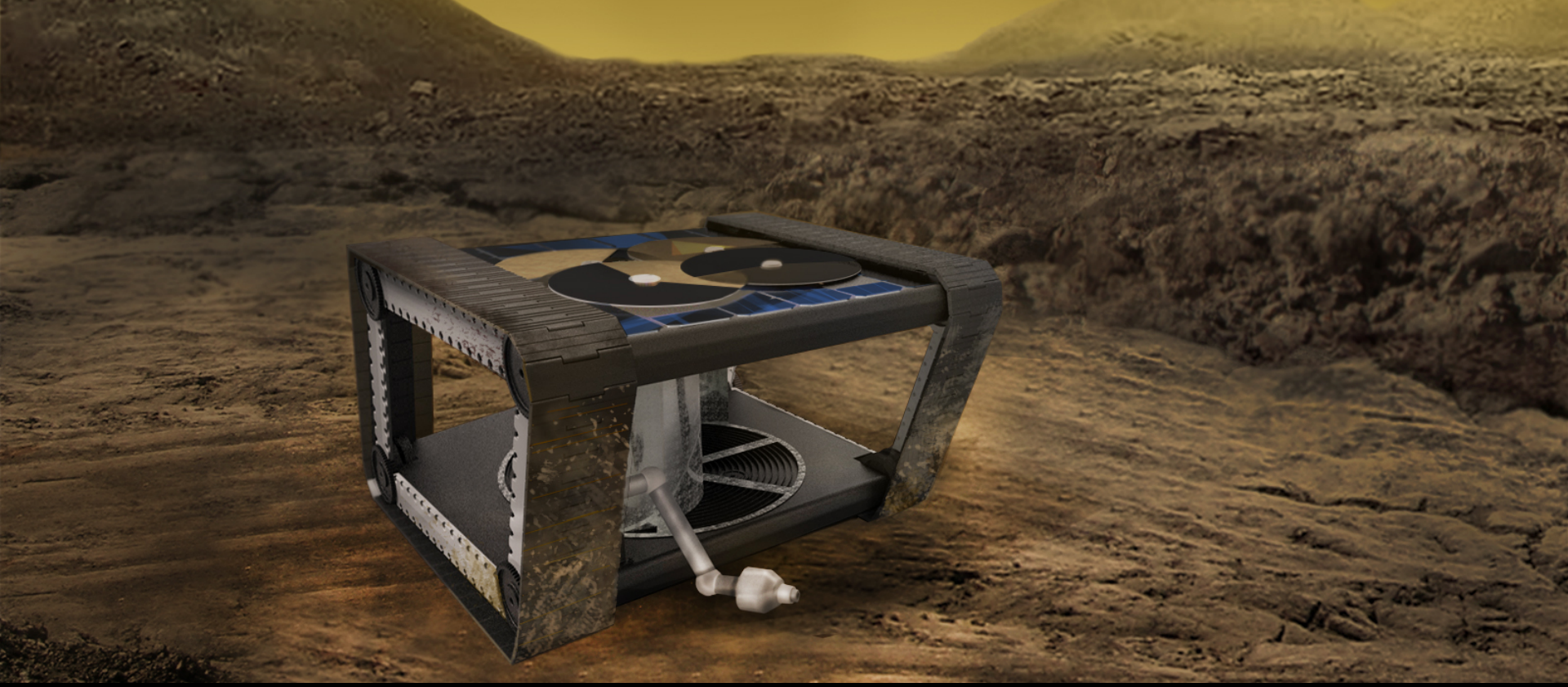

Automaton Rover for Extreme Environments (AREE)

Jonathan Sauder, Evan Hilgemann, Jessie Kawata,
Katie Stack, Aaron Parness, Michael Johnson

Key Interns: Sean Dunphy, Andre Shahinian

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Phase II, Year 2, Jul. 17, 2018

Jet Propulsion Laboratory
California Institute of Technology

NIAC
NASA Innovative Advanced Concepts

Todays Review

Introduction

Topic	Time Allocated	Start Time	End Time
Introduction	**20 min**	**8:30 AM**	**8:50 AM**
Technical Explorations	60 min	8:50 AM	9:50 AM
Break	10 min	9:50 AM	10:00 AM
Technical Explorations	40 min	10:00 AM	10:40 AM
Programmatics	15 min	10:40 AM	10:55 AM
Next Steps	10 min	10:55 AM	11:05 AM
Time for Additional Questions	15 min	11:05 AM	11:20 AM
Lab Tour	30 min	11:20 AM	11:50 AM

…but first, introductions around the room.

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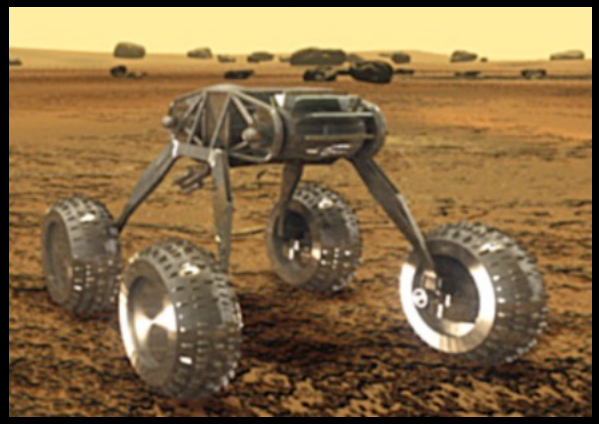
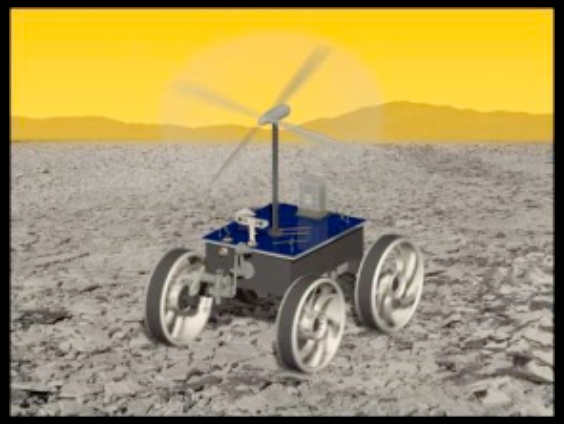
Image: Soviet Space Agency
Additional processing. Don P. Mitchell and wanderingspace.net

Prior Venus Rover Concepts

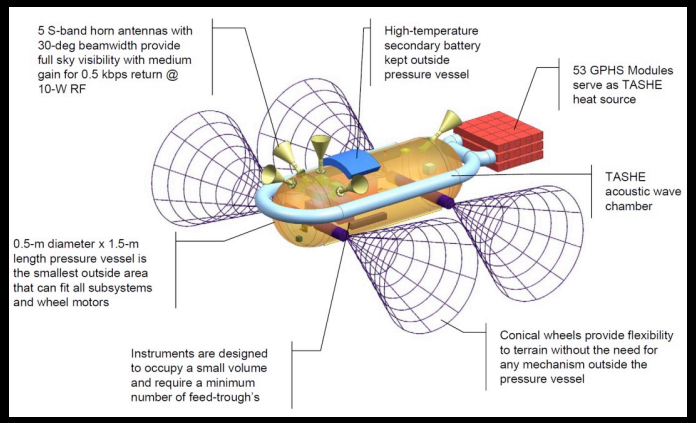
Requires Cooling System Development or Advanced High Temperature Electronics



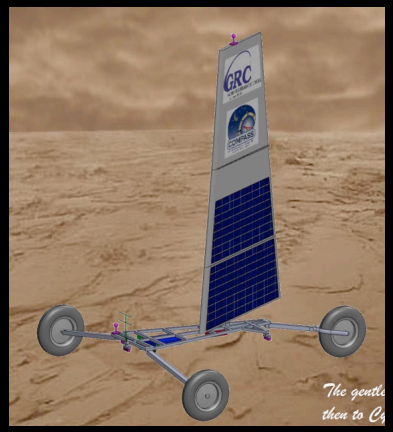
Landis et. al, NASA Glenn



Benigo et. al, NASA Glenn



Shirley et. al, NASA JPL



Landis et. al, NASA Glenn

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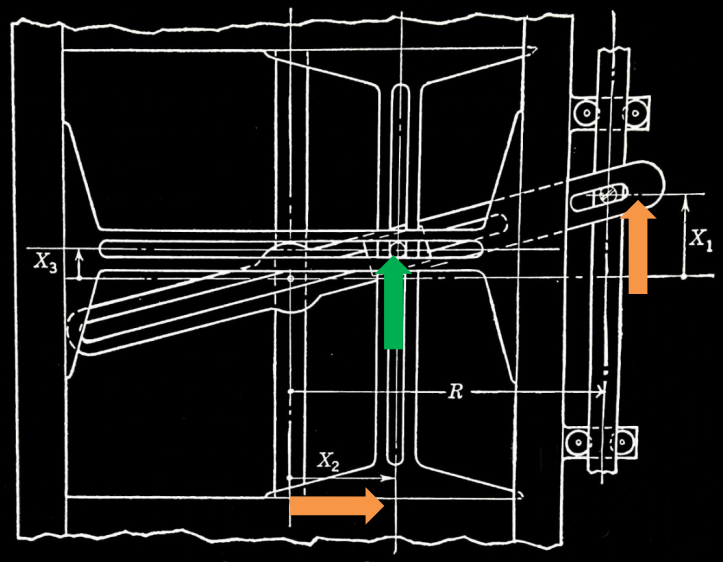
Inspirations From Mechanical Computing



A. Svoboda, “Computing Mechanisms and Linkages”

Input
Output

Utilize mechanisms to reduce requirements on electronics

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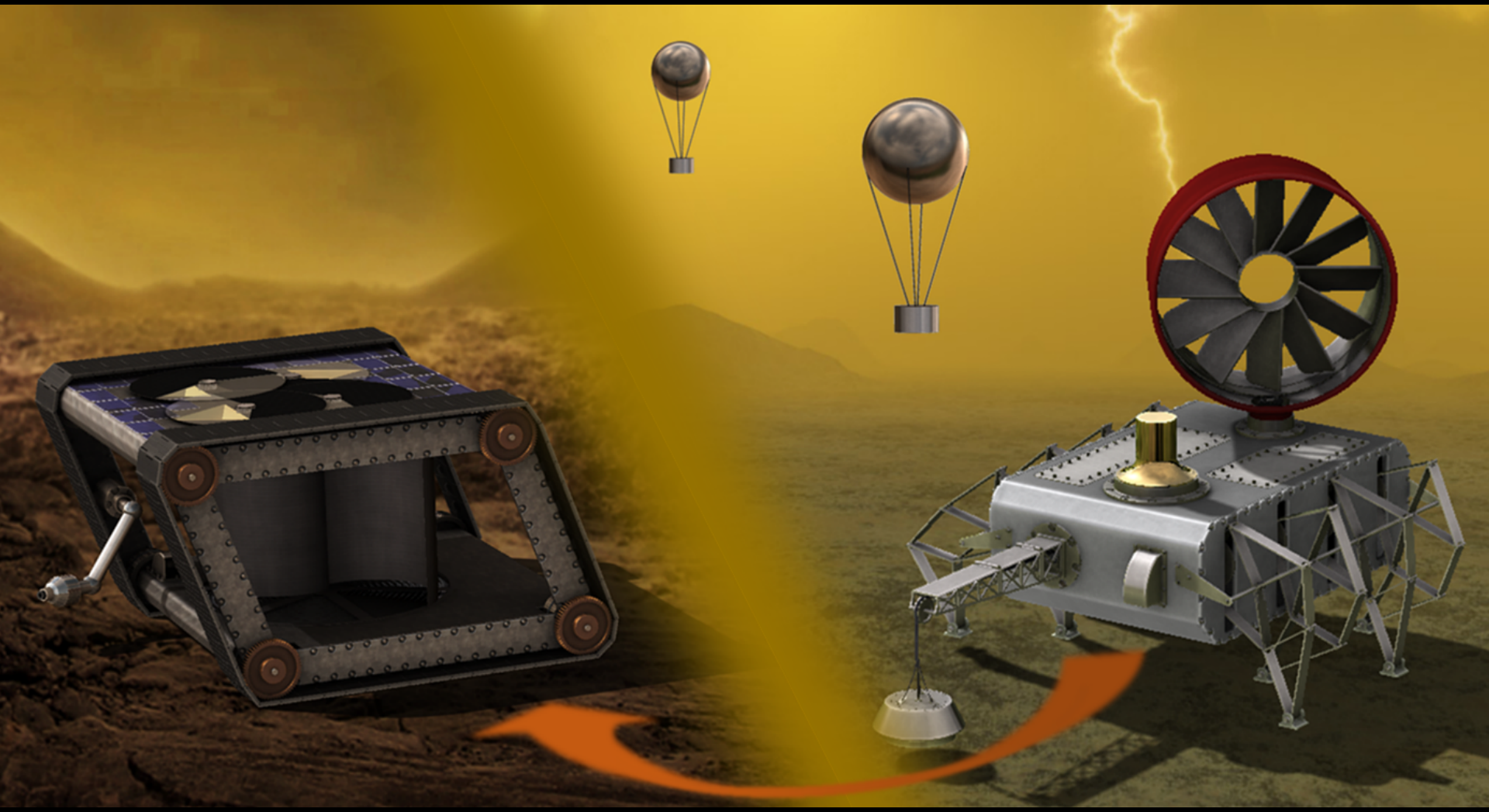
A Shift in Architecture

From an intricate walker to sturdy crawler



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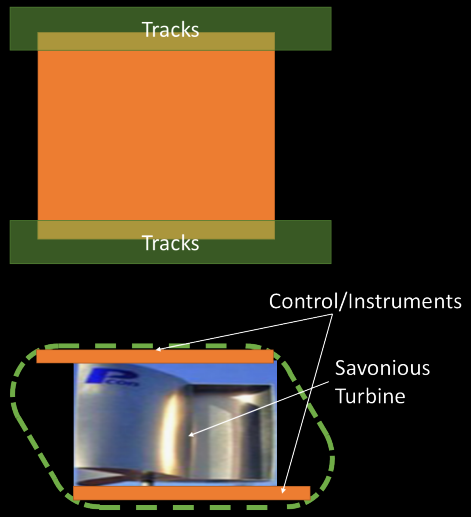
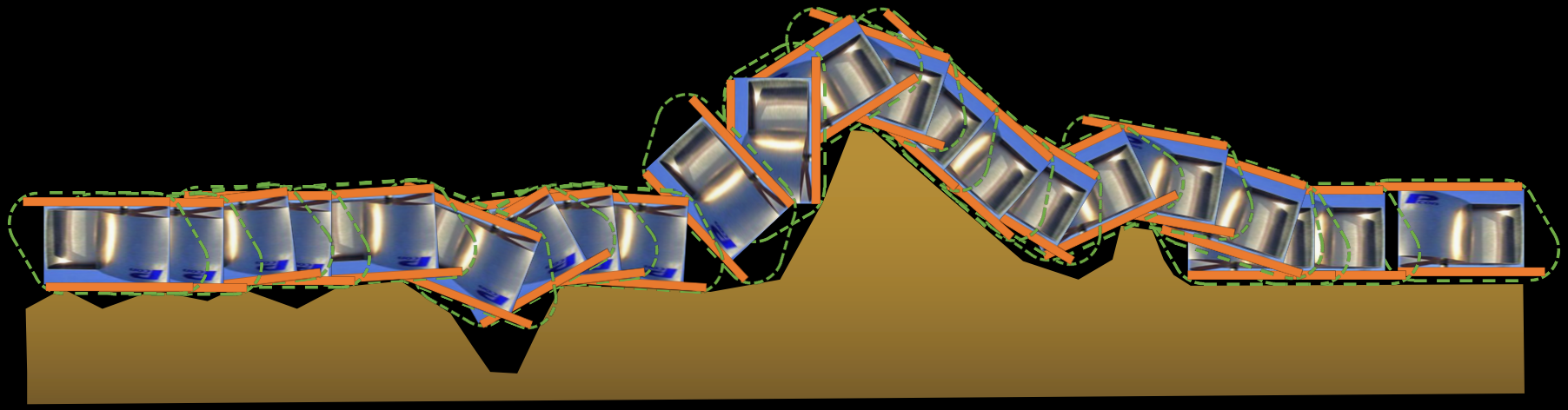
Locomotion System Design

Ability to Climb Large Objects and Operate Independently of Orientation





Robustness and resilience to reduce complexity

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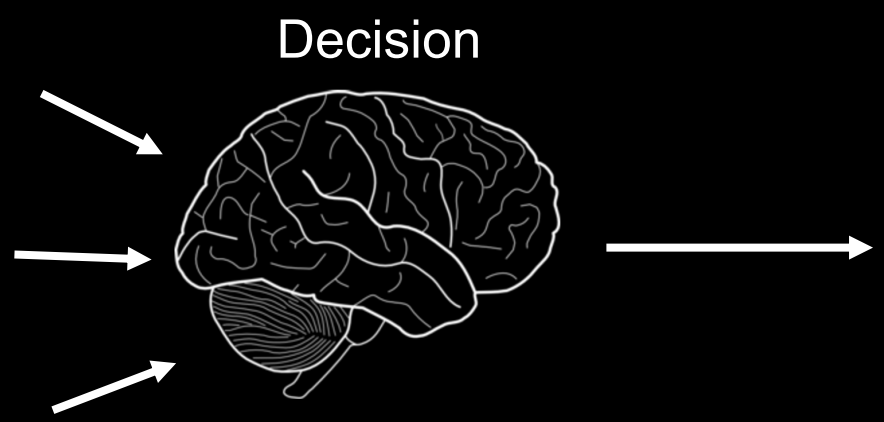
Robotic Architecture

Traditional Centralized Model

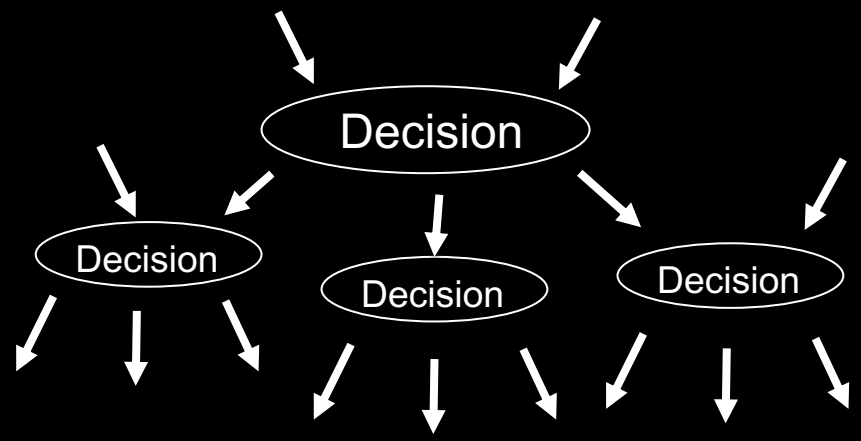
Inputs into a complex, high performance core



Don't purely replicate electrical systems mechanically

Distributed Model

Many simple rules produces ability to adapt



Brooks. Subsumpiton Architecture

Distributed, simple mechanisms → evolved, emergent behavior

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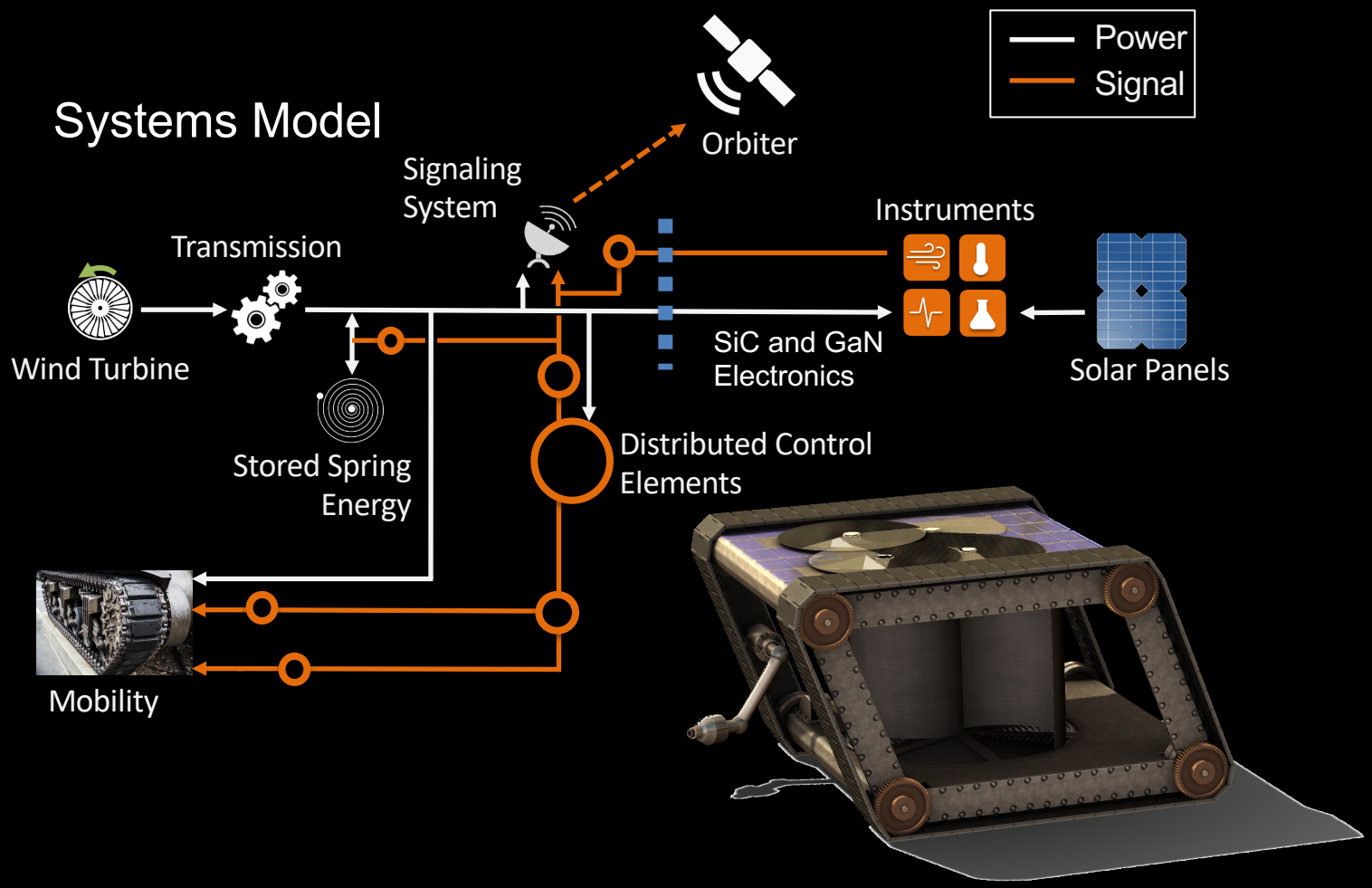
Developed Concept



A Hybrid Rover Architecture Maximizes Performance

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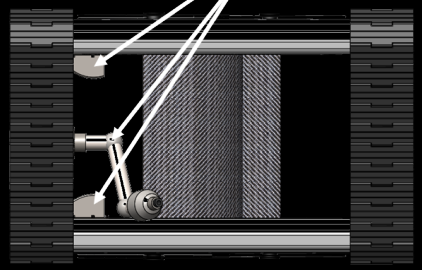
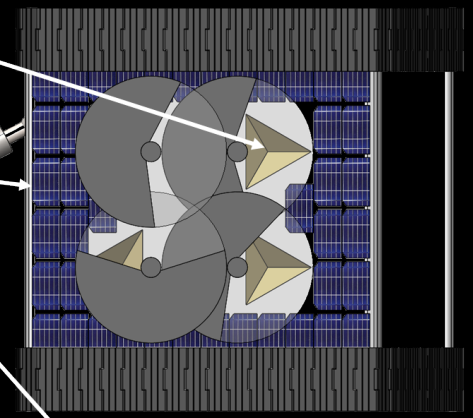
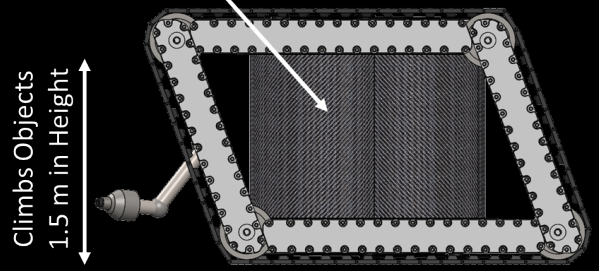
The Automaton Concept

