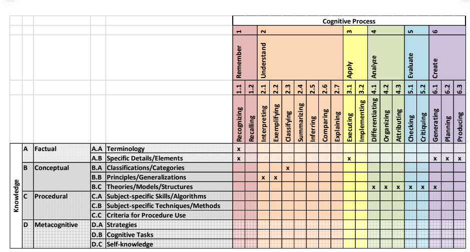








Apply Principles of Learning with Bloom's Taxonomy to Facilitate Learning



System Architecture Methodology

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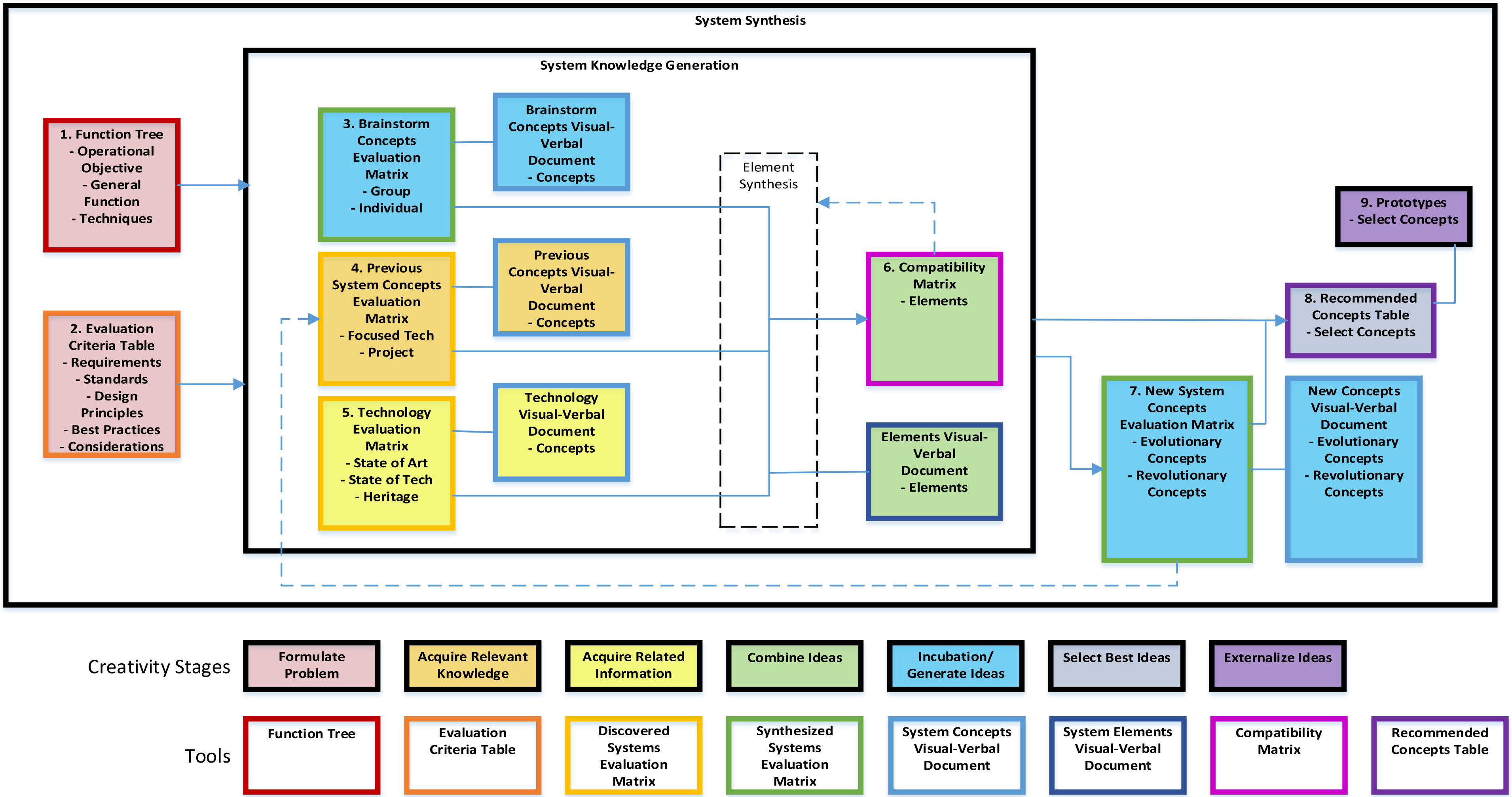
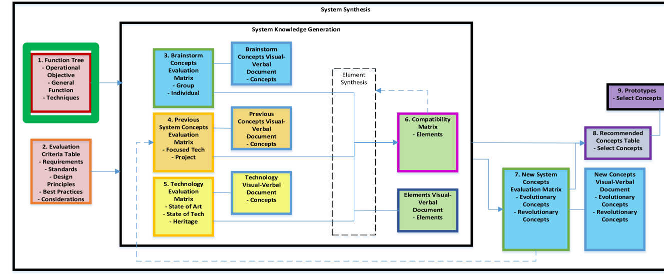
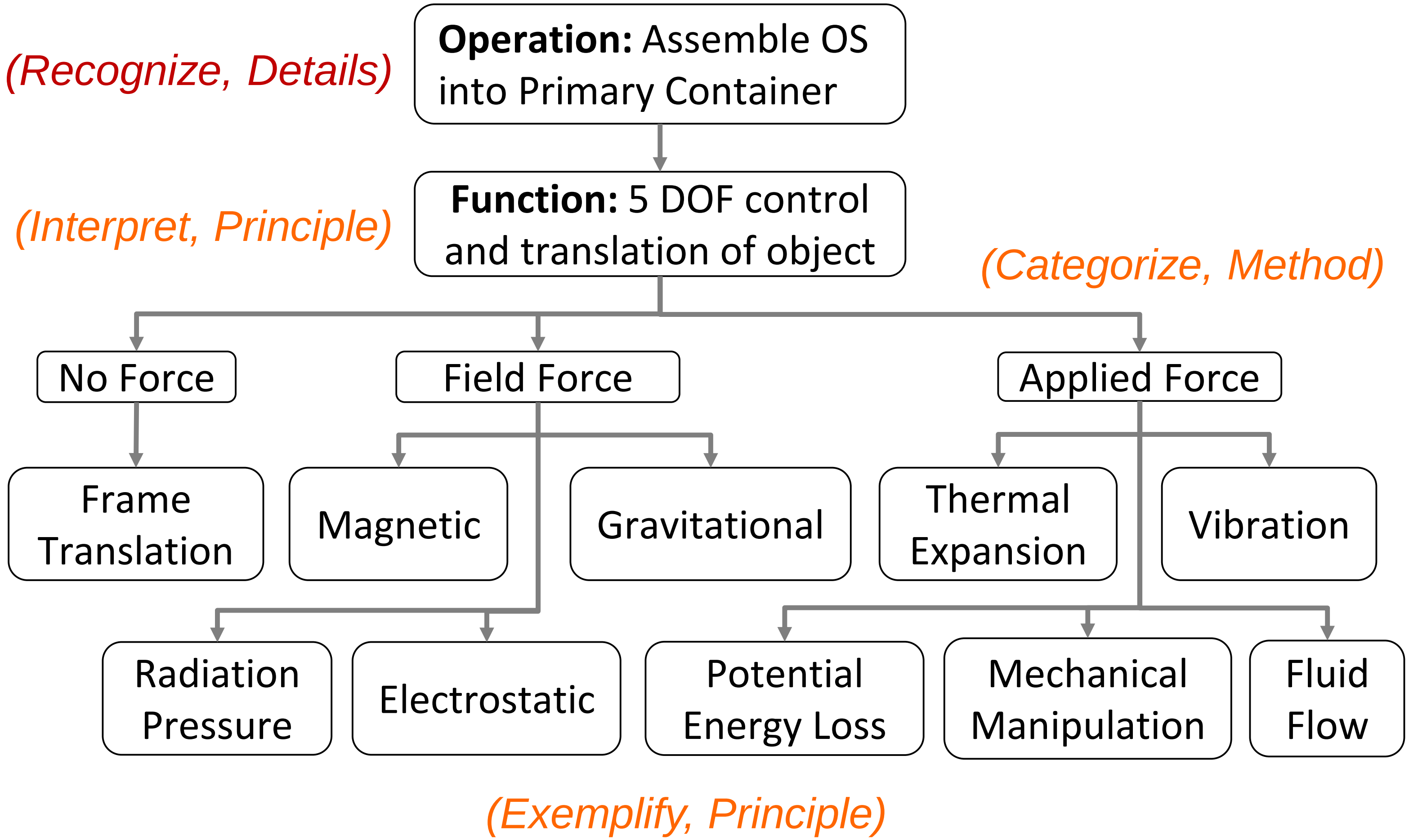
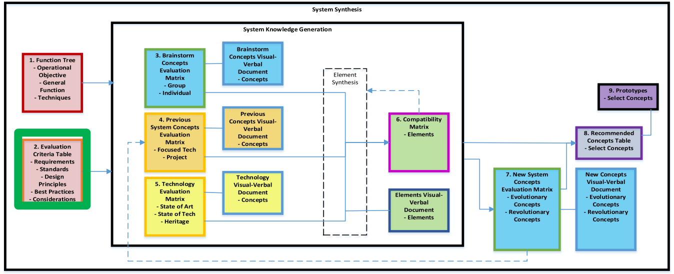