Item	Mass CBE (kg)	Contin-gency	Mass Estimate Value (kg)
Power Generation	30.03	30%	42.90
Power Storage	25.52	30%	36.46
Locomotion	326.69	30%	466.70
Communication	78.62	30%	112.32
Control/Sensing Mechanisms	45.50	30%	65.00
Structure	147.32	30%	210.46
Science Payload	150.00	30%	195.00
Total Mass	**804**		**1129**

To scale







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Automaton Rover Design Principles

Themes for Designing an Automaton Rover

1. **Mechanisms Enable, Electronics Enhance**
2. **Utilize mechanisms to reduce requirements on electronics**
3. **Distributed, simple mechanisms → evolved, emergent behavior**
4. **Use robustness and resilience to reduce complexity**
5. **A hybrid rover architecture maximizes performance.**

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Proposed Set of Tasks

From the Phase II Proposal/Contract

Year 1 Goals:

1. Locomotion trade and prototyping
2. Signaling / control analysis and test
3. High temperature instrument identification
4. Mechanical design for hot high pressure environment
5. TeamX concept study
6. Prepare the midterm review/ report

Year 2 Goals:

1. Further end to end rover design
2. Design of a representative test rover
3. Fabrication of a representative test rover
4. Environmental test of a representative rover
5. Prepare the final report

Final Deliverable/Milestone: Final Report

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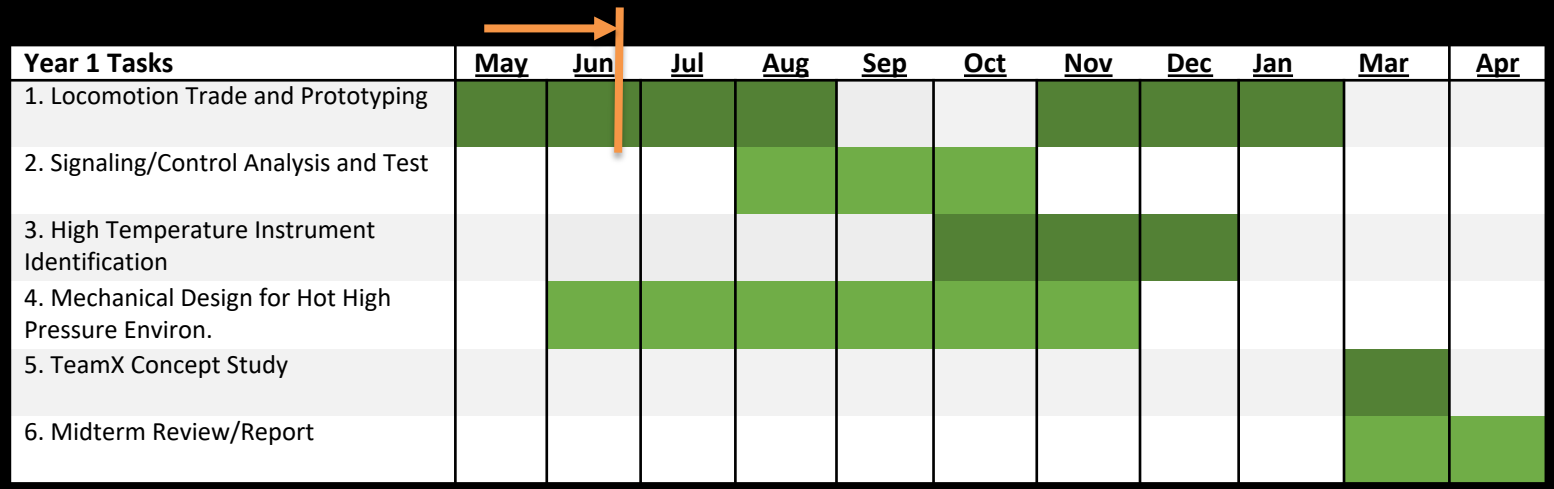
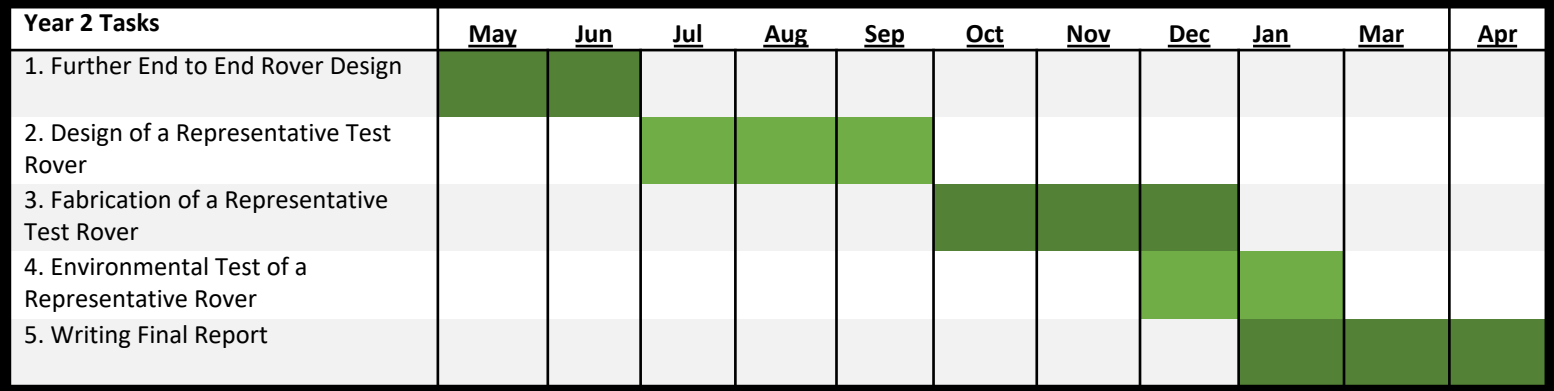
Proposed Gantt Chart of Tasks

From Phase II Proposal





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Task Summary from Symposium

From Symposium in September

Phase 1

Phase 1 Proposal
We have an idea.
Concept Model
Preliminary CAD and Details

- **A-Team Study:**
- **Phase 1**
- *Is the concept feasible?*
- **Phase 1 Back of Envelope Calcs**
- *Does power, mass and size close?*

- **A-Team Study:**
- **Phase 1**
- *What are the trades to consider?*
- **Phase 1 Trades**
- *What is the power system?*

- **Phase 1 Robust Rover**
- *Tracked wind powered rover.*
- **Phase 1 Final Report**

AREE Design Principles

1. Mechanisms Enable, Electronics Enhance
2. Distributed mechanisms → emergent behavior
3. Robustness and resilience to reduce complexity
4. A hybrid rover architecture maximizes performance.

Direct

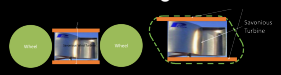
/ SMD full proposal
/ STMD Game-changing

CML 1	CML 2	CML 3	CML 4	CML 5	Future Opportunities
Cocktail Napkin	Feasibility *Science Requirements*	**Trade Space** *Component Proof of Concept*	Point Design	Baseline Concept Pre-Proposal Tech Demo	

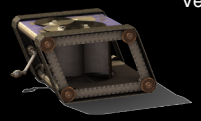
Phase 2

- **A-Team Science Study:** • What are the best mission targets for basic rover platform?
  • Identify Instruments.

- **Mobility System Design**
- Explore and demonstrate most robust mobility.
- **Proof of Concept**
- •High temperature mechanisms.
- • Radar target
- • Turbine Design



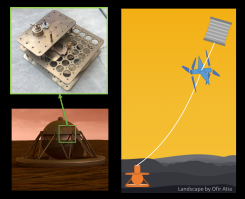
- **TeamX Study**
- • Formulate point design.



- **Develop Technology**
- Refine design from TeamX feedback.
- **Test**
  Test a representative rover in Venus conditions.

Indirect

/ Infusion of Tech.



/ Changing the Conversation

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Todays Review

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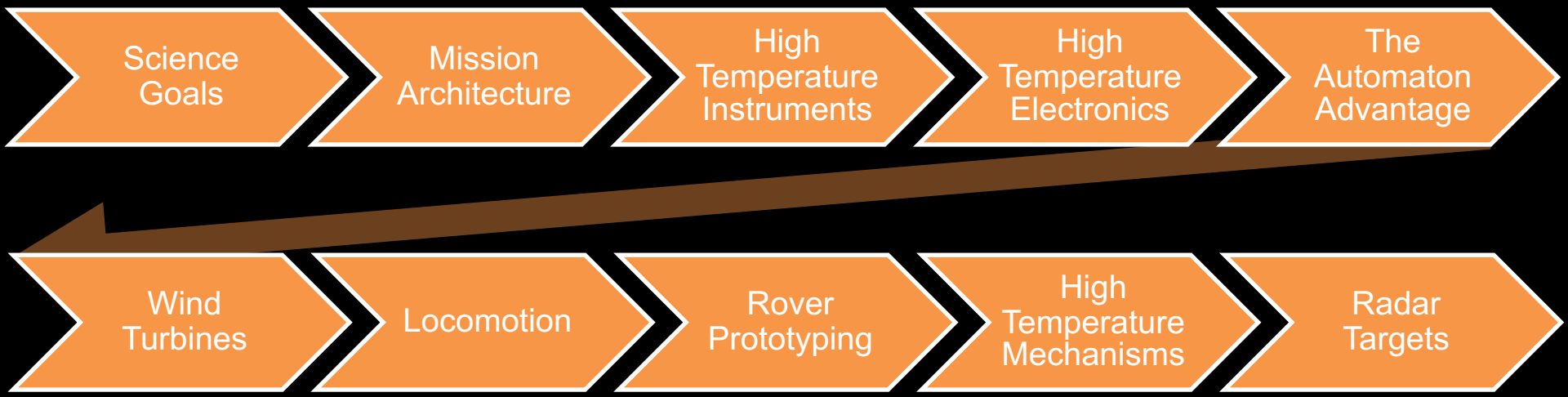
Technical Explorations

The topics to be discussed



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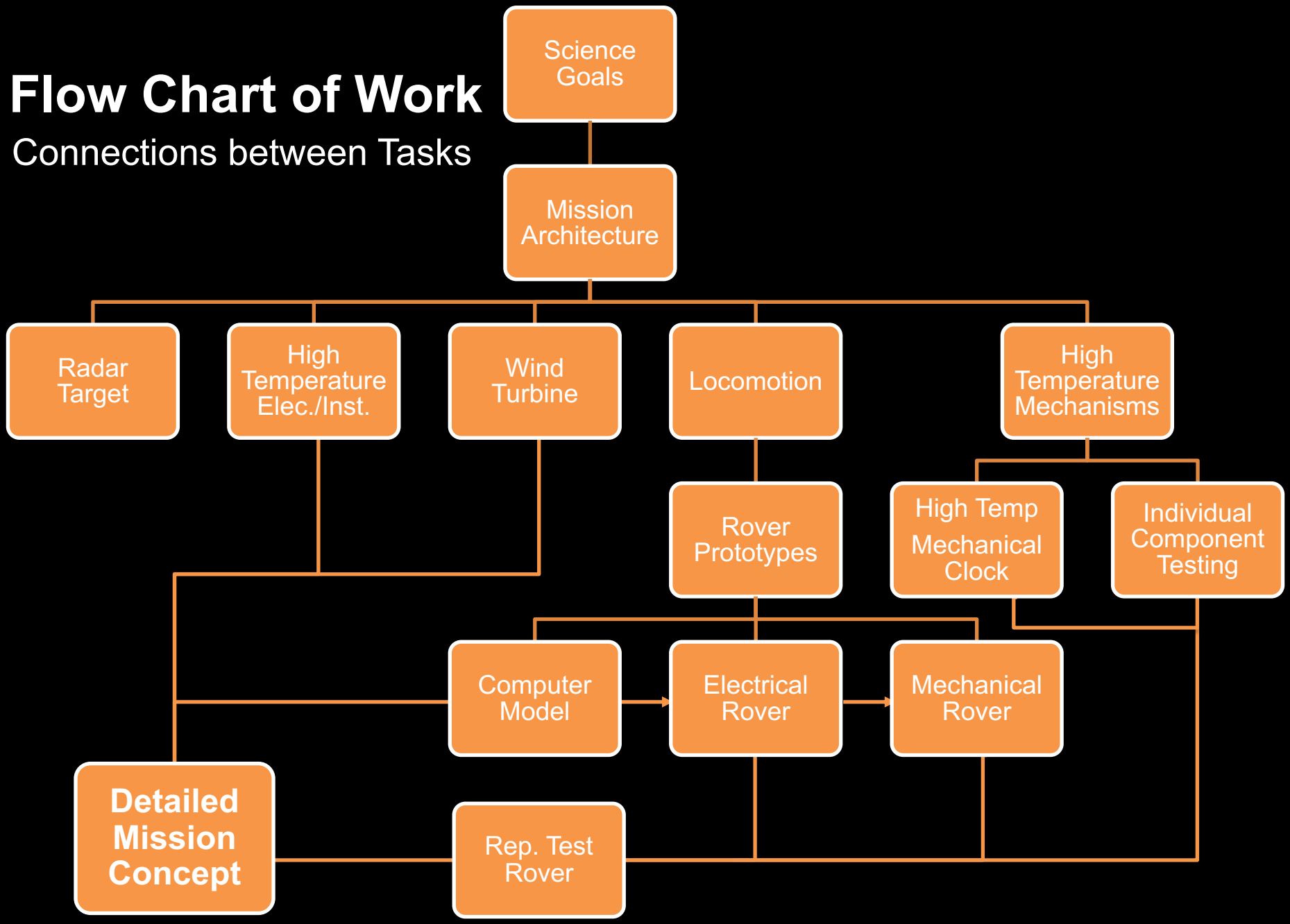
Flow Chart of Work

Connections between Tasks



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Why would we want to roam the surface?

“My most persistent emotion in working with the Viking lander pictures was frustration at our immobility. I found myself unconsciously urging the spacecraft at least to stand on its tiptoes, as if this laboratory were perversely refusing to manage even a little hop. How we longed to poke that dune with the sample arm, look for life beneath that rock, see if that distant ridge was a crater rampart. The ideal tool is a roving vehicle carrying on advanced experiments, particularly in imaging, chemistry and biology. It is within our capability to land a rover on Mars that could scan its surroundings, see the most interesting place in its field of view and, by the same time tomorrow, be there. Such a mission would reap enormous scientific benefits, even if there is no life on Mars. Public interest in such a mission would be sizable. Every day a new set of vistas would arrive on our home television screens. We could trace the route, ponder the findings, suggest new destinations. The journey would be long, the rover obedient to radio commands from Earth; a billion people could participate in the exploration of another planet."

-- Carl Sagan

Cosmos, Chapter V, "Blues for a Red Planet”

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Cosmos, Chapter V, "Blues for a Red Planet"

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The Evolution of Mission Modes

Probes lead to Landers, Landers lead to Rovers

The Driving Need for a Rover

- To explore different geologic units on the surface of Venus.
- Take samples and provide the context for those samples.
- Potential to place seismometer network.

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VEXAG Science Goals

Goals and Objectives Informed by Mobility

Determine the evolution of the surface and interior of Venus

- How did Venus differentiate and evolve over time? Is the crust nearly all basalt, or are there significant volumes of more differentiated (silica-rich) crust?
- How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonism or resurfacing varied with time? Specifically, did Venus ever experience a transition in tectonic style from mobile lid tectonics to stagnant lid tectonics?

Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.

- Did Venus ever have surface or interior liquid water, and what role has the greenhouse effect had on climate through Venus' history?
- How have the interior, surface, and atmosphere interacted as a coupled climate system over time?

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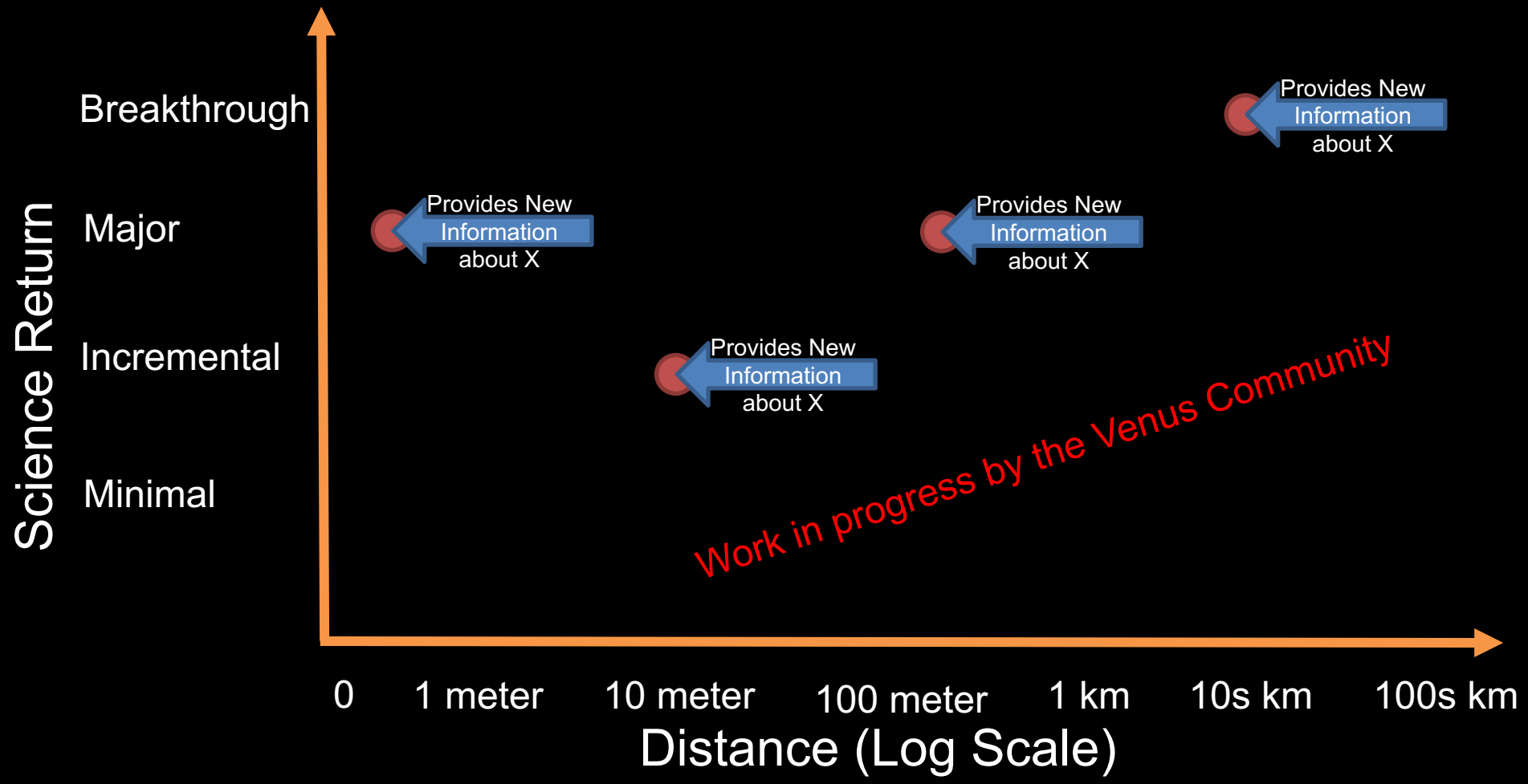
NASA Landed Platform Study

Leading the Technology Panel which Collaborates w/ 3 science panels



Science Goals | Mission Architecture | High Temperature Instruments | High Temperature Electronics | The Automaton Advantage

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Mission Architecture and Requirements on a Rover

Completed through a Team-X Study

- Previously decadal survey reference missions were used.
- But decadal missions only had fly-bys with landers or orbiting elements with a 24 hour orbit.
- But, need to understand the implications of a RADAR orbiter with a frequent orbit.
- Study treats rover as a black box, as asks, how big can the black box be?
- This builds on Team X's strengths.

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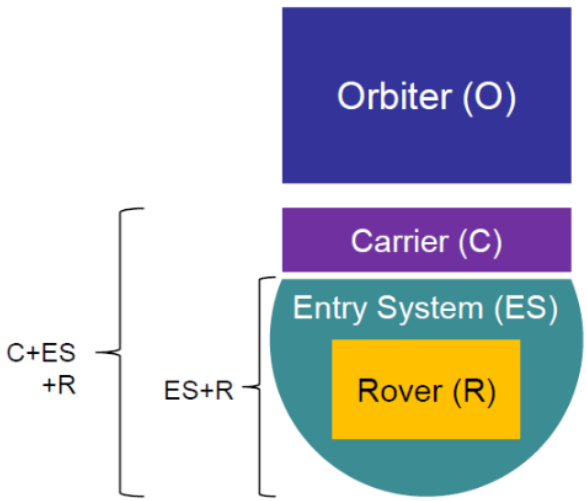
Systems
Architecture A

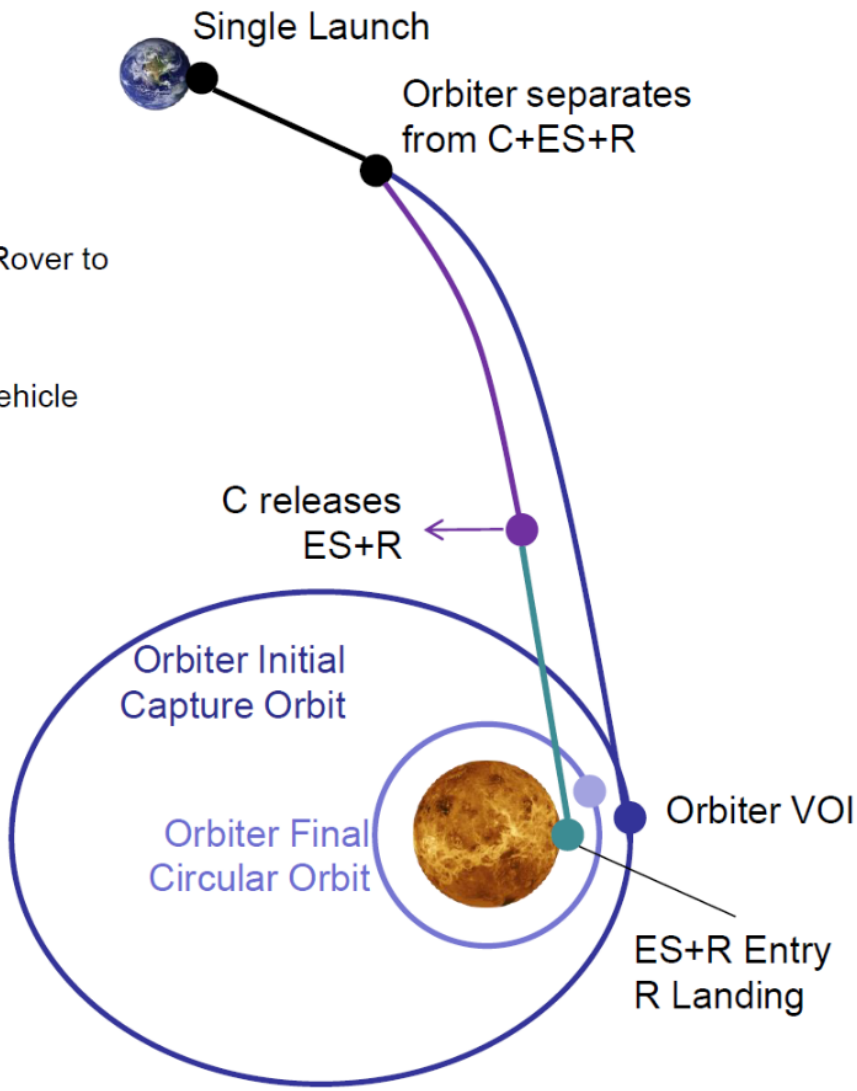


Orbiter (O) provides telecom relay for the Rover (using radar to get data from Rover)

Carrier (C) delivers ES+R to Venus

Entry System (ES) brings Rover to terminal descent in Venus atmosphere

Rover (R) is allocation for vehicle that lands on surface



Architecture A uses a split trajectory that allows one flight element (the Orbiter) to arrive at Venus several months prior to the rest (Carrier + Entry System + Rover). This seems feasible based on an analogous trajectory design by Damon Landau.

Timeline:

- Single Launch
- Orbiter separates from C+ES+R
- Orbiter arrives at Venus several months prior to C+ES+R. Orbiter performs Venus Orbit Insertion (VOI) burn
- Orbiter aerobrakes down to circular orbit
- Carrier releases Entry System with Rover on correct trajectory
- Entry System with Rover enters atmosphere in view of orbiter
    - And/or Rover lands on surface in view of orbiter
    - Timing of entry and landing needs to be studied; period of orbit could be tuned to duration of descent

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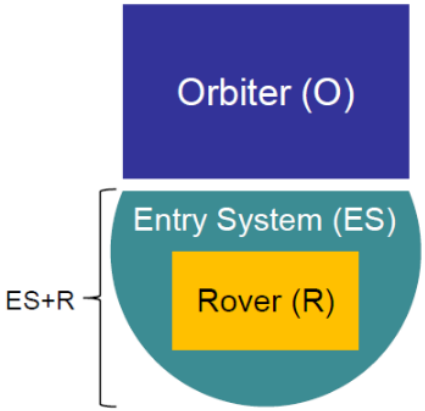
Systems
Architecture B



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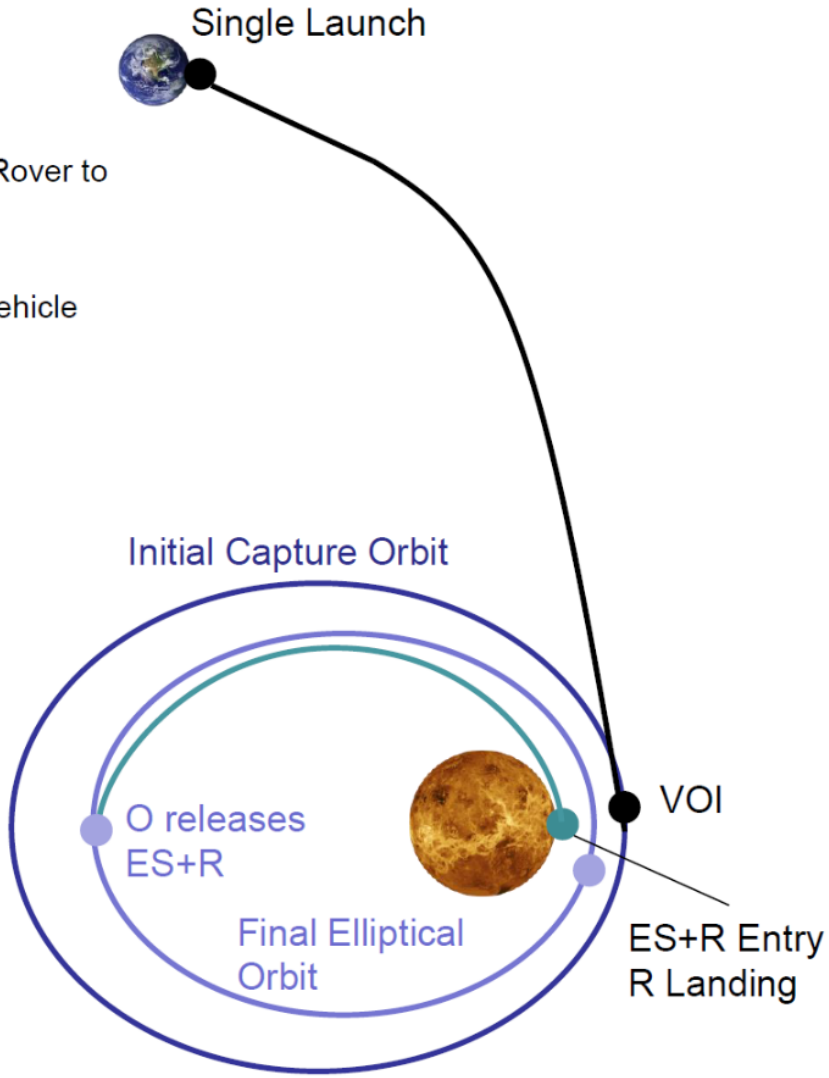

Architecture B uses a single trajectory to Venus. The entire stack (O+ES+R) is captured into Venus orbit prior to release of the Entry System with Rover. This is based on analogous designs for Venus atmospheric probes and short-lived landers, but **further work is needed** to verify that it is valid for a long-lived surface element requiring active radar-based communications.

Timeline:

- Single Launch
- Orbiter performs Venus Orbit Insertion (VOI) burn carrying ES+R
- Orbiter aerobrakes down to a lower elliptical orbit
- Orbiter releases Entry System with Rover at apoapsis (requires burn prior to and after release)
  - (see note on next slide about doing this from a low orbit)
- Entry System with Rover enters atmosphere in view of orbiter
  - Or Rover lands on surface in view of orbiter
  - Long period of orbit may preclude both
- Due to long duration of Rover mission, an elliptical orbit for the Orbiter is not desirable, because **periapsis will soon not coincide with the Rover location**

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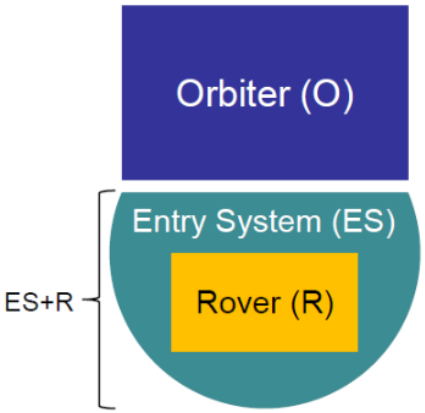
Systems
Architecture C



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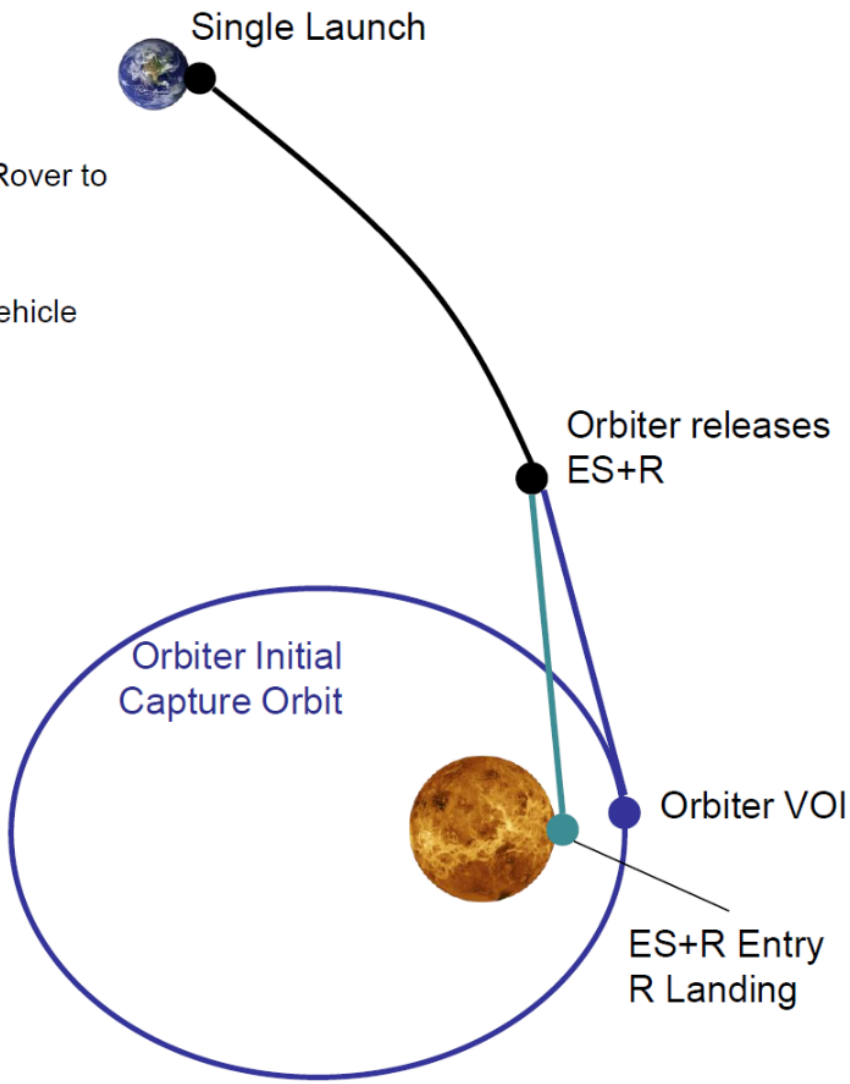

Architecture C drops off the Entry System + Rover prior to VOI (saving propellant vs. Architecture B), but does not include a separate Carrier stage for the ES+R, so the drop-off must occur at most a few days prior to VOI to avoid needing ES+R TCMs. This means that VOI and atmospheric entry are close together in time, and it may be a challenge for the orbiter to view entry/landing. **This architecture was not used for any of the design options, because it is not clear from analogy whether this is feasible.**

Timeline:

- Single Launch
- Orbiter releases ES+R
- Orbiter performs Venus Orbit Insertion (VOI) burn
- Entry System with Rover enters atmosphere
  - Can it be in view of Orbiter, and still allow Orbiter to perform TCM?

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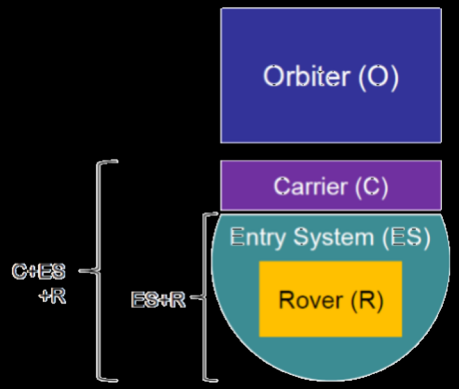
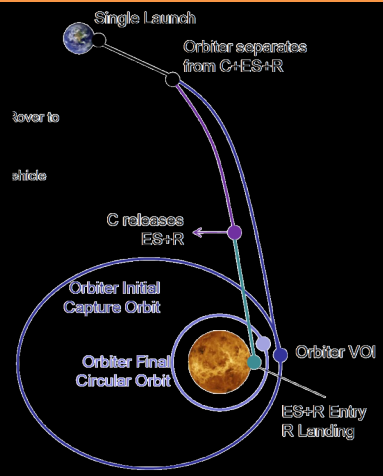
Comparison of the Mission Options

From the Team X Study

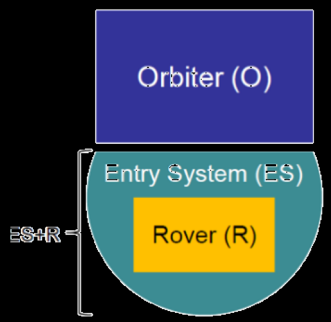
	Option 1	Option 2	Option 3	Option 4	Option 5
Name	Conventional NF	Alternative NF	Smallsat NF	Conservative Flagship	Insertion Flagship
Total Cost ($M)	$ 850	$ 850	$ 850	$ 2,000	$ 2,300
Architecture	B	A	A	A	B
Rover Mass (kg)	**200**	370	630	**1400**	**1102**
Rover Cost ($M)	$ 126	**$ 106**	**$ 191**	$ 295	$ 392
$/kg of Rover	$ 0.63	$ 0.29	$ 0.30	$ 0.21	$ 0.36

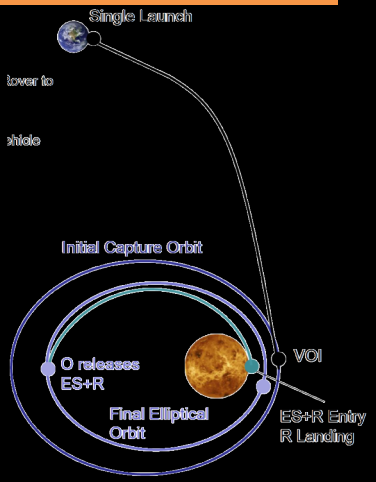
Architecture A





Architecture B





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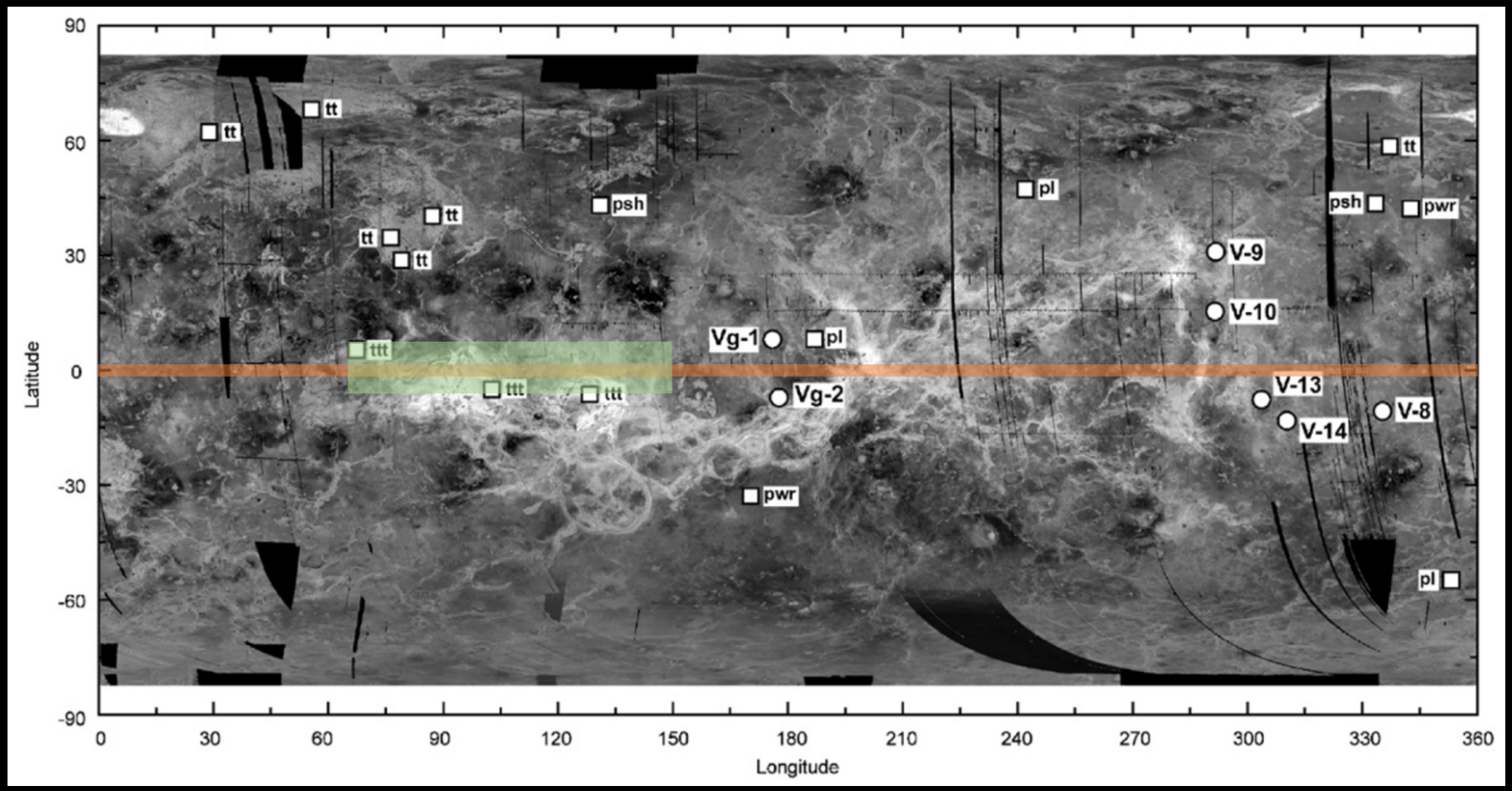
Where to Land on Venus

Balancing Wind, Communications



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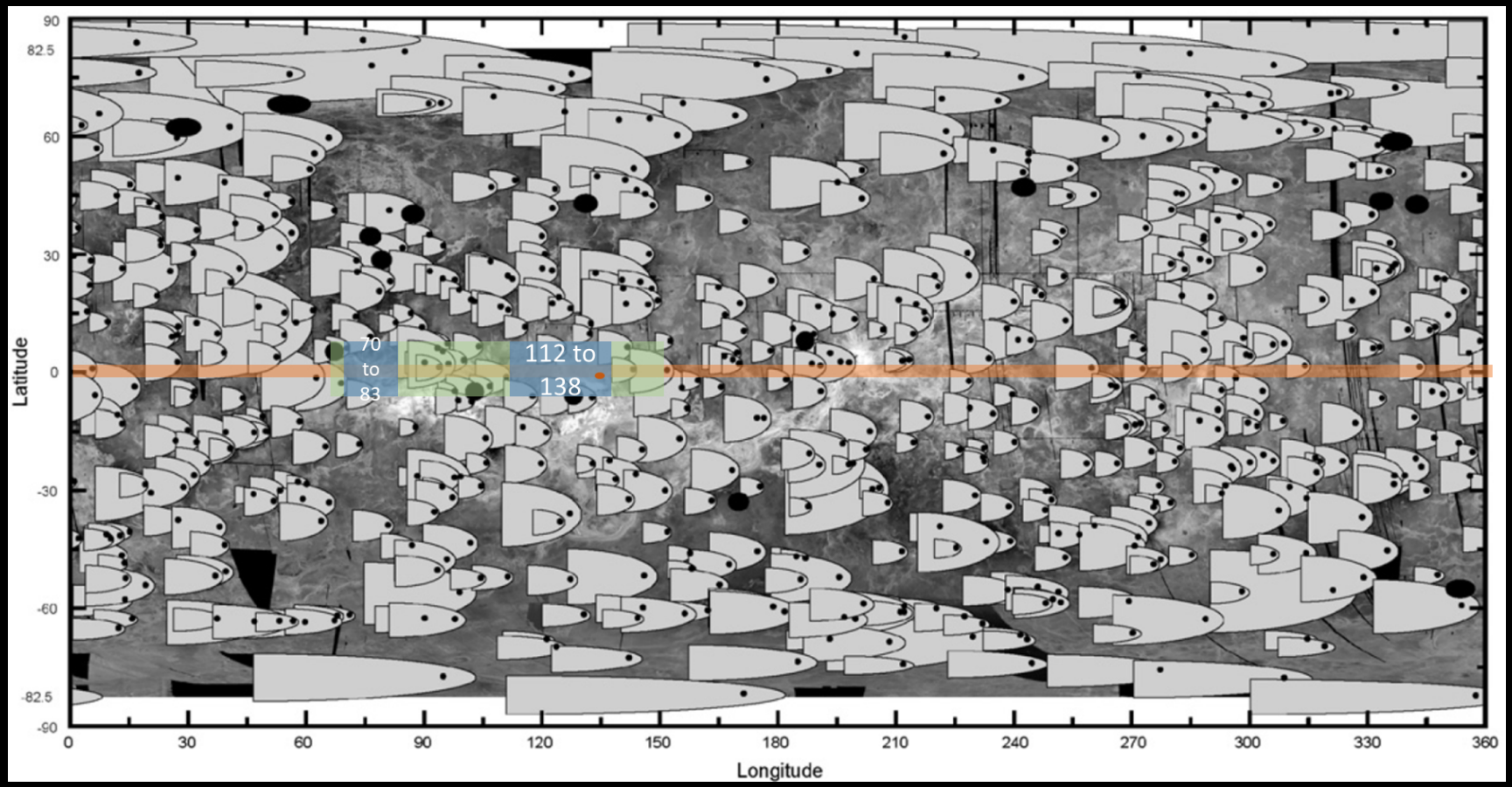
Where to Land on Venus

And Science



Background Map from A.T. Basilevsky et al.

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AREE Requirements

Level 1, Providing Design Guidance

		Level 1	
Req. Number		**Reqt. Title**	**Reqt. Text**
L1-Rover-1		Mission Goal	AREE shall obtain, provide for analysis, and return data on geologic samples from multiple geologic units.
L1-Rover-2		Mission Lifetime	AREE shall make science observations over at least 1 diuranal cycle (114 days)
L1-Rover-3		Mission Architecture Constratins	AREE L1-1 and L1-2 shall not require future developments in high temperature electonics to achieve minimum requirments.

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AREE Requirements

Level 2, Providing Design Guidance

	Level 2		
Req. Number	**Reqt. Title**	**Parent Requirement**	**Reqt. Text**
L2-Rover-1	Distance Traversed	L1-Rover-1	AREE shall traverse a minimum of 35 km
L2-Rover-2	Design for Terrain	L1-Rover-1	AREE shall traverse wrinkle ridges
L2-Rover-3	Sample acquisition	L1-Rover-1	AREE will take samples during traverse
L2-Rover-4	Weather Observations	L1-Rover-2	AREE shall observe weather over 114 days
L2-Rover-5	Design Lifetime	L1-Rover-2	AREE shall be built robust enough to survive 114 days
L2-Rover-6	EDL	L1-Rover-3	AREE shall fit within the constraints of existing EDL systems
L2-Rover-7	Data Transmission	L1-Rover-3	AREE shall transmit data without the development of high temperature electronics
L2-Rover-8	Naviation	L1-Rover-3	AREE shall navigate the Venus terrain without modern electronics

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AREE Requirements

		Level 3		
Req. Number		Reqt. Title	Parent Requirement	Reqt. Text
L3-Rover-1		Mission	L2-Rover-1	AREE shall produce at least TBD Watts of Power/day for mobility
L3-Rover-2			L2-Rover-1	AREE shall have survival power to 0.3 m/sec. Nominal mission case shall be designed around 0.6 m/sec
L3-Rover-3			L2-Rover-2	AREE shall be able to ascend or descend slopes of at least 35 degrees with obstacles up to 50 cm high and 200 cm wide
L3-Rover-4			L2-Rover-2	AREE shall be able to drive against a wind speed of 2.2 m/s
L3-Rover-5			L2-Rover-3	AREE shall take 1 sample every TBD km on flat terrain
L3-Rover-6			L2-Rover-3	AREE shall take 1 sample every TBD m on sloped Terrain
L3-Rover-7		Mission	L2-Rover-4	AREE shall carry instruments to make weather observations.
L3-Rover-8			L2-Rover-5	AREE shall be designed so it is not in operable if it flips, or so that it will not flip.