Function Tree





Evaluation Criteria Table

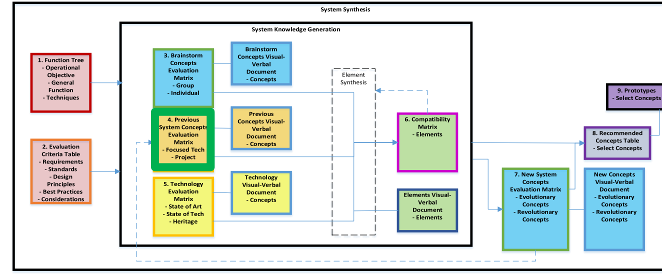


(Recognize, Terminology) *(Summarize, Principle)* *(Exemplify, Principle)*

(Categorize, Details) *(Critique, Principle)*

Criteria			Definition	Example of a Satisfactory System	Example of an Unsatisfactory System	Weight	Rationale
Intrinsic Design Criteria	System Resources	Mass	Physical mass of system (CBE + contingency) measured in kg	Hinged link with 1 actuator to close PCV Lid over OS and onto PCV Base has a mass of 5 kg	6 DOF arm for OS manipulation plus 6 DOF Stewart platform for PCV Lid placement has a mass of 50 kg	9	System mass critically affects the mission timeline due to longer acceleration times
		Volume	Stowed volume measured in m^3	Hinged link with 1 actuator to close PCV Lid over OS and onto PCV Base occupies 0.03 m^3	Four bar linkage with PCV Lid and link transfer with cone occupies 0.5 m^3 when stowed	7	Larger stowed volume limits volume availability for supplemental payloads (e.g., sensors, instruments)
	System Parameters	Mechanism Count	Number of independent moving elements within the system	Linear actuator with PCV Lid to assemble OS into PCV Base (1 mechanism)	1 DOF arm to load OS in PCV Base, 1 DOF arm to position PCV Lid over PCV Base, 1 DOF arm to assemble PCV (3 mechanisms)	4	Larger number of mechanisms requires additional engineering support and development program (more resources, but implementable)
		Actuator Count	Number of actuators within the system	Hinged link with 1 actuator to close PCV Lid over OS and onto PCV Base (1 actuator)	6 DOF arm for OS manipulation plus 6 DOF arm for PCV Lid manipulation (12 actuators)	6	Larger number of actuators requires more drivers and avionics support (important, but not driving)
Life Cycle Criteria	Development	Concept Maturity Level	Concept Maturity Level (CML) as defined in [33]	Detailed design of concept developed to level of Critical Design Review criteria (CML 9)	High-level concept sketch without supporting analysis (CML 1)	3	Higher CML reduces risks and development time, but ample development time currently available
		Complexity	C = (N1 x N2 x N3)^(1/3), where N1 = number of elements, N2 = number of types of elements, N3 = number of interfaces [1]	Hinged lid with 1 actuator (N1 = 2, N2 = 2, N3 = 3, C = 2.3)	6 DOF arm for OS manipulation plus 6 DOF Stewart platform for PCV Lid placement (N1 = 24, N2 = 4, N3 = 50, C = 16.9)	4	Higher complexity increases design, assembly, integration, and test challenges (important, but not driving)

Discovered Systems Evaluation Matrix

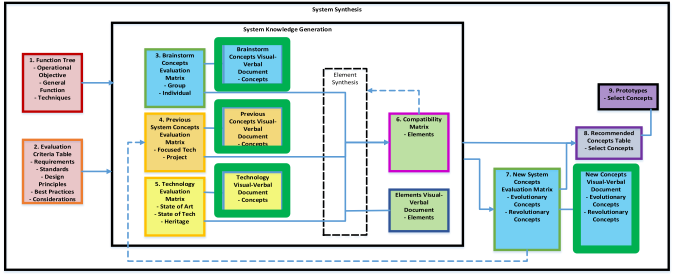


System Concept		DOF	Actuation: Rotary Motor	Transmission: Gearing	Transmission: Belt	Transmission: Lead Screw	Linkage: Link End at Joints	Linkage: Four Bar	Criteria	System Resources: Mass	System Resources: Volume	System Parameters: Mechanism Count	System Parameters: Actuator Count	Development: Concept Maturity Level	Development: Complexity	Normalized Concept Structure Score	Normalized Total Concept Score
									Weight	9	7	4	6	3	4		
Link Transfer	Blades	3	3	3			2	1		3	3	3	3	4	2	0.6	0.8
Arm Transfer	3 DOF Turret Arm	3	3	3			2			2	4	5	3	3	3	0.6	0.8
	Gripper Arm	6	6	6			5			1	4	4	1	1	1	0.4	0.7
Paddle Transfer	Dorade	1	1	1			1			5	3	5	5	1	5	0.8	0.9
	Douter	1	1	1	1		1			4	5	4	5	2	4	0.8	0.9
Linear Actuator	Pick-Place Arm	2	2	1		1	1			2	3	3	4	2	3	0.6	0.7
	Crane	2	2	1		1	1			2	3	5	4	1	3	0.6	0.7

Criteria		Weight	Rotary Motor	Gearing	Belt	Lead Screw	Link End at Joints	Four Bar
System Resources	Mass	9	5	3	5	1	5	1
	Volume	7	5	5	4	2	5	3
System Parameters	Mechanism Count	4	5	5	3	3	5	1
	Actuator Count	6	5	5	5	5	5	5
Development	Concept Maturity Level	3	5	5	4	2	5	3
	Complexity	4	5	5	3	1	5	3
Normalized Element Score			1	0.9	0.8	0.5	1	0.5

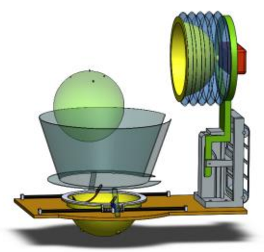
Synthesized Systems Evaluation Matrix similar, except for systems are generated