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AREE Requirements

	Level 3		
Req. Number	**Reqt. Title**	**Parent Requirement**	**Reqt. Text**
L3-Rover-9		L2-Rover-5	AREE shall be designed to be in the Venus atmosphere for 114 days.
L3-Rover-10		L2-Rover-5	AREE shall operate at 482C for 114 days
L3-Rover-11		L2-Rover-5	AREE shall opearte at 90 bar for 114 days
L3-Rover-12	Mission Lifetime	L2-Rover-3, L2-Rover-4	AREE shall product at least TBD watts of power/day for science measurements.
L2-Rover-13	Landing Size	L2-Rover-6	AREE shall fit in an aeroshell of 3.2 meters in diameter
L2-Rover-14	Landing Mass	L2-Rover-6	AREE shall have a payload mass of less than 1100 kg, including margin
L2-Rover-15	Landing	L2-Rover-6	AREE shall be take landing loads without damage.
L2-Rover-16		L2-Rover-8	AREE shall sense obstacles it can not overcome
L2-Rover-17		L2-Rover-8	AREE shall circumnavigate obstacles it can not overcome
L2-Rover-18		L2-Rover-8	AREE continue in its mission determined direction

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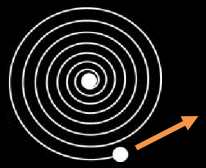
Mechanical Approach to Science

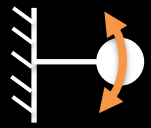
Wind Speed

Temperature



Pressure

Seismic Events



Chemical Composition

Measurements are Rough, and Don't Get at Core Goal, Geology

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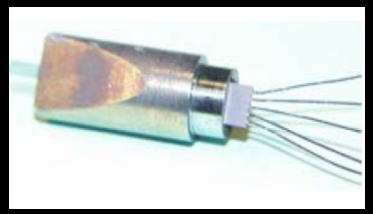
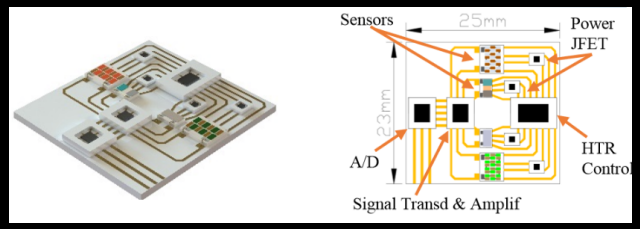
Current High Temperature Instruments

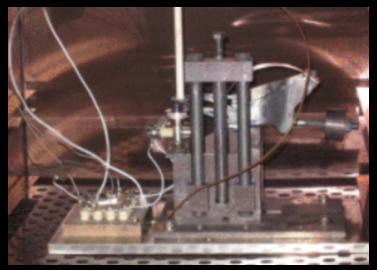
Several Under Development by Hot Tech, Others are Proposed

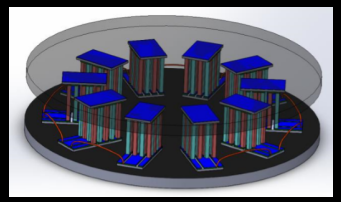


Weather Sensor, NASA Glenn

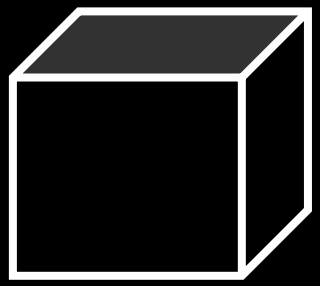


Chemical Sensor, Markel Eng.





Geophysical Instruments, JPL, Glenn



Mineralogy Sensor, NASA Glenn

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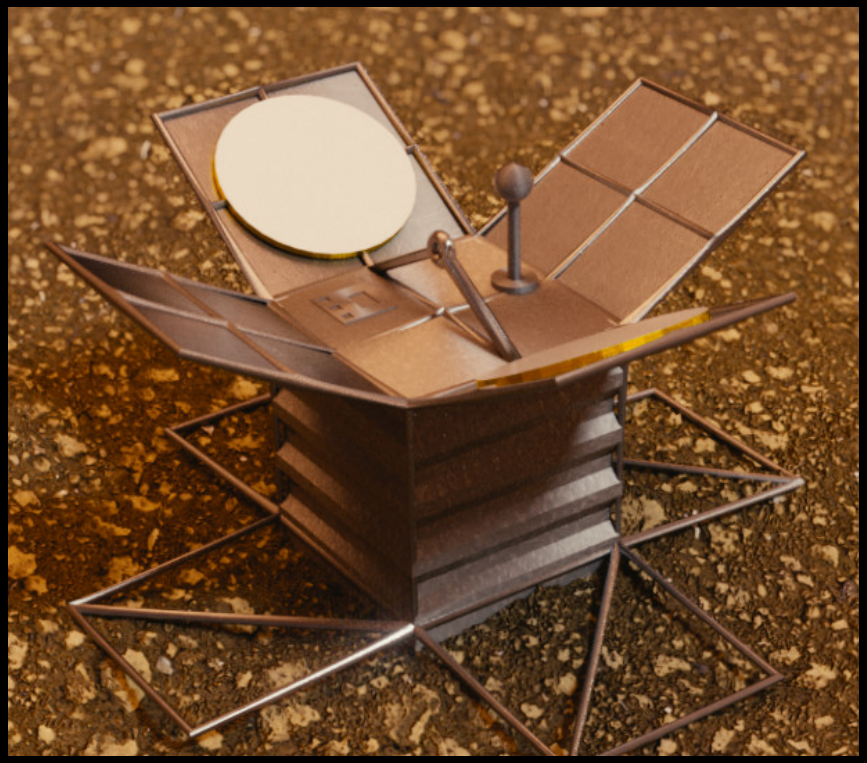
The LLISSE Concept – NASA Glenn

Long Life In-situ Solar System Explorer



Kremic, Hunter, Rock, et. al. 2018

Technology	Current TRL	Estimated TRL 6
Electronics Circuits: (SiC): Sensors and Data Handling	4-5	Aug-19
Electronics Circuits: (SiC): Power Management	3-4	Sep-21
Communications (100 MHz)	3-4	Sep-21
MIREM Spectral Imager	3-4	2022
Wind Sensor	4	Aug-19
Temperature Sensor	4-5	Aug-19
Pressure Sensor	4-5	Aug-19
Chemical Sensors	5	Aug-19
Bolometer	3-4	Sep-21

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Honeybee Robotics Electric Motor

Providing high temperature actuation and generation

3-Phase Brushless DC Motor

Motor tested at Venus temperature and pressure in CO_2

- Efficiency = ~43%

Generator test at Venus temperature

- Efficiency = ~33%

Tested at 20 hours of operation

Requires controller in cooled chamber

Rehnmark, Zacny, et. al. 2017

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Automaton Rover Advantage

Why is AREE required for mobility on Venus

- **Energy Generation**
- **Energy Storage**
- **Obstacle Avoidance Approach**

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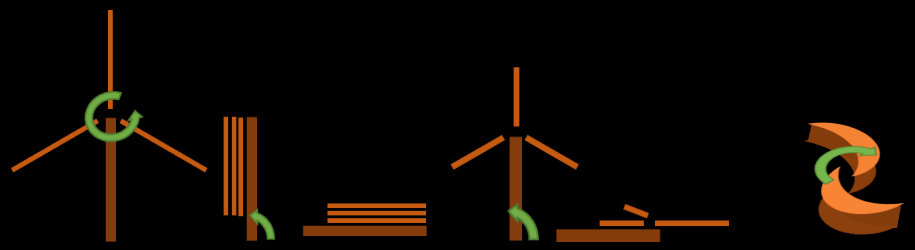
Energy Generation

Wind power is the most realistic, long duration power source



	2x Deployable Turbine 6.4m	Deployable Turbine 3.2m	Savonius Turbine 1.5m	RTG	Solar (averaged over 58 Earth days)
Average Power (W)	114.85	28.71	3.18	25.70	3.95
Power Gen. Density (W/kg)	1.10	0.91	0.20	1.35	2.40
Risk & Investment	High	Moderate	Moderate	Very High	Low

Assumes a wind speed of 0.6 m/sec

Solar assumes 32 W/m^2 at peak with 2.0m^2 of deployed area. Assumes no dust on panels.

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Energy Storage

Low RPM, High Torque In, Low RPM High Torque Out

	NaS Battery	NaCl Battery	Metal Spring	Composite Spring	Gravity (3m tower)	Flywheel (in vacuum)	Compressed Atmosphere
Energy Density (W-h/kg)	220	143	0.09	0.75	0.01	10	15
Risk & Investment	Very High	High/ Moderate	Low	Low/ Moderate	Low	High	High/Moderate

	Mechanical System	Electrical System
Power Loss	Frictional Loss	Frictional Loss Generator Efficiency (33%) Resistive Losses Motor Efficiency (43%)
Gearbox Requirements	25 RPM → 2 RPM 12.5:1 Gearbox	25 RPM → 3,000 RPM 1:120 Gearbox

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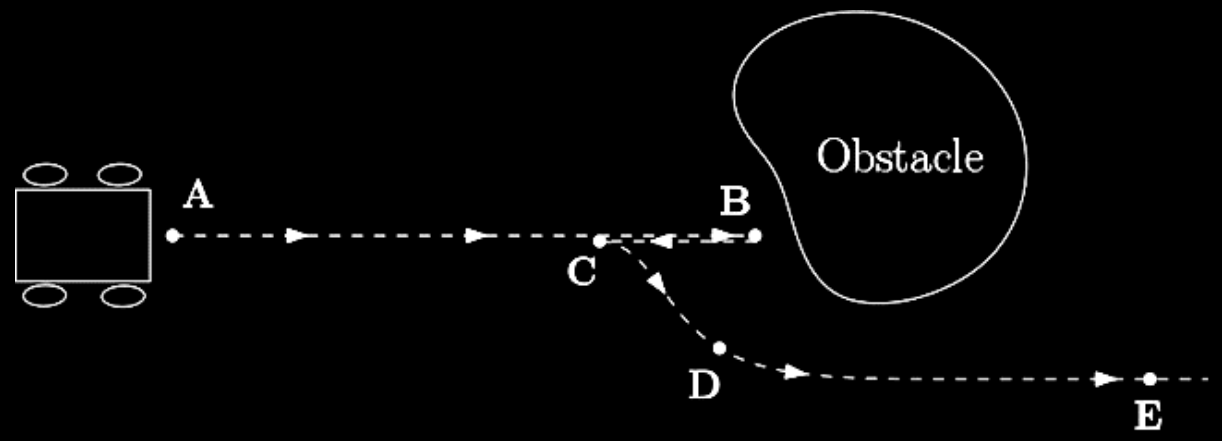
Obstacle Avoidance

A mechanical approach is required

You can't perform traditional image processing

Need to take a manual approach:

- It may be bumpers
- It may be sonar, LIDAR, or something else.



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Venus Wind Turbine Research

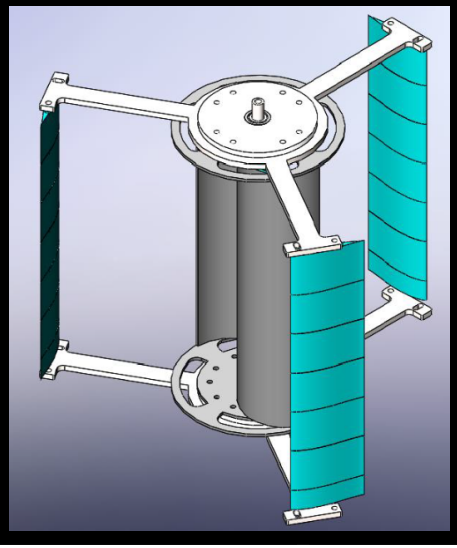
Development, Design, and Testing by Senior Project Teams

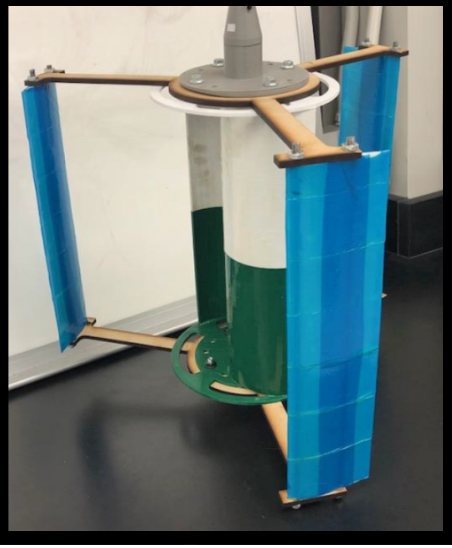
CSULA Work

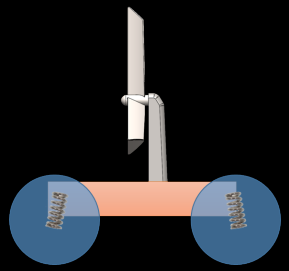
- Completed a design for a HAWT.
- 1.5 meter diameter by 1 meter tall.
- Scale model testing extrapolated to a performance of ~1W at 0.6 m/s and 9W at 1.3 m/s

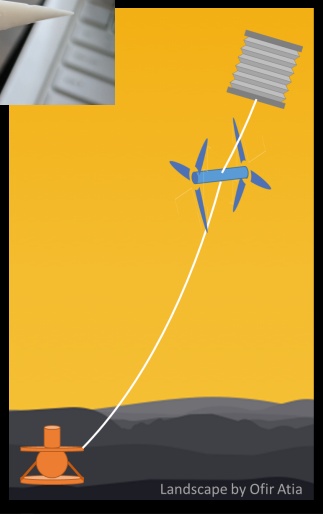
Bradley University

- Performing design of a VAWT.
- Specifically investigating low speed airfoils.









Wind Turbines | Locomotion | Rover Prototyping | High Temperature Mechanisms | Radar Targets

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A Brief Background on Turbine Performance

Simpler Systems Provide Less Power

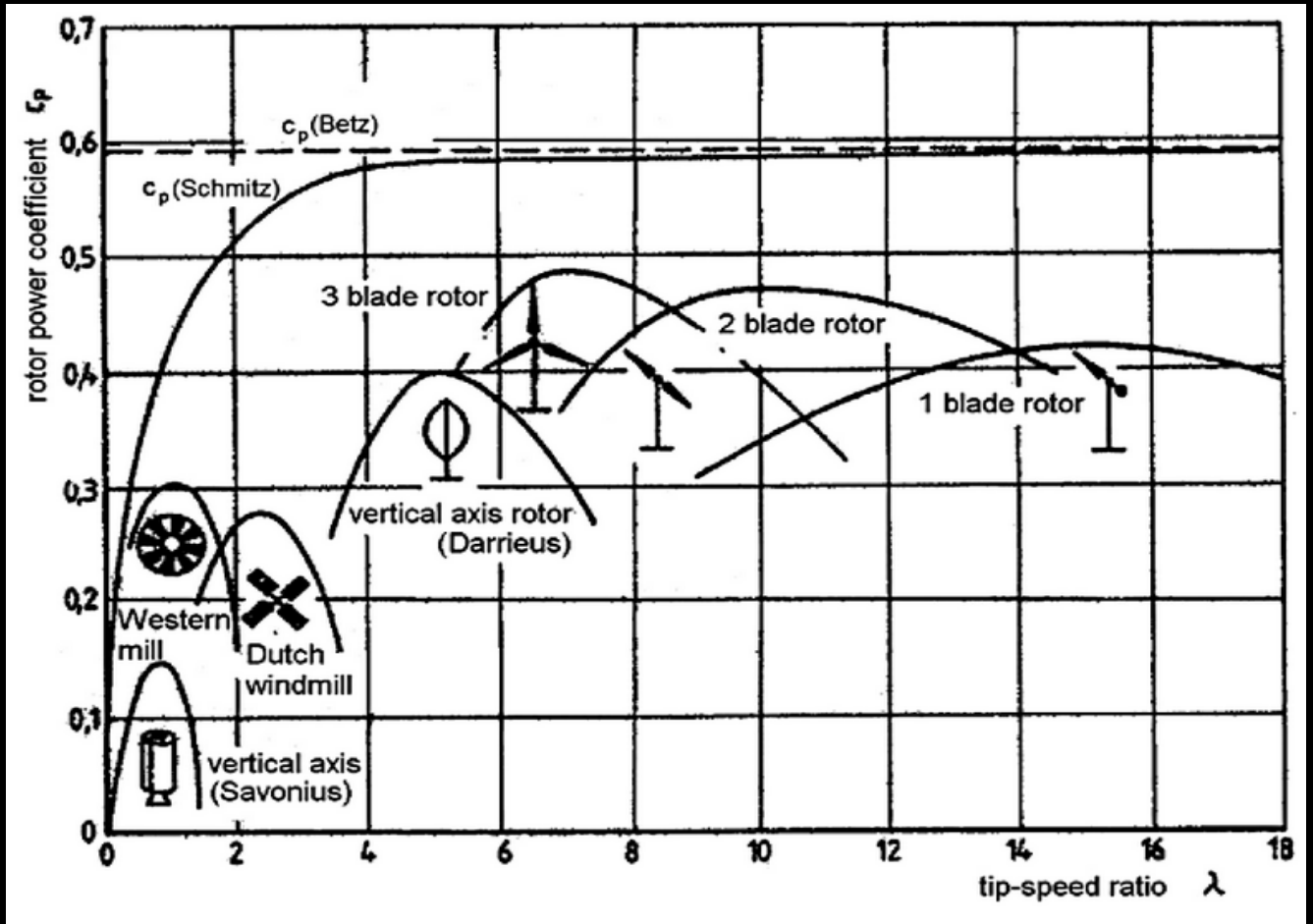

Fig. 2.2 Typical power coefficients of different rotor types over tip-speed ratio

Wind Energy Systems for Electric Power Generation

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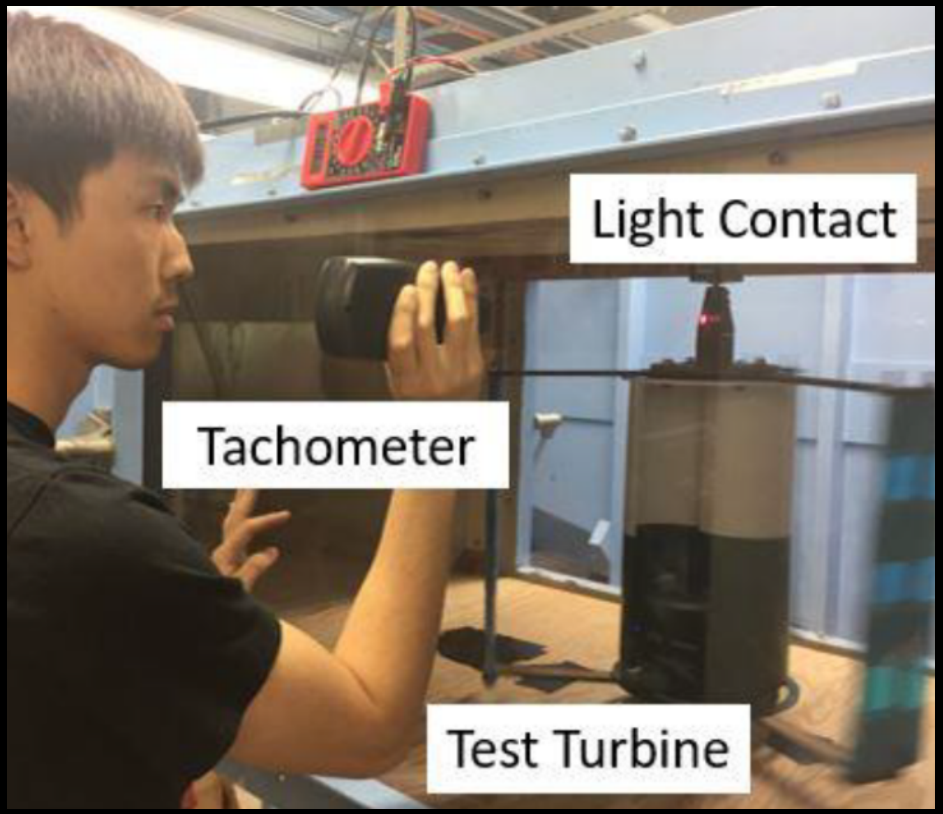
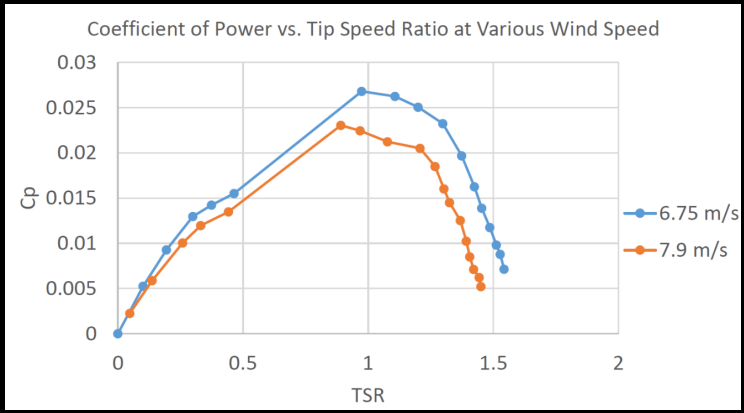
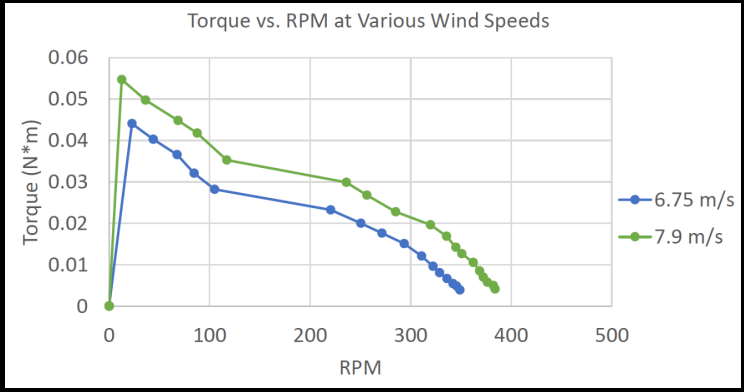
Venus Wind Turbine Research

By CSULA







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Potential for Future Investigation

What to Match: Reynolds, Force, or Power?

		Matching Re Number				Matching Force				Matching Power			
Value	Venus V	V	Re	F Change	P Change	V	Re	F Change	P Change	V	Re	F Change	P Change
Units	m/s	m/s	m/s	%	%	m/s	m/s	%	%	m/s	m/s	%	%
Water Full Scale	1.00	2.59	2272727	10286 %	26658 %	0.26	224091	100%	26%	0.40	353132	248%	100%
Water 1/2 Scale	1.00	5.18	2272727	10286 %	53316 %	0.51	224091	100%	51%	0.64	280281	156%	100%
Air Full Scale	1.00	34.34	2272727	2121%	72836 %	7.46	493491	100%	746%	3.82	252598	26%	100%
Air 1/2 Scale	1.00	68.68	2272727	2121%	145673 %	14.91	493491	100%	1491%	6.06	200487	17%	100%

Options for testing

- In Water
- In Air

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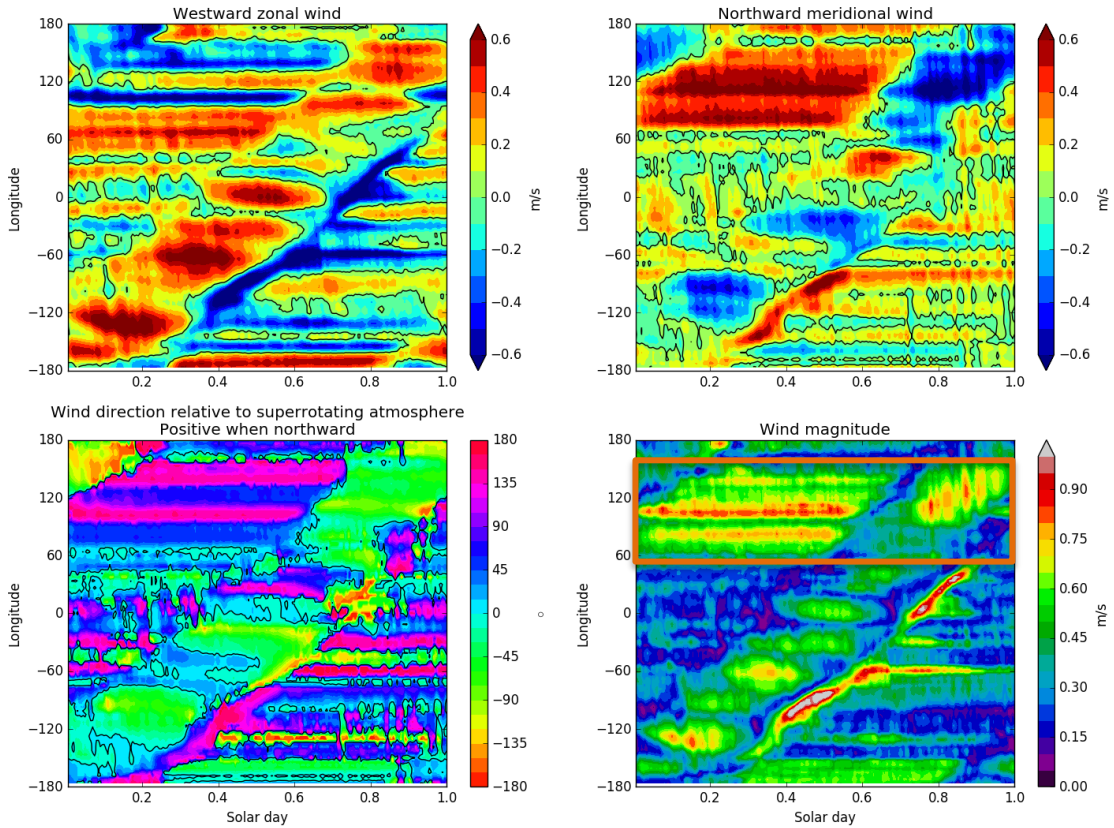
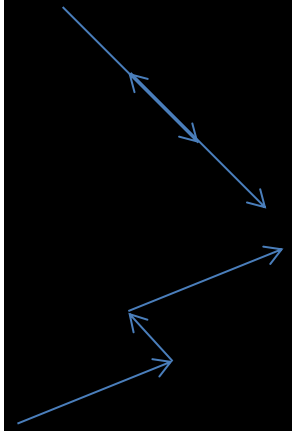
The Wind on Venus

Provides both Power and Navigation



Valid for Latitudes 5N to 5S at 4 m, from LMD/IPSL Venus GCM



Thomas Navarro

Wind Turbines | Locomotion | Rover Prototyping | High Temperature Mechanisms | Radar Targets

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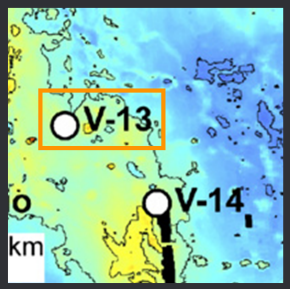
Venus Obstacle Consideration



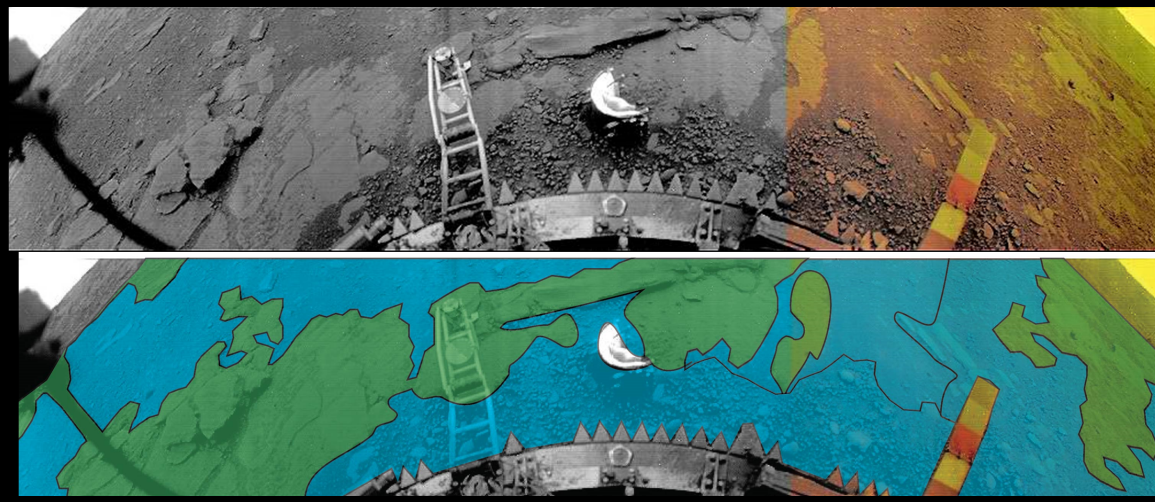
Venera 13

Venera 13 and 14 landers measured the **composition of the surface material** using (XRFS) and took two TV panoramas each A few cm^3 sample was taken by the drilling device on each lander from the top few centimeters of the surface material, delivered inside the lander capsule, and then analyzed. The photos again showed the presence of two types of the surface materials: **soil and finely bedded rock.**
Landing Site: Crater materials, Regional plains, shield plains

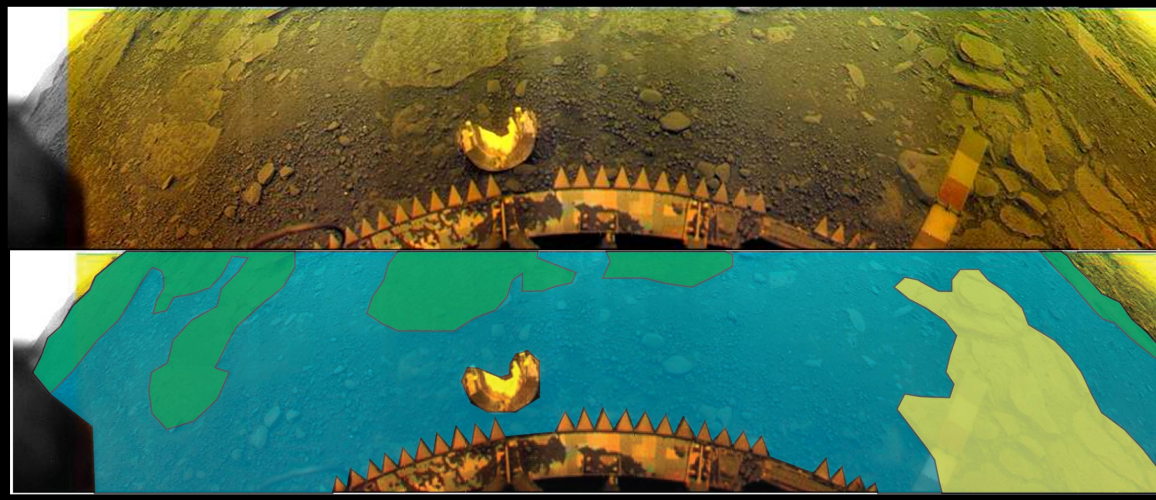
0.5 M/S

BEDROCK / SMALL BLOCKS
PEBBLES / FINES

PANOMARA A



PANOMARA B



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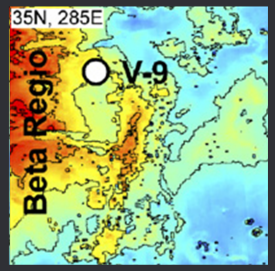
Venus Obstacle Consideration

Maximum Size: 0.5 meters



Venera 9

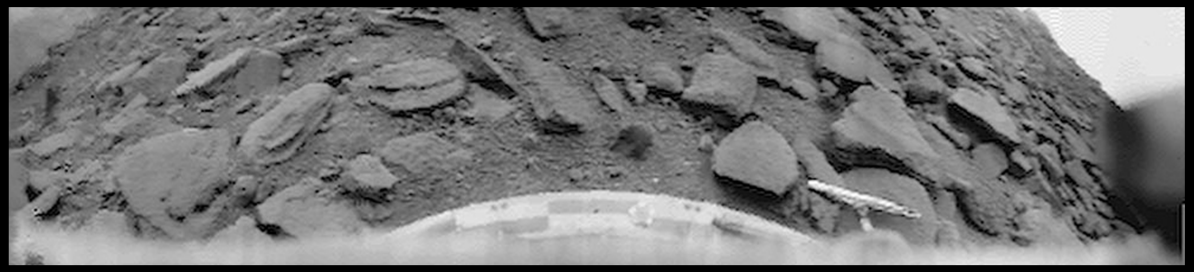
Venera 9 & 10 measured the contents of K, U and Th in the surface material by the GRS technique and took TV panoramas of the close vicinity of the landing sites. The panoramas revealed the presence of two types of the surface materials: **soil and finely bedded rock.**

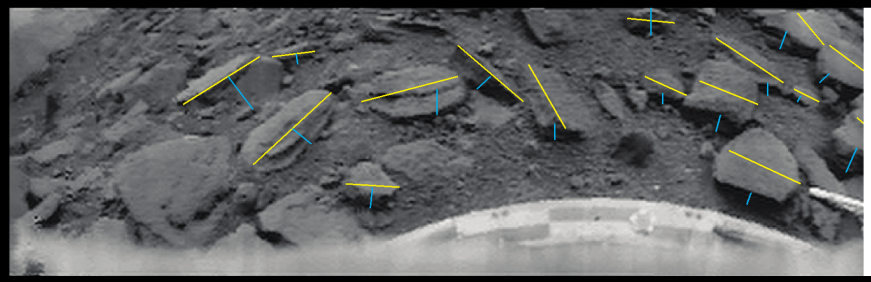
Landing Site: Crater materials, shield clusters, shield plains

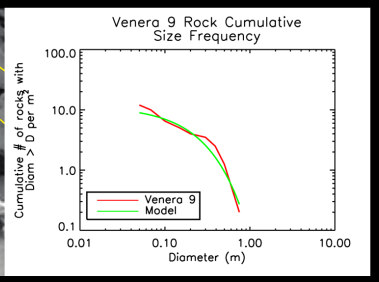
0.4 - 0.7 M/S

BLOCKS / COBBLES
SMALL BLOCKS /PEBBLES / FINES

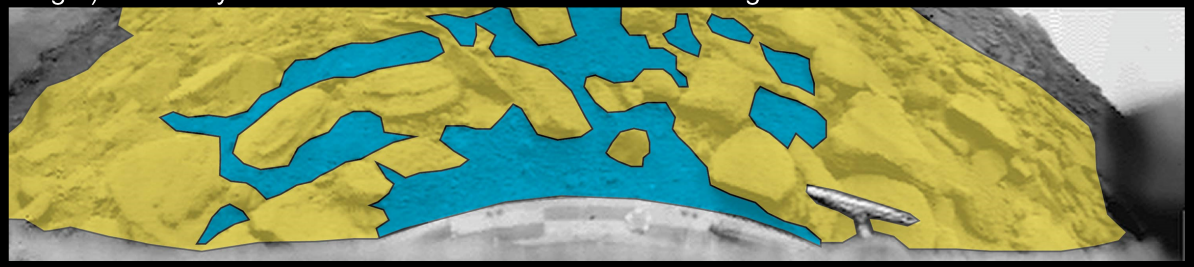
PANORAMA A







Average aspect ratio is 0.35. Rover is ~1 m wide. Probability of rock > 1.0 m in diameter (0.35 m height) is 1 every 100 meters. Rock size to climb with margin was determined to be 0.5 meters



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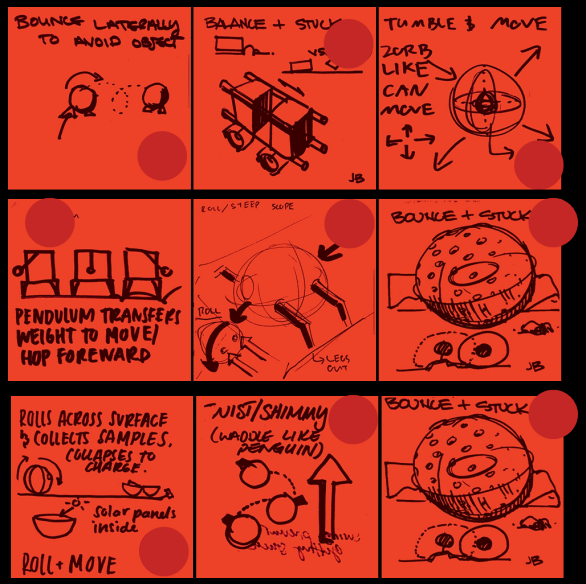
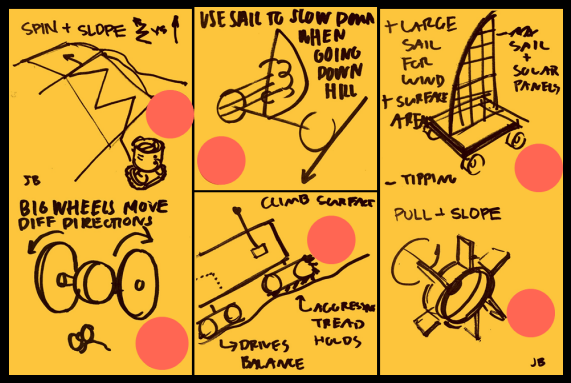
Mobility System Brainstorming

Initial Broad Search

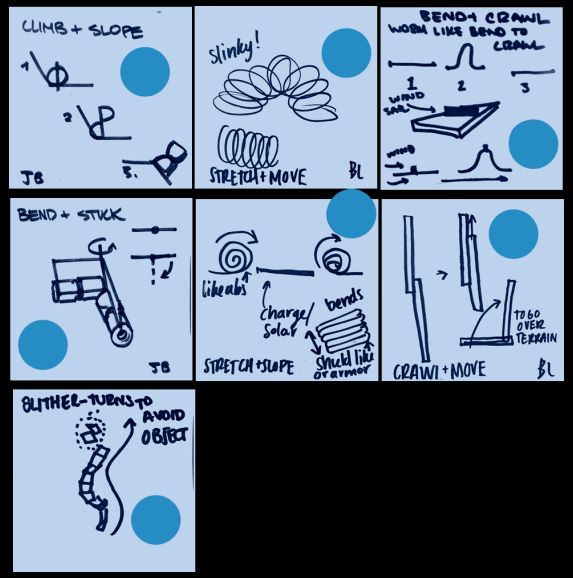
Rolling Spheres



Wheeled/Tracked



Walking/Gait



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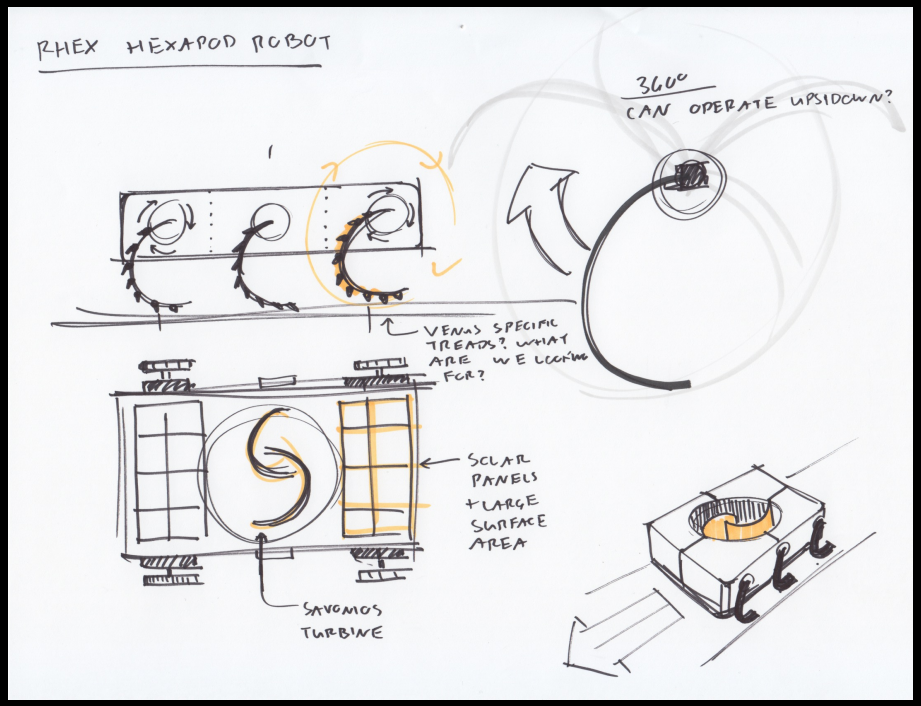
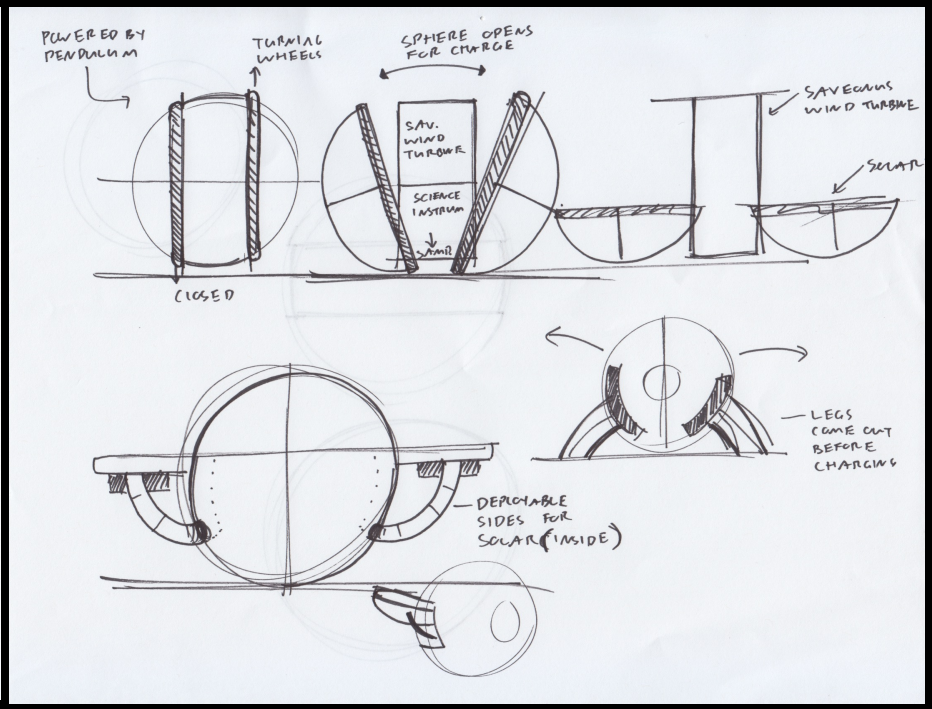
Mobility System Brainstorming

Concepts of Interest





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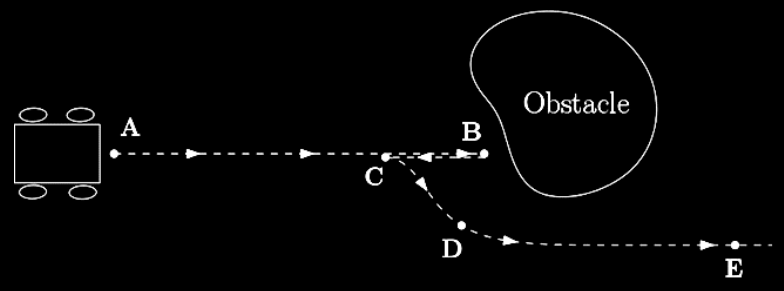
Obstacle Avoidance Approaches

Reactive Rover

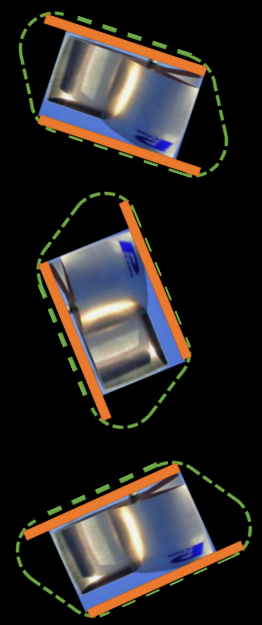
Repeats 1-3 predetermined obstacle avoidance routines.

May or may not of global navigation (likely using wind as a guide)



Non-Reactive Rover

Rover designed to ignore obstacles.



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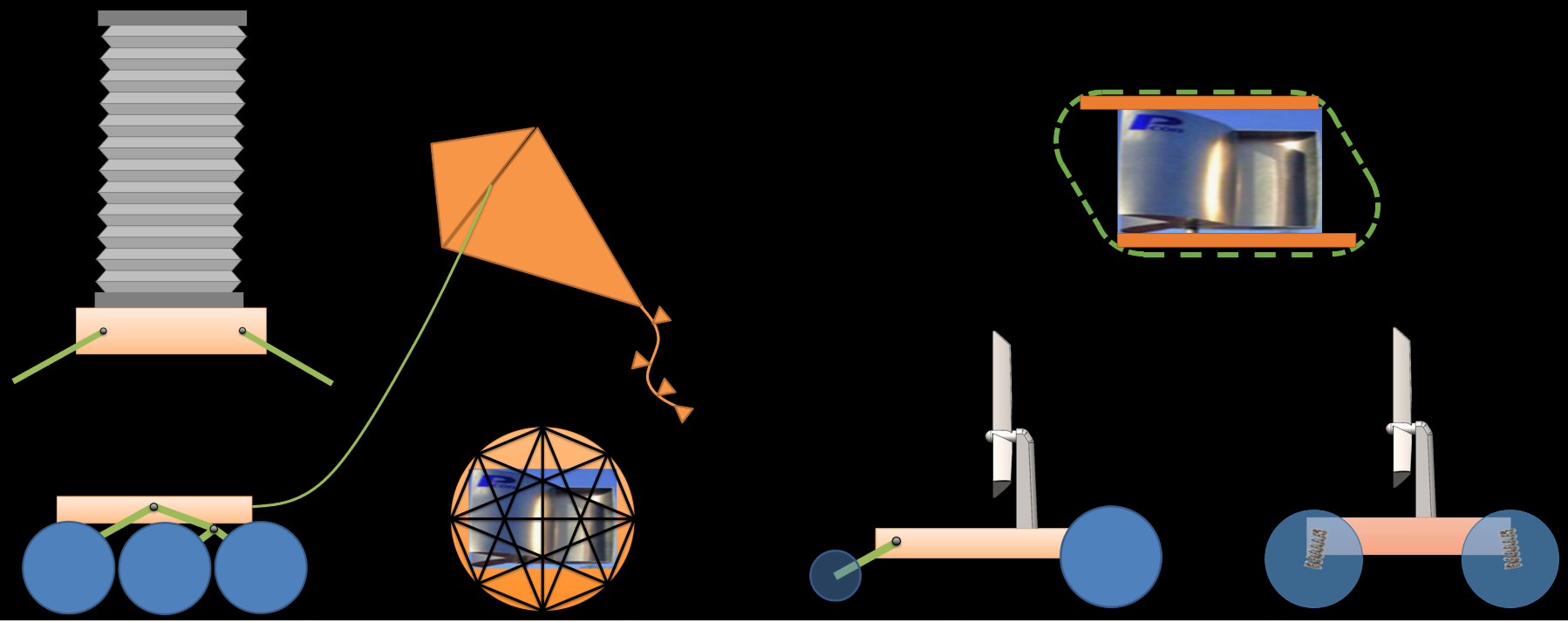
Approaches to Using Wind Power

Direction of Wind

Restricted to traveling in the direction that the wind blows it.

Wind Direction Independent

Captures wind energy, but then redirects it with a locomotion system.