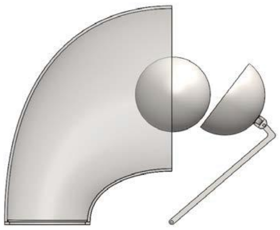
System Concepts Visual-Verbal Document

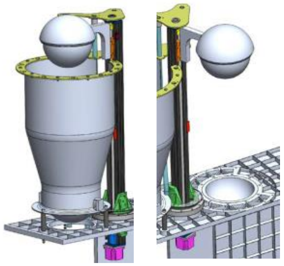


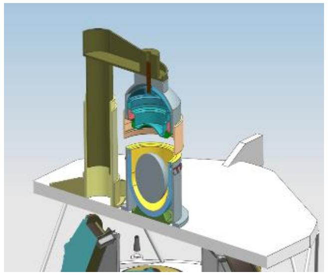
Previous ROCS Transfer Concepts

MOSTT Task


Douter


Dorade


Pick-Place Arm

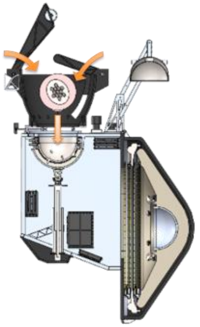

Crane


Gripper Arm

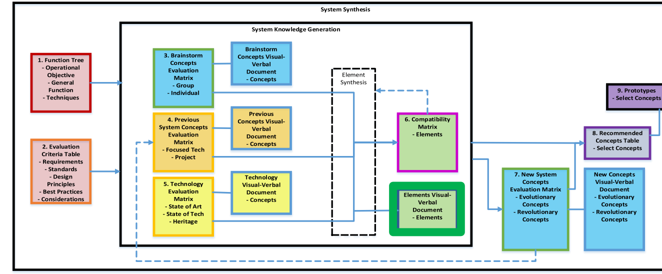
NeMO Project


3 DOF Turret Arm

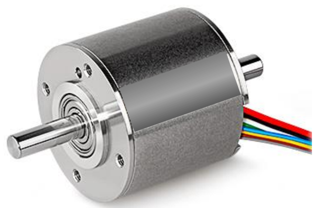
Atelier Study


Blades

System Elements Visual-Verbal Document

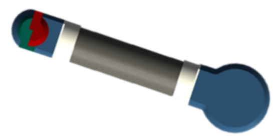


Actuation

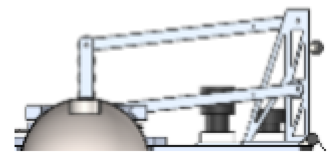


Rotary Motor

Linkage



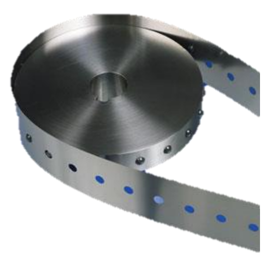
Link End at Joints



Four Bar

Transmission

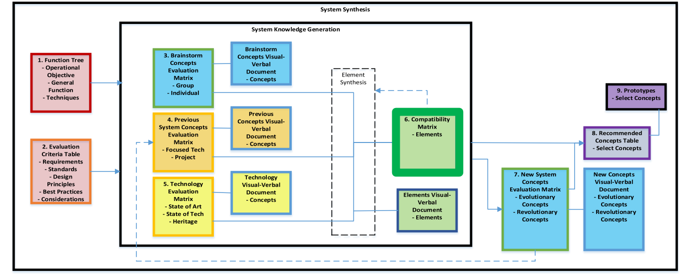
Gearing



Belt

Lead Screw

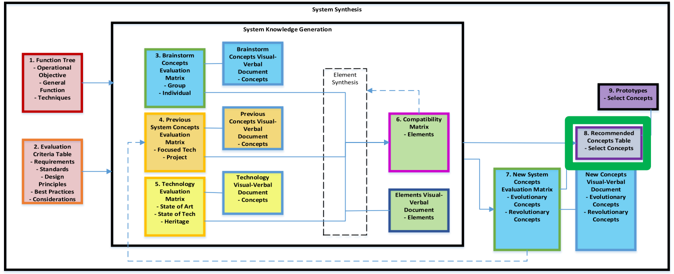
Compatibility Matrix

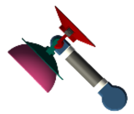
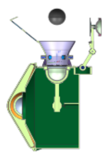
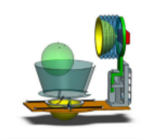
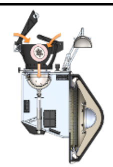
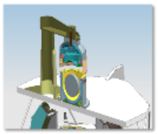


System Element		Actuation: Rotary Motor	Transmission: Gearing	Transmission: Belt	Transmission: Lead Screw	Linkage: Link End at Joints	Linkage: Four Bar	**Normalized Sum**
Actuation	Rotary Motor	5	5	5	5	5	5	**1**
Transmission	Gearing	5	5	3	3	3	3	**0.7**
	Belt	5	3	5	3	3	3	**0.7**
	Lead Screw	5	3	3	5	4	3	**0.8**
Linkage	Link End at Joints	5	3	3	4	5	4	**0.8**
	Four Bar	5	3	3	3	4	5	**0.8**

Legend/Score	
Positive Synergy	5
N/A	4
Independent	3
Indeterminable	3
Negative Synergy	2
Not Compatible	1