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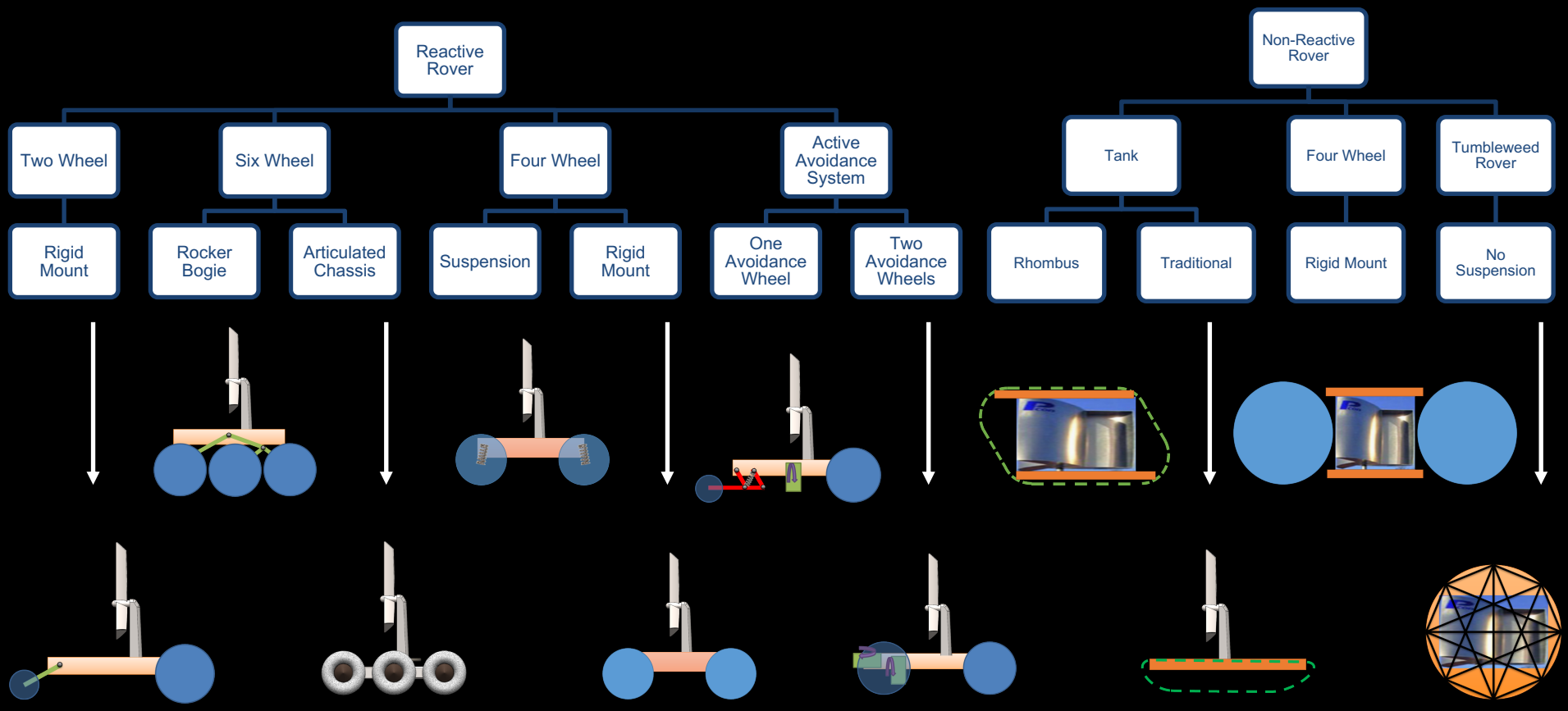
Mobility Trade Tree



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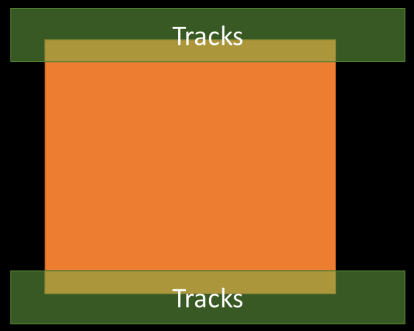
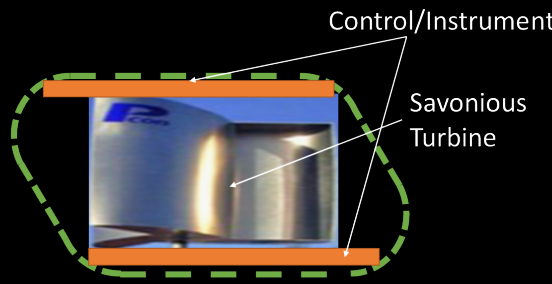
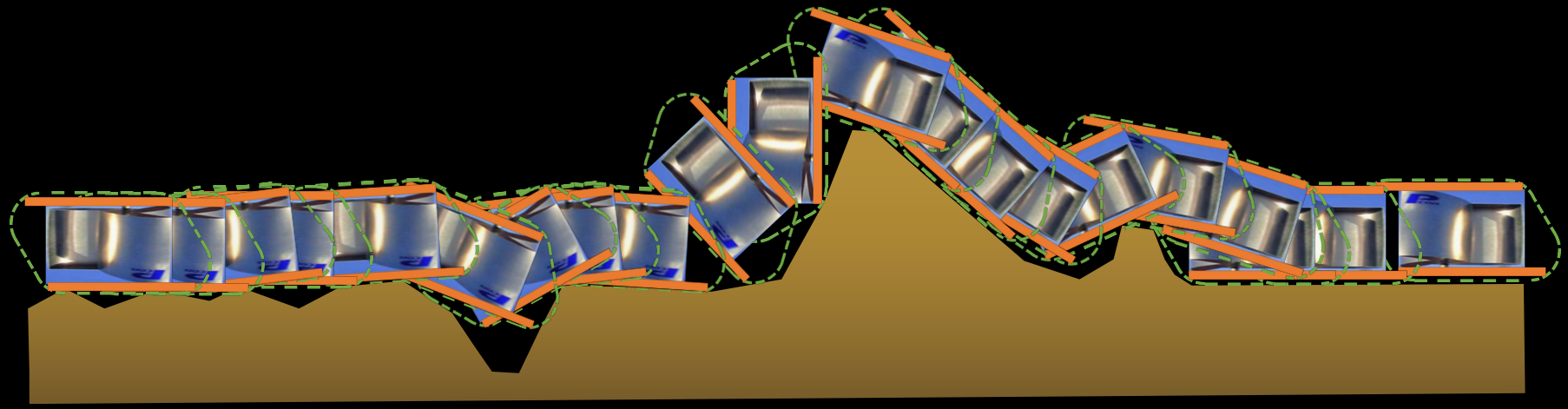
Non-Reactive Rover

Design the rover to be robust against obstacles

Low Terminal Velocity in Venus's Atmosphere







And perhaps an inherent design, where if it rolls, it rolls into a new direction.

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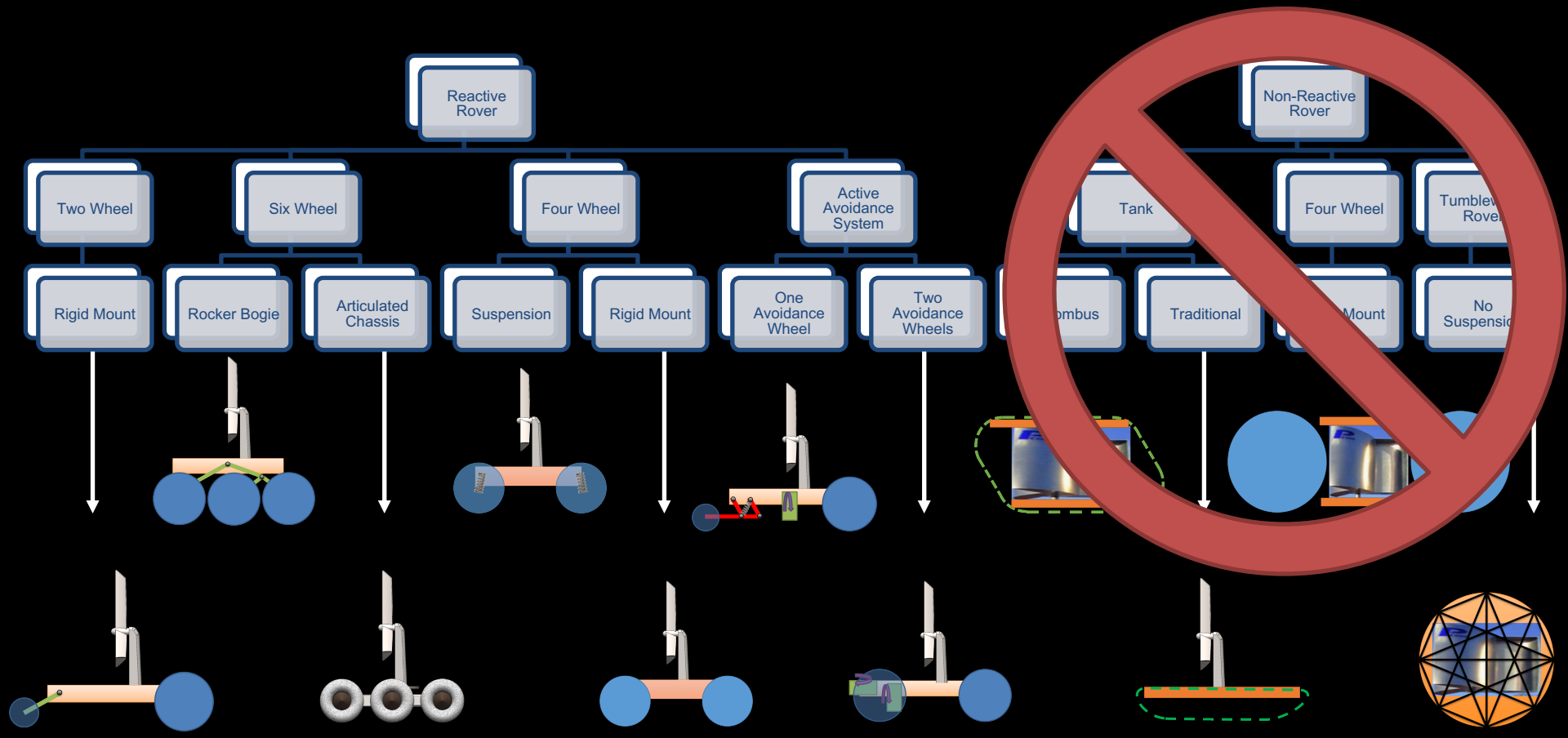
Mobility Trade Tree



In developing a reactive rover, we develop the same key systems required by a non-reactive rover, and we develop critical, under investigated short range obstacle avoidance capability.

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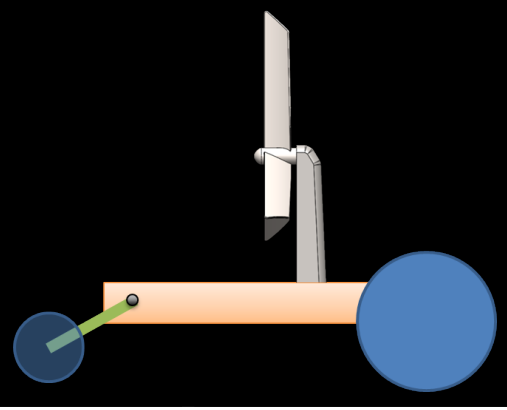
Reactive Rover Comparison

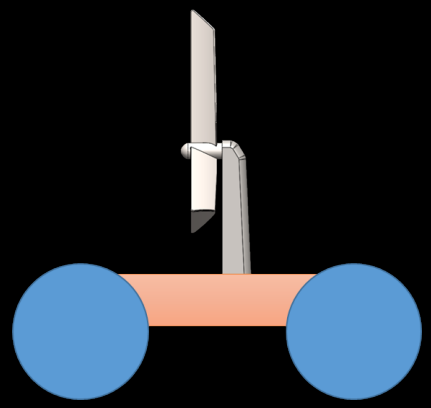
Two Wheel

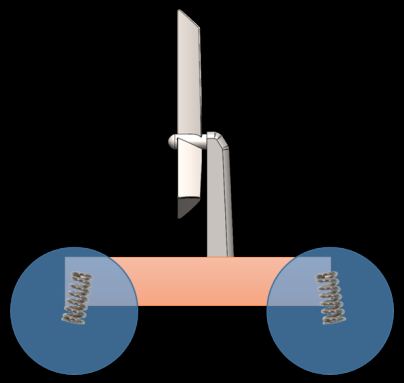
- Lightweight
- Easy to fit in an aeroshell
- Differential steering without skidding
- Zero turn steering means rover moves in prior path
- Only two wheels putting power to the ground
- Small payload volume



Four Wheel

- Copies existing vehicle designs
  - Large amount of prior work
- Large payload volume
- Stable
- May require separate drive and steering system.





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Reactive Rover Comparison

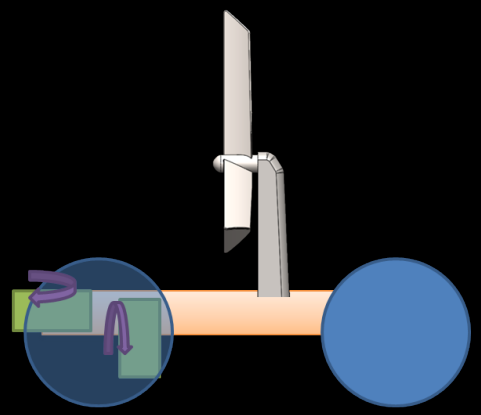
Active Avoidance

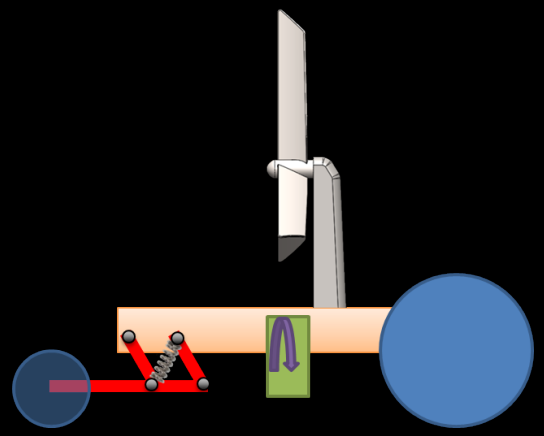
Two Avoidance Wheels

- No logic required to avoid obstacles
- Very Inefficient (constantly rotating wheels)
- What happen immediately after wheel clears obstacle?

One Avoidance Wheel

- Only a linkage required to avoid obstacles
- Inefficient
- Chance of getting wedged/jammed





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Reactive Rover Comparison

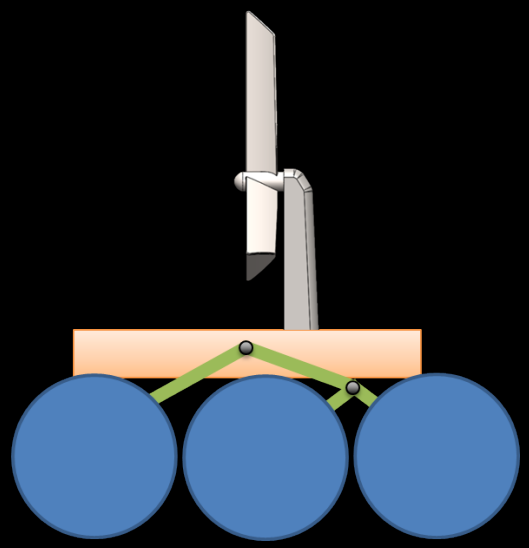
Six Wheel Rover

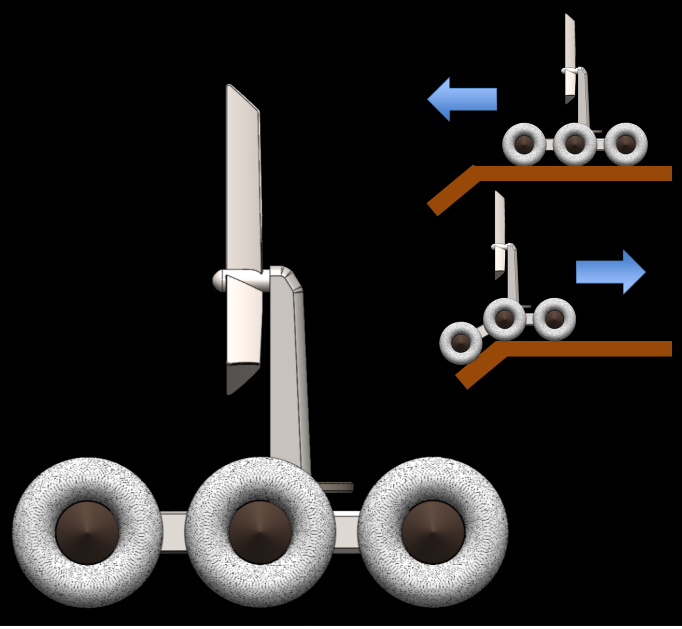
Rocker Bogie

- Most capable over unknown terrain
- Significant mission heritage
- 9 degrees of freedom in chassis
- Complex power transmission
- Difficult to steer

Articulated Chassis

- Integrated obstacle avoidance in chassis
- 6 degrees of freedom in chassis
- Small payload volume
- Slightly less capable than rocker bogie





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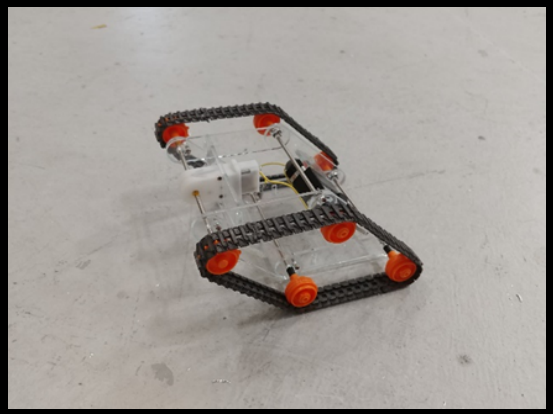
Early Prototyping

Tank Lessons Learned

- Deformation in tracks is necessary to prevent backwards rollover
- Low ground clearance poses risk of high centering or getting hit “between the eyes”
- While it is easy to turn by running the tracks in opposite directions, minor adjustments are difficult



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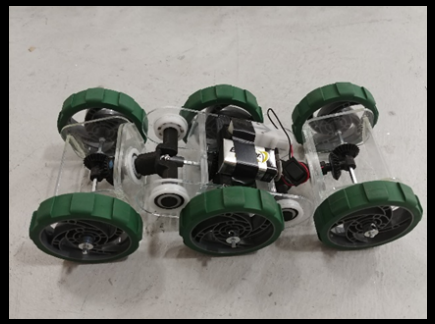
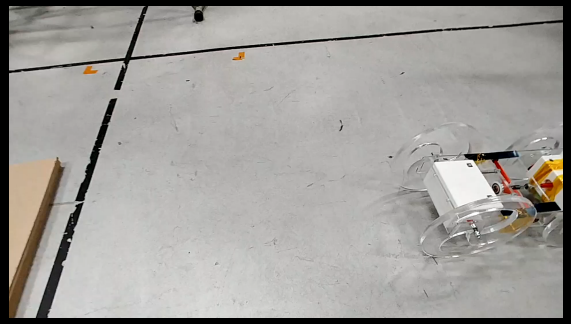
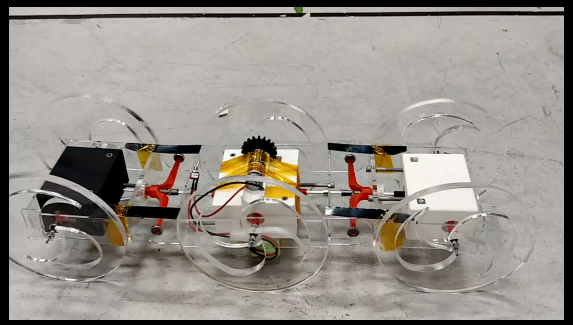
Early Prototyping

Six Wheel Lessons Learned

- Springs are necessary for driving even when not climbing
- The pivots may be able to be replaced with flexures
- Mass balance around the axles is very important
- It is very difficult to steer







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Todays Review

Introduction

Topic	Time Allocated	Start Time	End Time
Introduction	20 min	8:30 AM	8:50 AM
Technical Explorations	60 min	8:50 AM	9:50 AM
Break	**10 min**	**9:50 AM**	**10:00 AM**
Technical Explorations	40 min	10:00 AM	10:40 AM
Programmatics	15 min	10:40 AM	10:55 AM
Next Steps	10 min	10:55 AM	11:05 AM
Time for Additional Questions	15 min	11:05 AM	11:20 AM
Lab Tour	30 min	11:20 AM	11:50 AM

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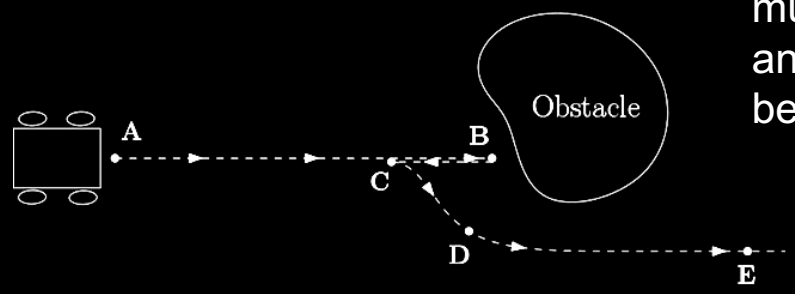
Rover Prototype Approach

Three prototypes in parralell

Computer Model

- Determine obstacle avoidance algorithms.
- Very basic, but very quick iterations



Electronic

- This version is used to test the behaviors with a focus on rapid iteration.
- By using bump sensors and a Raspberry Pi multiple behaviors and reactions can be tested in a day.

Mechanical

- This version is used to test the behaviors decided upon using lessons learned from the electronic rover.
- This process will be a prototype of a mechanical reaction mechanism that with slight modification can operate in a Venus environment.

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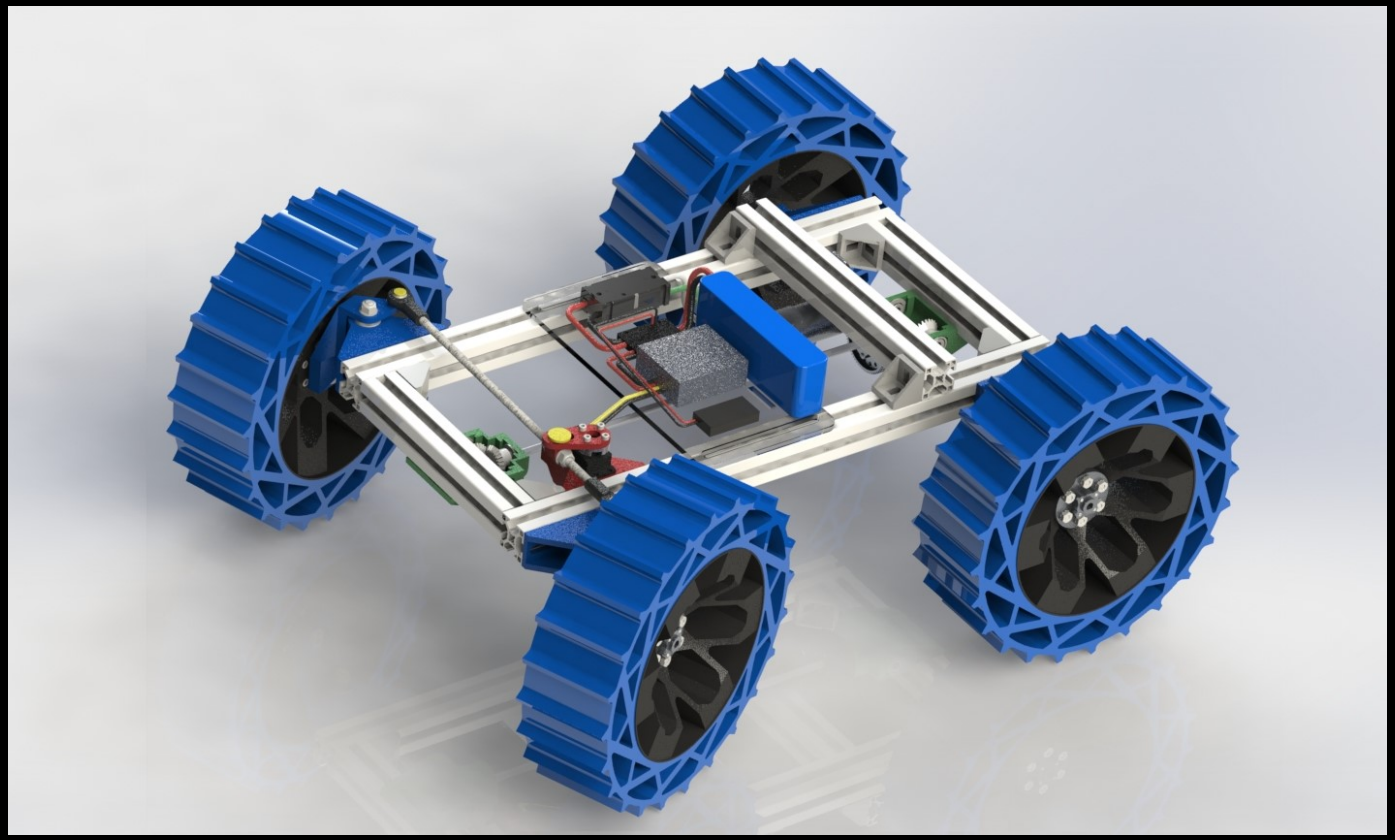
Current Prototype Chassis



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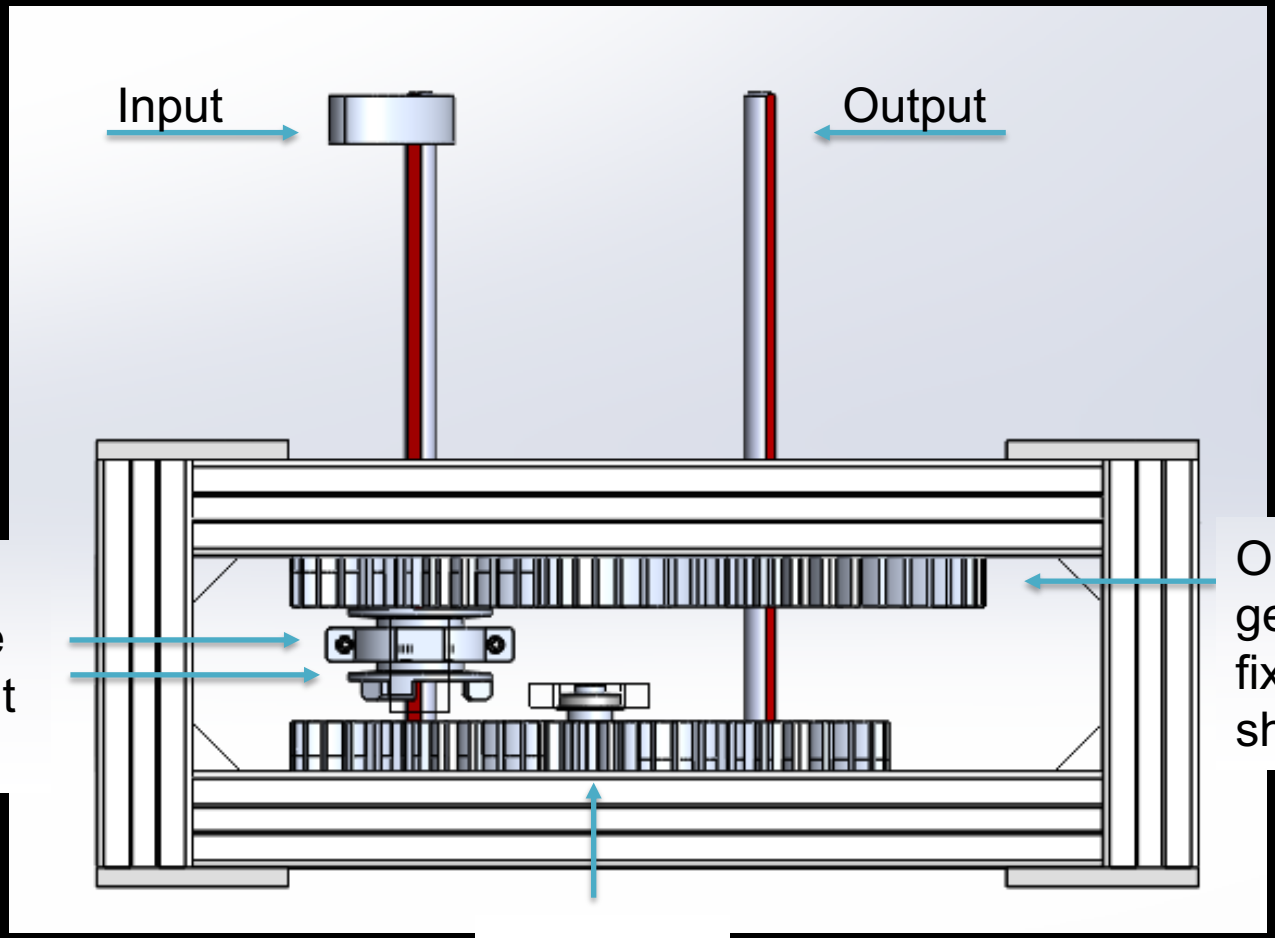
Reverse Mechanism

Takes input from state machine to reverse the rover



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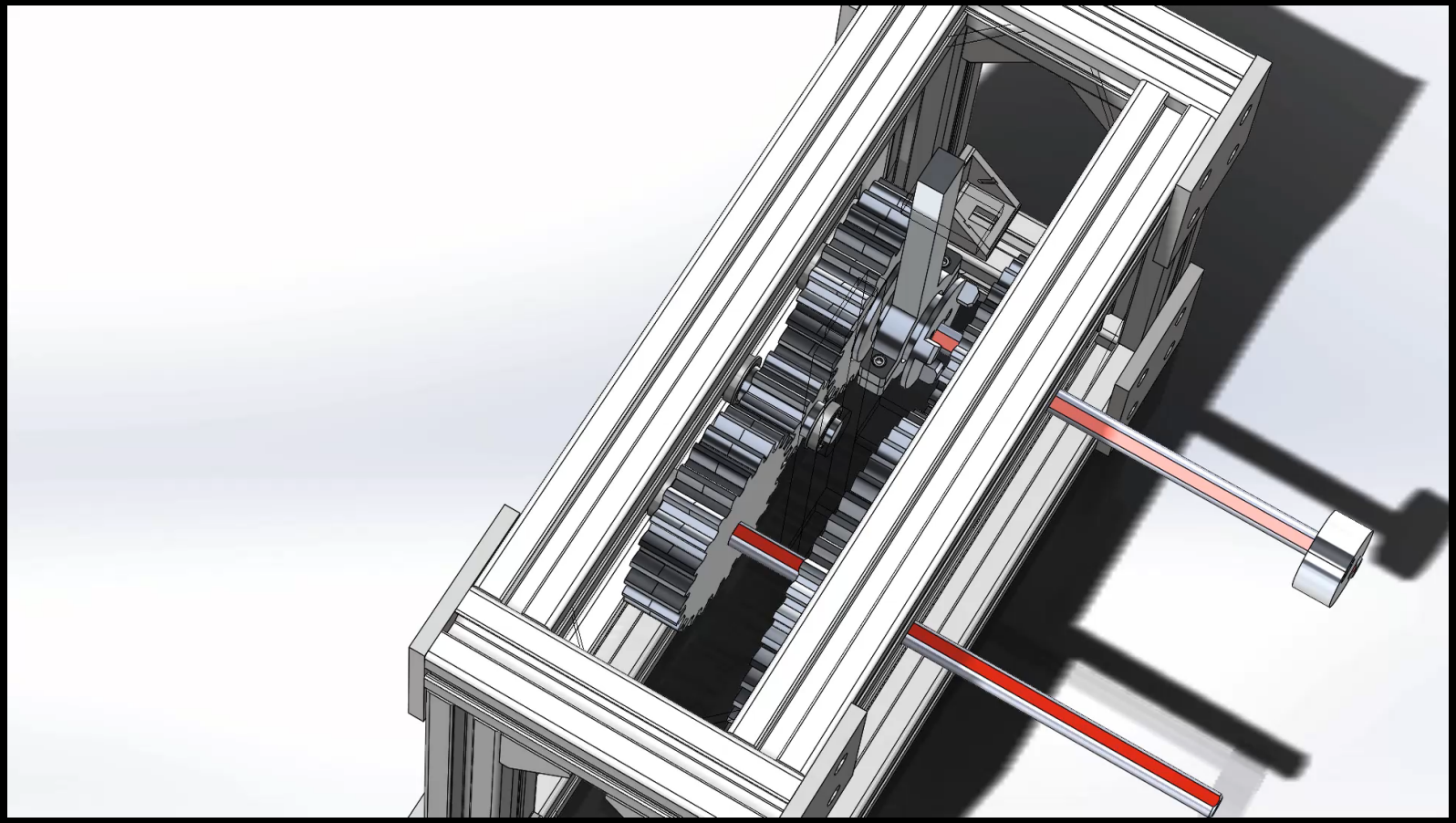
Reverse Mechanism

In Action



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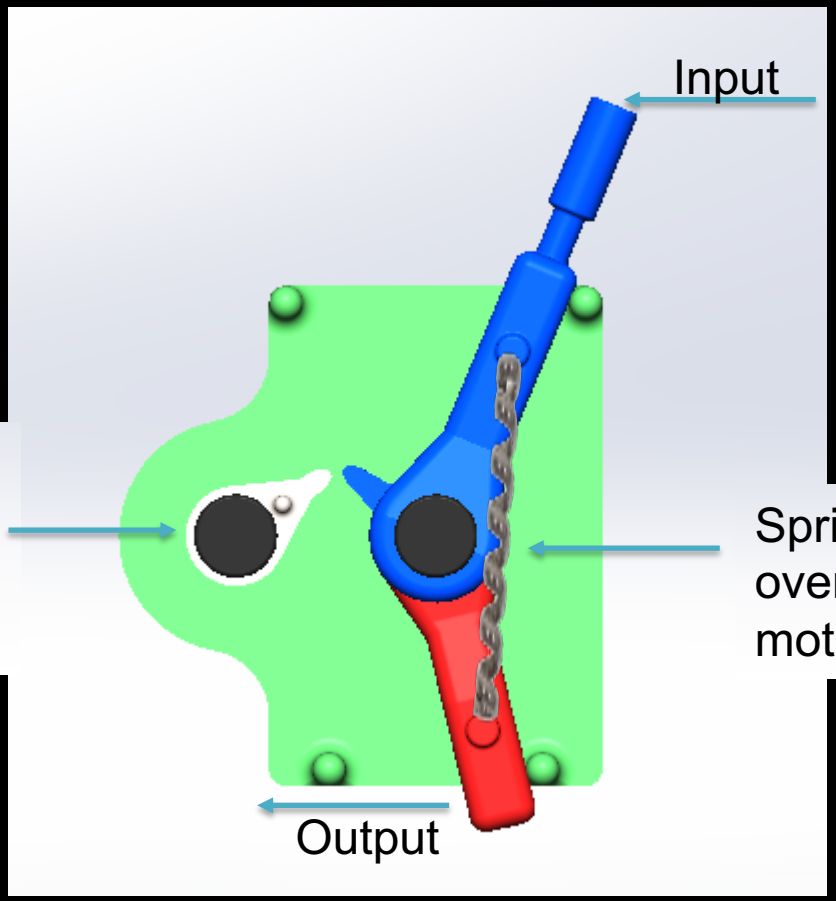
Reverse Mechanism Switch

Takes input from bumper to shift into reverse



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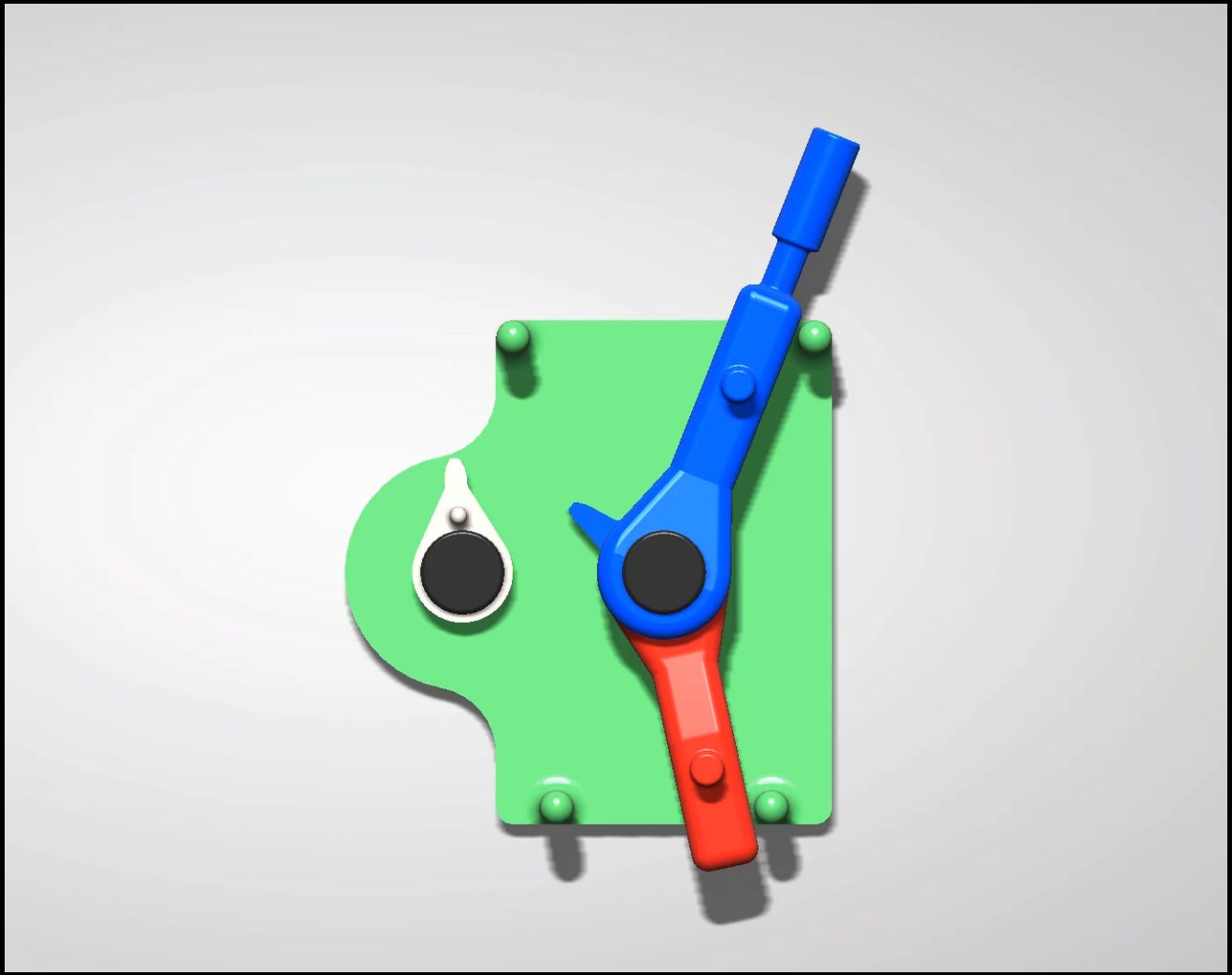
Reverse Mechanism Switch

In Action



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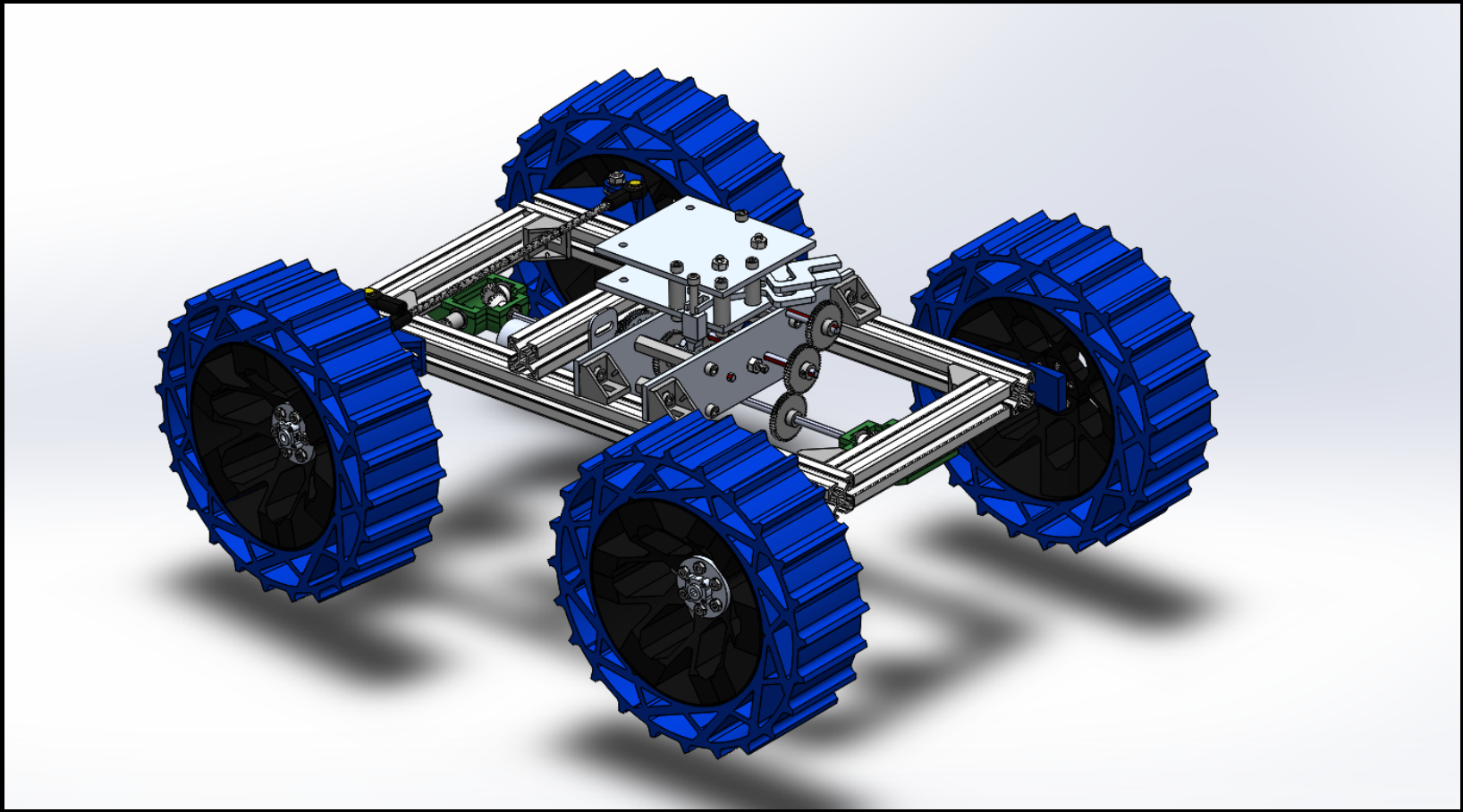
Integrated Mechanical System



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High Temperature Mechanisms

Build and Fail	Component Development	Mechanism Development
Build experience in constructing and testing high temperature mechanisms Understand failure modes	Demonstrate/characterize basic mechanical components such springs, gears, and bearings at 450°C.	Demonstrate moderately complex high temperature mechanisms, and eventually a desktop rover

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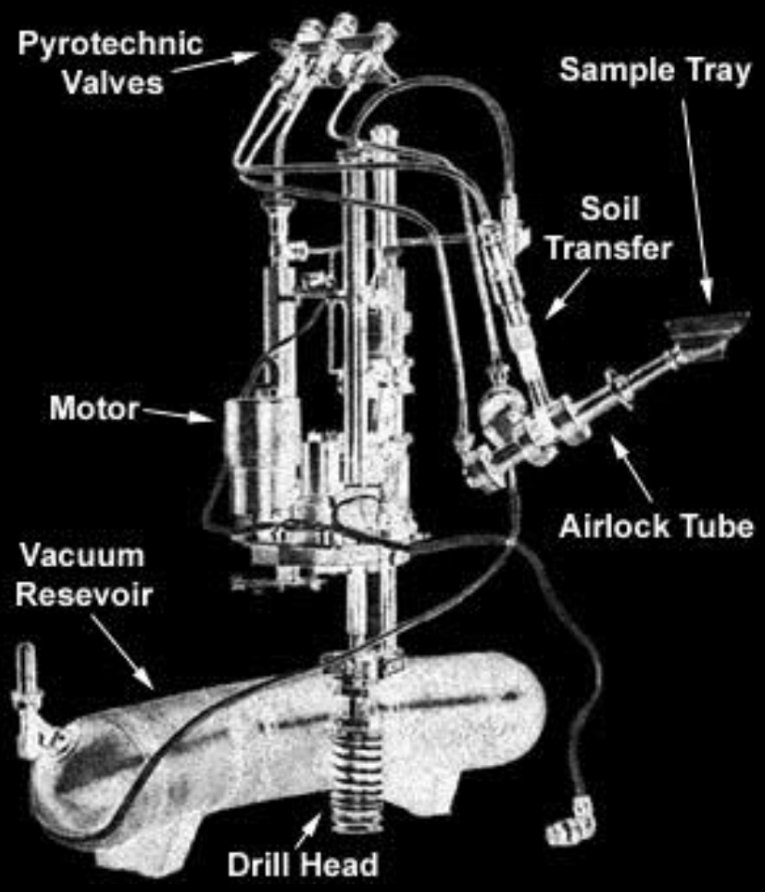
State of the Art Venus Mechanisms

Vega/Venera

Sampling system consisting of a drill successfully deployed on Venus 3 times

- Drill was the only moving object outside the pressure vessel.
- Could ONLY be operated at Venus conditions due to CTE
- Used a molybdenum disulfide lubricant.
- Autonomously operated, acquired sample within ~200second

Precious few detail about this instrument survive today



Zacny, Development of Venus Drill

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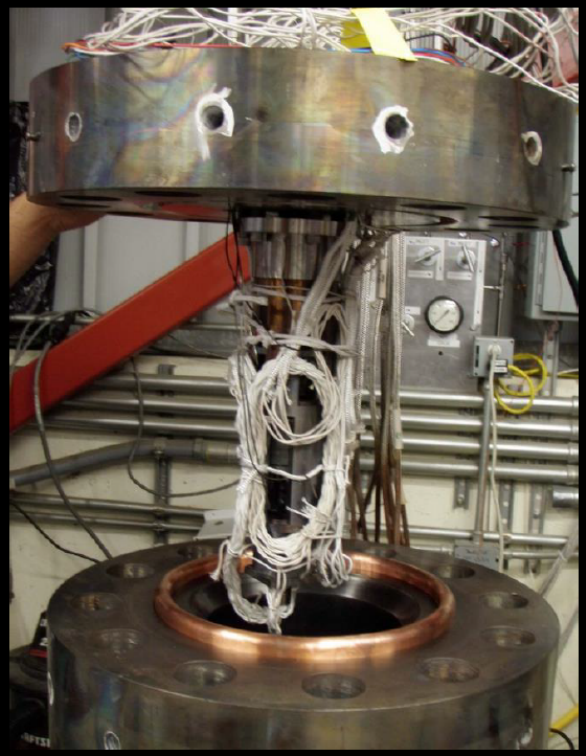
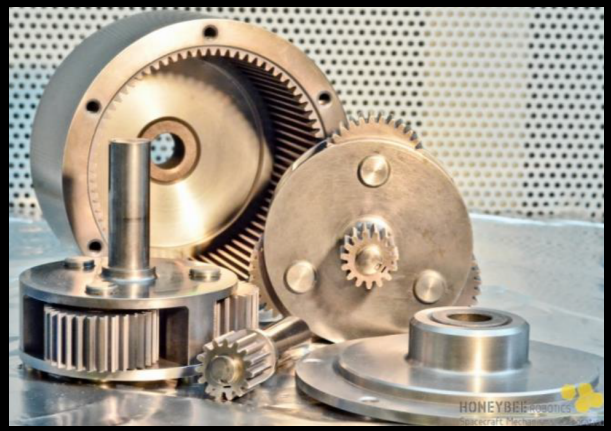
State of the Art Venus Mechanisms

HoneyBee Robotics – Technology Development.