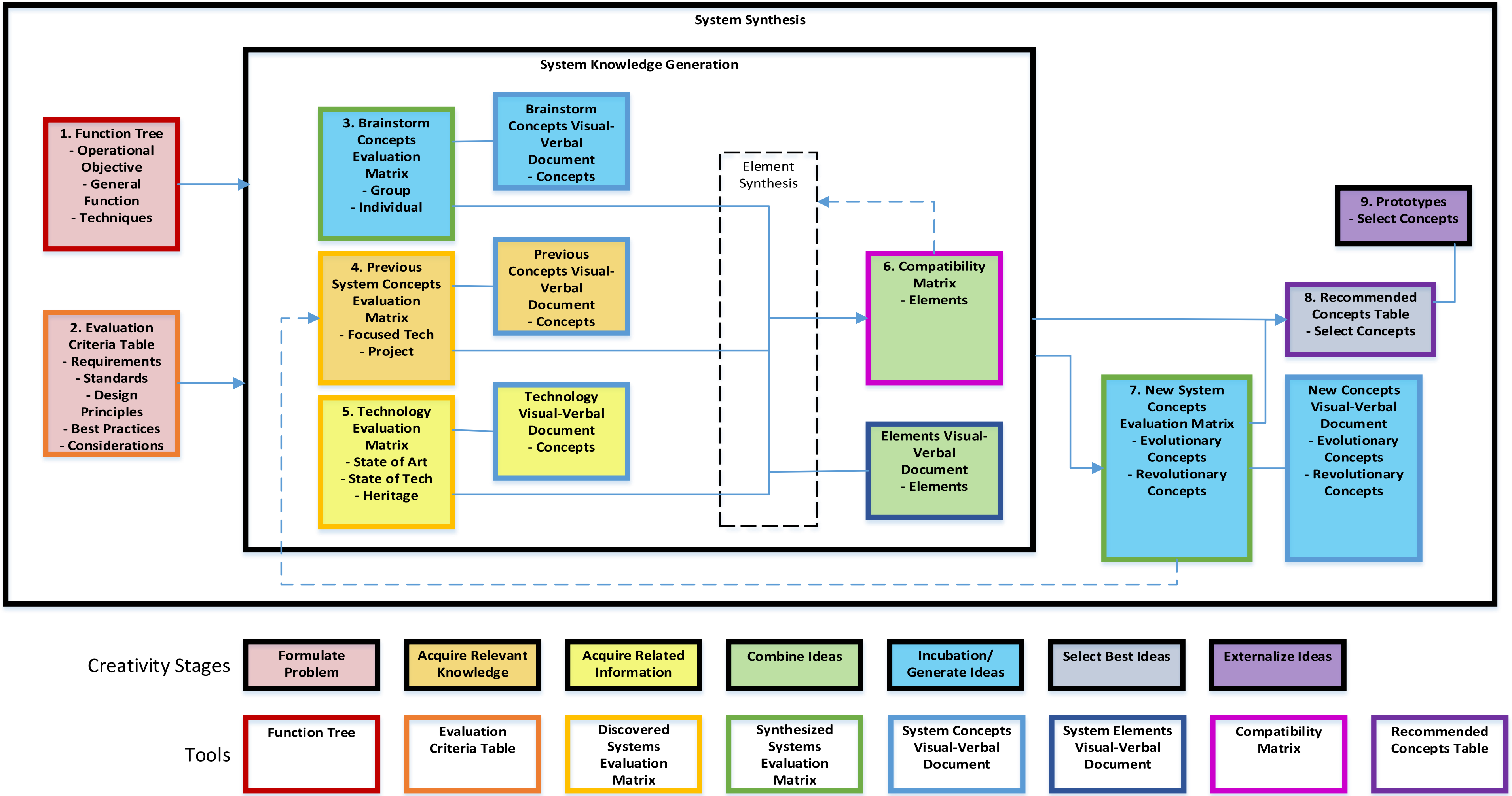
Recommended Concepts Table



Transfer		Mass	BTC Hardware Protection	Complexity	Actuator Count	Compatibility w/BTC	Rank
	**2 DOF Turret Arm**	17 kg	BTC hardware protected from energetic OS	Complexity, C = 5.1	2 actuators	Provides curved motion during PCV assembly	**1**
	**3 DOF Turret Arm**	23 kg	BTC hardware protected from energetic OS	Complexity, C = 7.1	3 actuators	Provides full linear motion during PCV assembly	**2**
	**Douter**	15 kg	BTC Lid and Base contact energetic OS	Complexity, C = 5.1	1 actuator	Provides full linear motion during PCV assembly	**3**
	**Blades**	22 kg	BTC Base contacts energetic OS	Complexity, C = 7.1	3 actuators	Provides limited linear motion during PCV assembly	**4**
	**Crane**	25 kg	BTC Lid and Base contact energetic OS	Complexity, C = 4.9	2 actuators	Provides full linear motion during PCV assembly	**5**

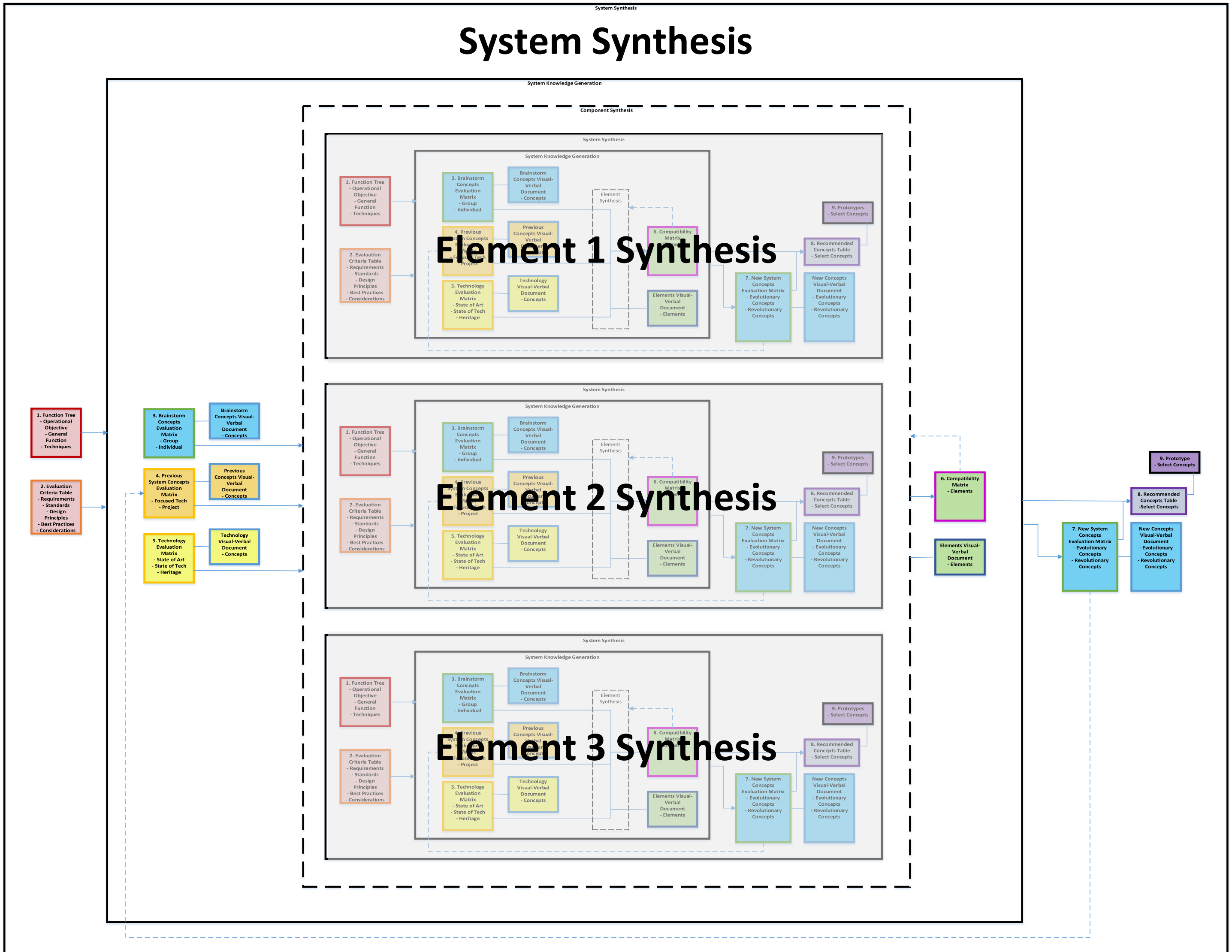
System Architecture Methodology

Jet Propulsion Laboratory
California Institute of Technology



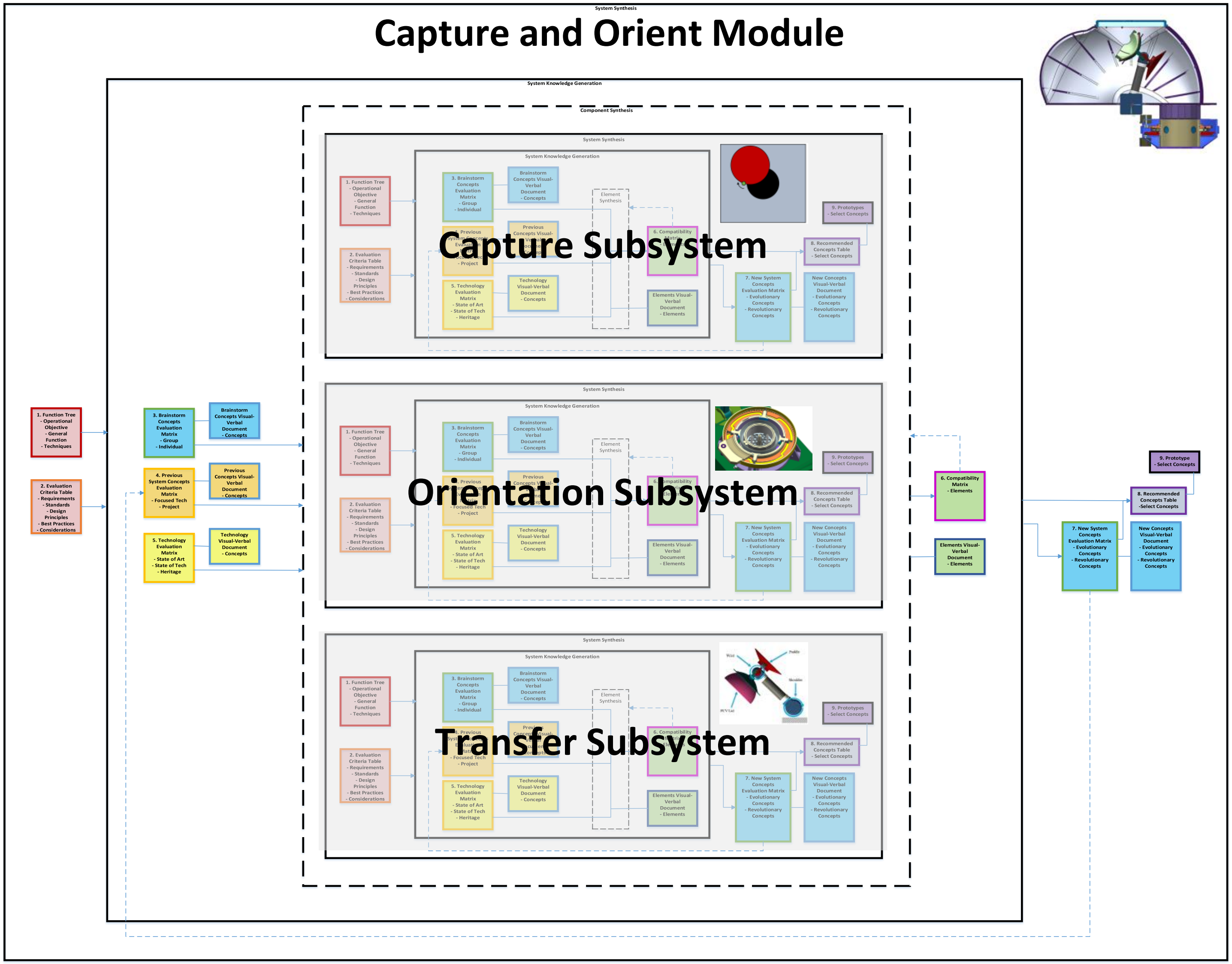
Multi-Level System Architecture Methodology

Jet Propulsion Laboratory
California Institute of Technology



Multi-Level System Architecture Methodology

Jet Propulsion Laboratory
California Institute of Technology



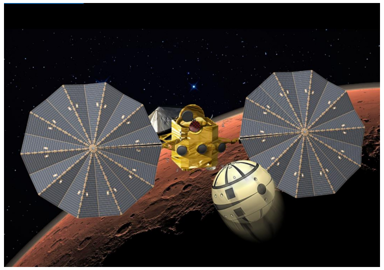
Benefits

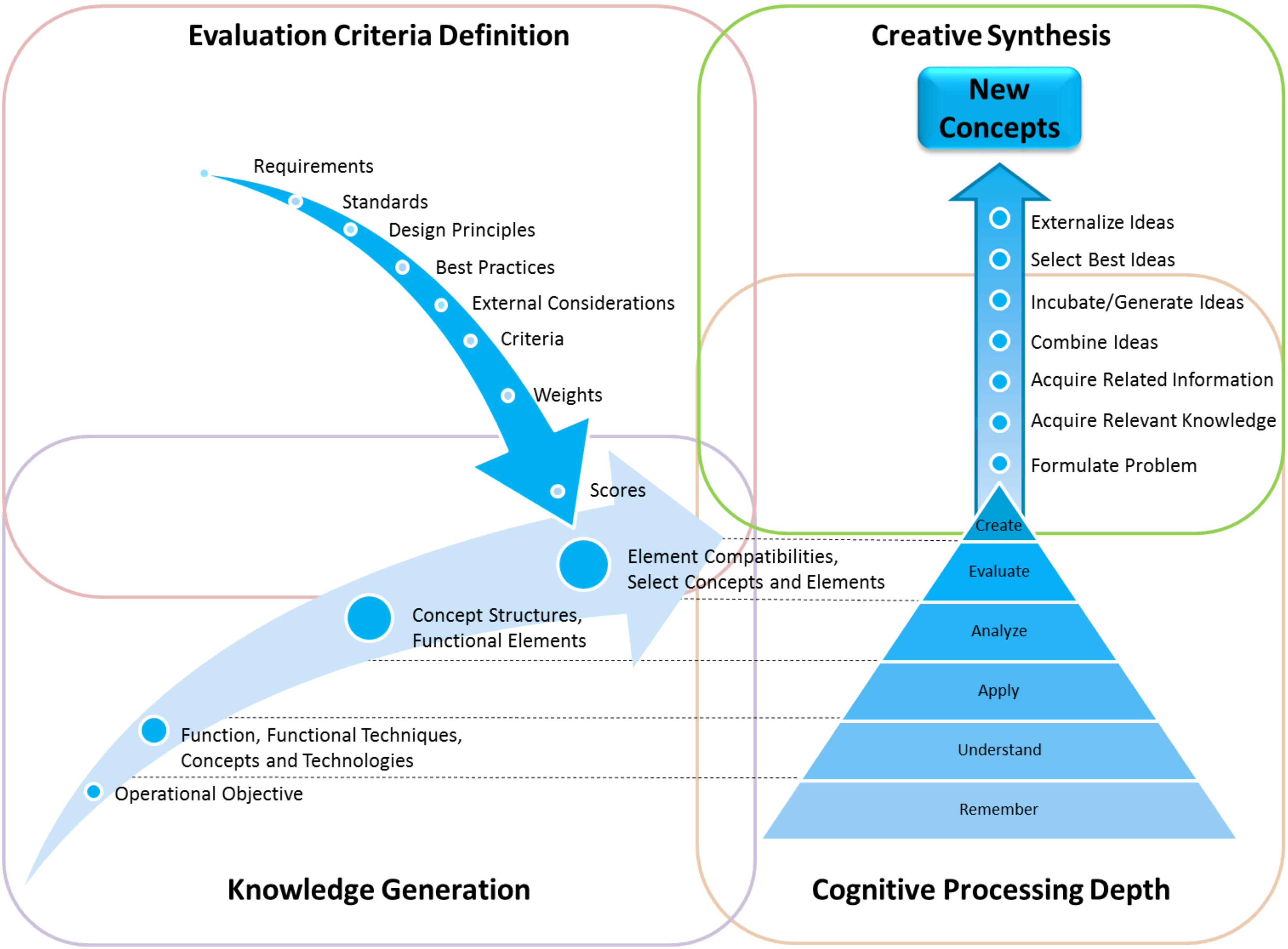
- Tools used as learning activities (not simply for information capture)
- Tools capture and classify higher level knowledge (aids in knowledge retention and transfer)
- Focus on system evaluation prior to creation aids in generating quality ideas (not just quantity of ideas)
- Breadth and depth of knowledge enhances flexibility with problem redefinition
- Expands system leadership's role as an educator (not simply a task manager or information dispenser):
  - Cognitive guide
  - Implementation of learning tools and management of learning activities (aided by Bloom's classifications)
  - Formative assessment of knowledge

Future Work

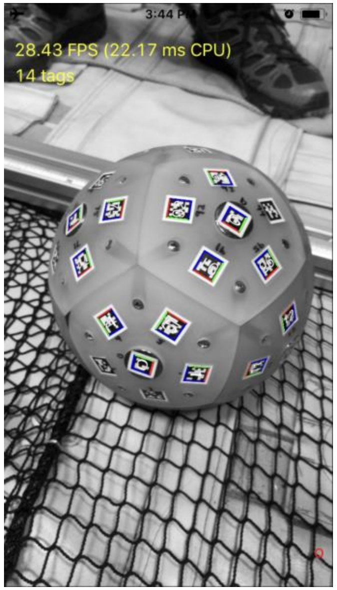
Jet Propulsion Laboratory
California Institute of Technology

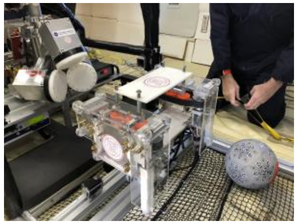
- Collaboration with systems engineering, cognitive psychology, educational psychology, creativity, and education researchers and practitioners to further develop aspects of the methodology
- Development of assessment methods
- Determination of boundary conditions
- Integration of metacognitive knowledge elements, affective domain elements, and promotion methods from marketing and consumer behavior fields
- Application of the methodology to elements of the Mars Sample Return Capture and Orient Module

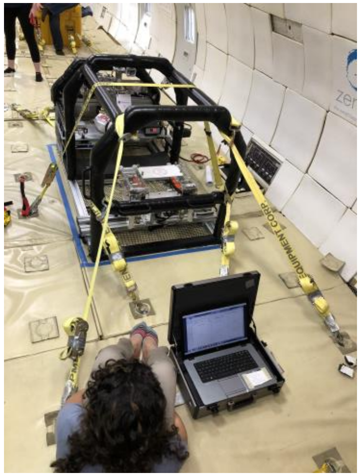


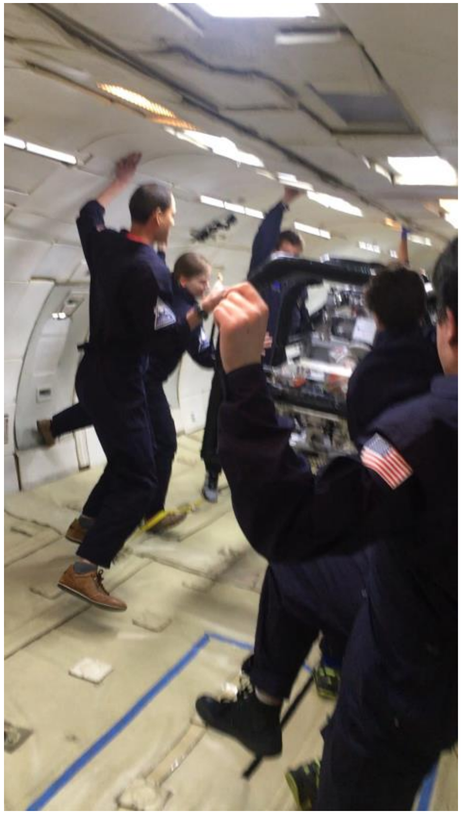

Evaluation Criteria Definition
Creative Synthesis
New Concepts
Requirements
Standards
Design Principles
Best Practices
External Considerations
Criteria
Weights
Scores
Externalize Ideas
Select Best Ideas
Incubate/Generate Ideas
Combine Ideas
Acquire Related Information
Acquire Relevant Knowledge
Formulate Problem
Create
Evaluate
Analyze
Apply
Understand
Remember
Element Compatibilities,
Select Concepts and Elements
Concept Structures,
Functional Elements
Function, Functional Techniques,
Concepts and Technologies
Operational Objective
Knowledge Generation
Cognitive Processing Depth

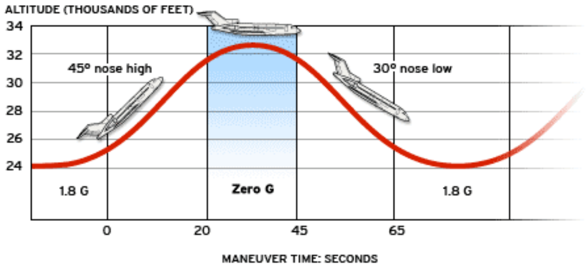
Flux Pinning Technologies











SOURCE: The Zero Gravity Corporation MSNBC