Electric motors, gearbox, and drill demonstrated at Venus conditions

- Can be operated at room temp
- Uses dry-run ceramic/steel bearings
  - All “high temperature” lubricants tested failed





Zacny, Development of Venus Drill

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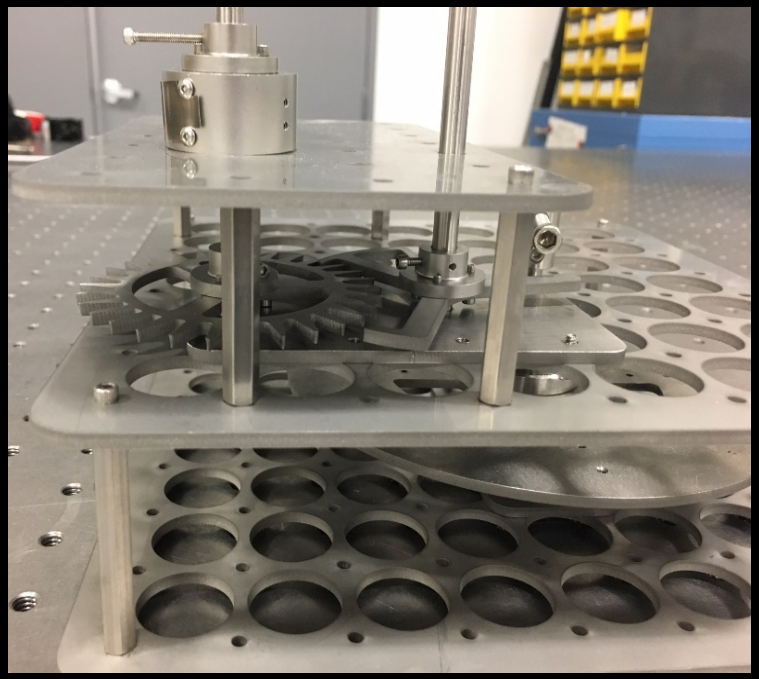
High Temperature Mechanical Clock

Phase 1 Effort

Why a clock:

- Extensively studied in earth applications
- Able to demonstrate various components including gears, bearings/bushings, and springs
- Useful for an automaton rover



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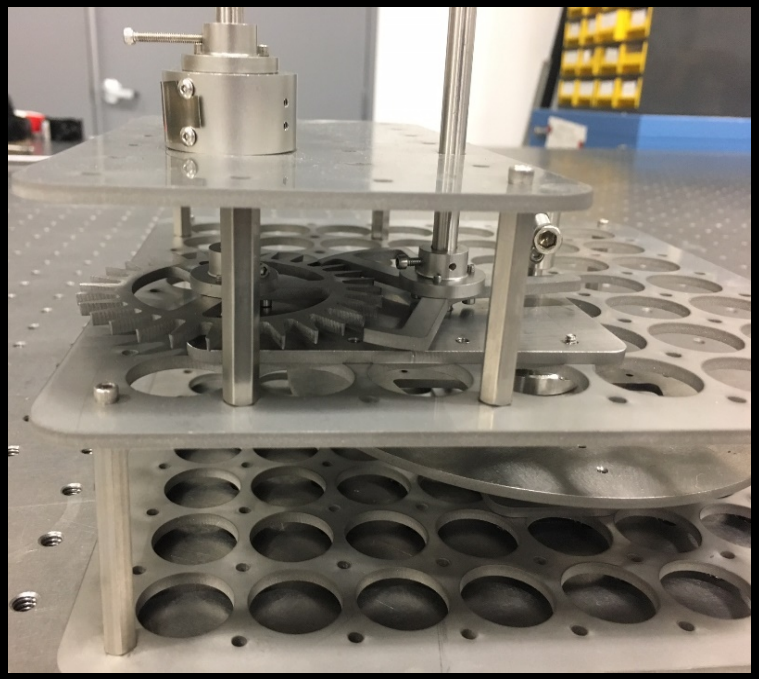
High Temperature Mechanical Clock

Phase 1 Effort

Features:

- Mostly 300 series stainless to match CTE
- Constant torque spring
- Deadbeat escapement
- Waterjet parts, low tolerance holes



Operated at room temp after some tuning, but failed in the oven

- Spring material not compatible
- Deformation in components

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High Temperature Mechanical Clock

Phase 2 Effort

A second clock is under development to address the shortcomings of the Phase 1 effort

Phase 1:

- Mostly 300 series stainless to match CTE
- Constant torque spring
- Deadbeat escapement
- Waterjet parts, low tolerance holes

Phase 2:

- Major components stress relieved 300 series
- Inconel power spring
- Pin-pallet escapement
- Waterjet parts where precision is not required. Reamed holes, machined escapement/pallet

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High Temperature Mechanical Clock

Escapement

Phase 1 design used a deadbeat escapement which we later realized needs to be held to fairly tight precision to work well.

Phase 2 Design uses a Pin-pallet which is historically mass produced in watches and low precision watches

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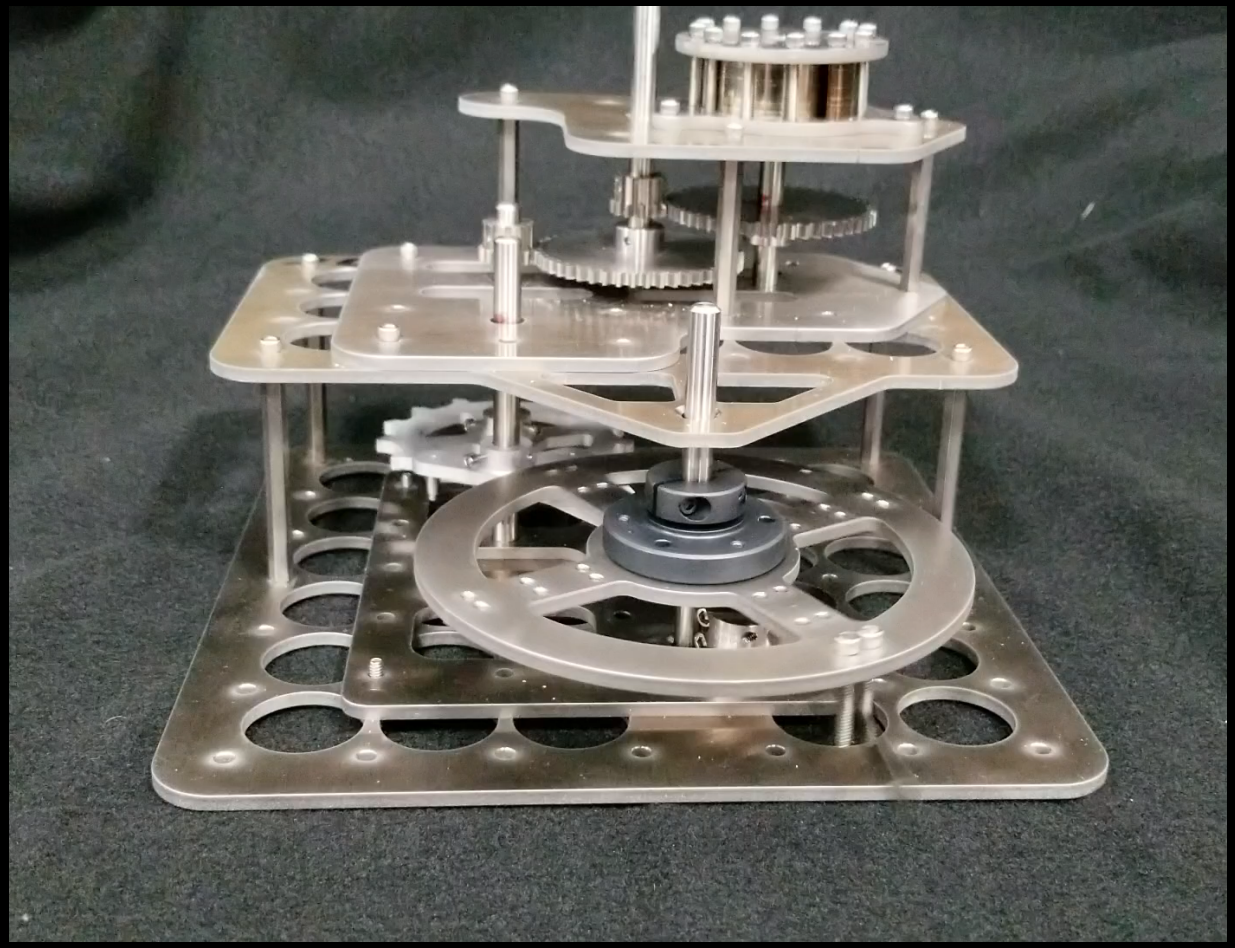
High Temperature Mechanical Clock

Current State



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High Temperature Mechanisms

Spring Development

Common spring material properties degrade at Venus temps

303 Stainless

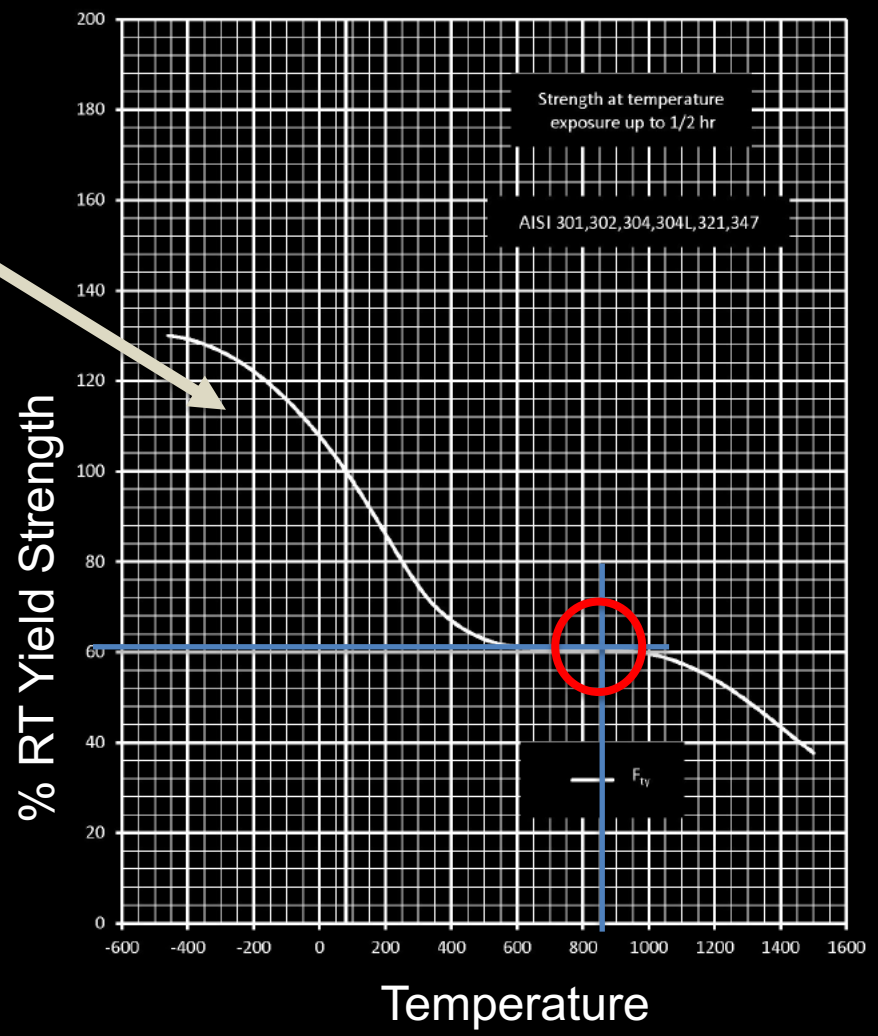
Simple Solution: Use Inconel

Custom Parts

- Expensive
- Long lead times

Can we utilize “common” materials instead?

Practically, what does temperature due to material performance?



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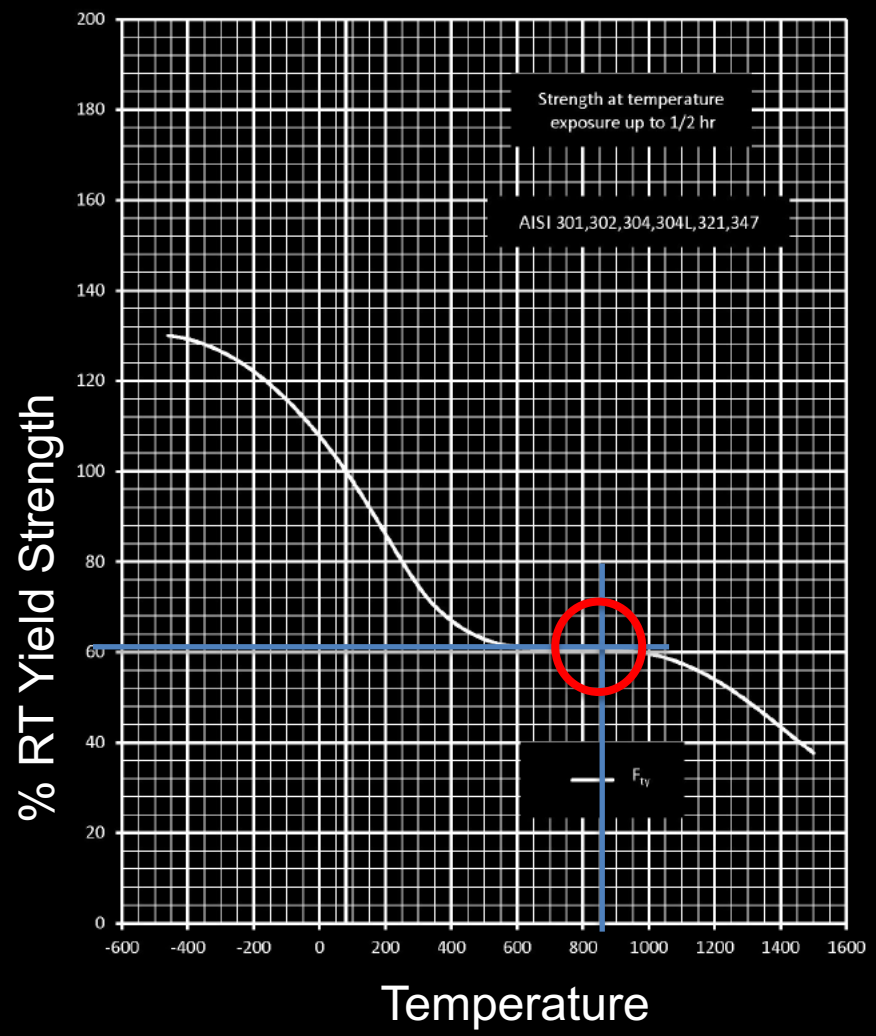
High Temperature Mechanisms

Spring Development

MMPDS predicts that common materials like 300 series stainless might work at 500°C assuming you stay under the % yield strength degradation.

So… Maybe we can design a spring that works if we keep the yield low enough. **<u>Lets test it!</u>**



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High Temperature Mechanisms

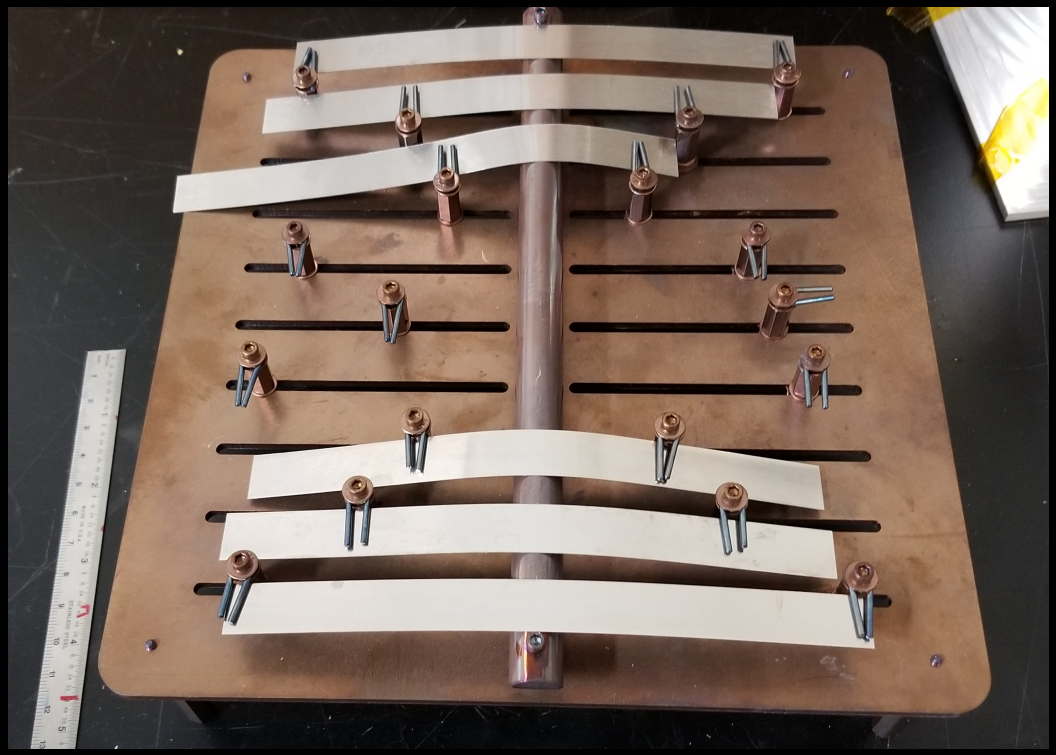
Spring Development

3-point bending rig adjustable to set % yield for shims.

- Stress in material calculated using standard bending equations, and verified to within 10% using a strain gauge

Samples brought to Venus temp in strained condition

Candidate materials include: Materials tested: Ti, Ti64, 17-7, 1095, Inconel 718, Inconel 600, BMG, Silicon (from Firehouse Horology).



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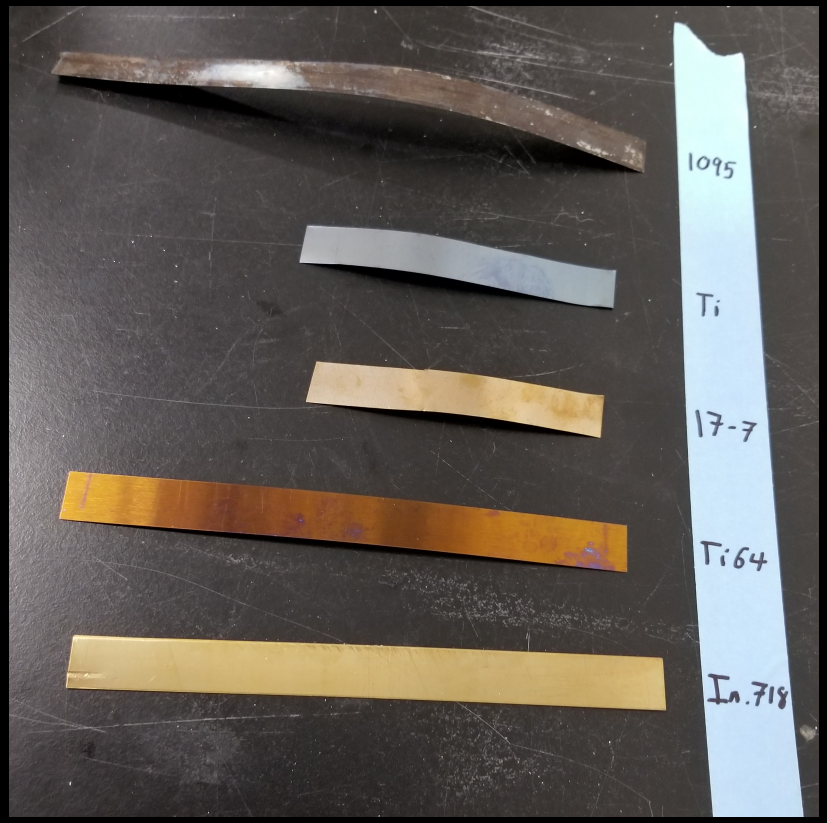
High Temperature Mechanisms

Spring Development

Results

All material took a set except for Inconel alloys, even at <10% yield.

This is why we test. Existing data tells a different story.



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High Temperature Mechanisms

Spring Acquisition

Multiple paths being pursued:

- Inconel 718 power spring procured from John Evans & Sons (delivery in 2-3wks)

- Heat treat available shim stock
  - Off the shelf stock is too soft to form a spring
  - Ageing in oven increases hardness
  - Cold rolling also a possibility

- 3D printing
  - JPL/Caltech owns an Inconel 3D printer
  - Printer staff have agreed to run a trial piece

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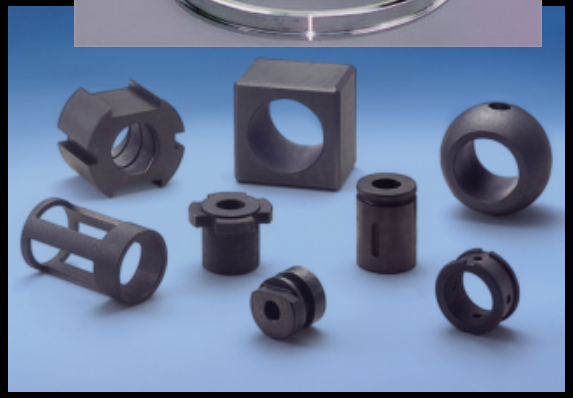
High Temperature Mechanisms

Component Characterization

Goal: Determine expected performance of components at Venus Temperatures

- Feeds into system level models
- Limited prior test data available



Procurements of high temperature components in progress:

- Ceramic Bearings from Cerobear
  - Aerospace grade quality
- Self Lubricating bushings from Graphalloy
  - Commonly used in forging, other high temp applications

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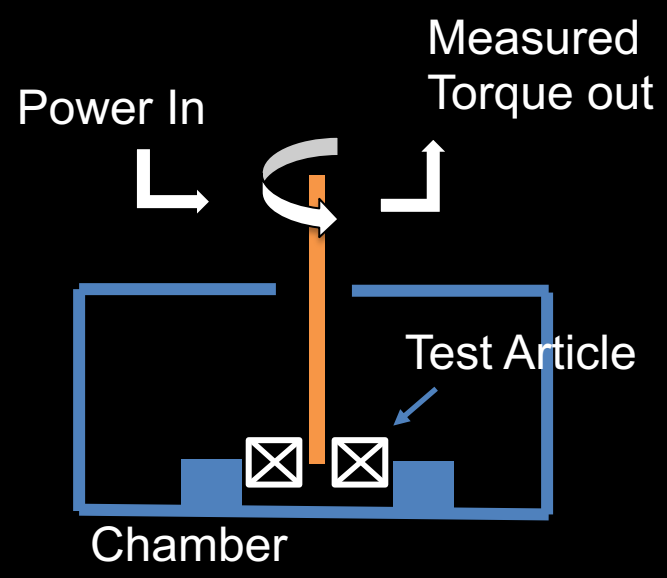
High Temperature Mechanisms

Component Characterization

Test Setup:

- Place article in oven
- Run shaft through pass through
- Drive the component and measure performance (motor torque) over temperature and time



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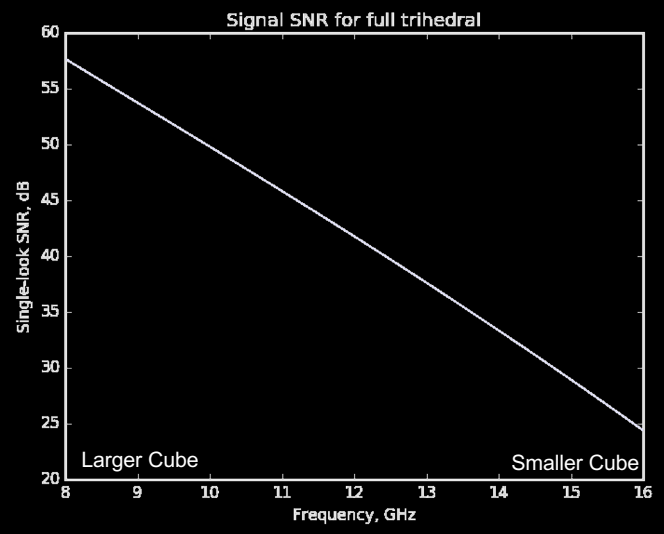
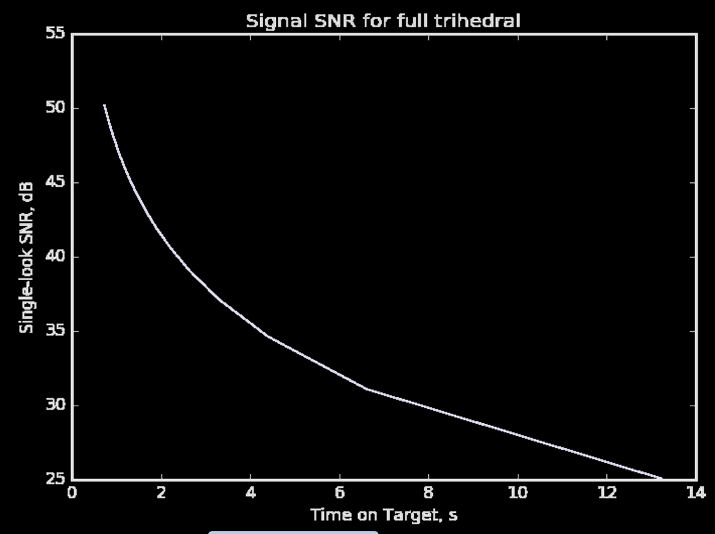
Signaling Using a RADAR Target

Varying Corner Cube Size (and freq.)



Varying Radar Antenna Size



	Records and Balloons	Vacuum Tube Radio	Radar Target	High Temperature Transceiver
Data Rate (bits/day)	10E4 bits	10E6 bit	10E3 bits	10E6 bits
Risk and Investment	Very High	Moderate/High	Low	Moderate

This has been an underexplored option.

Wind Turbines → Locomotion → Rover Prototyping → High Temperature Mechanisms → Radar Targets

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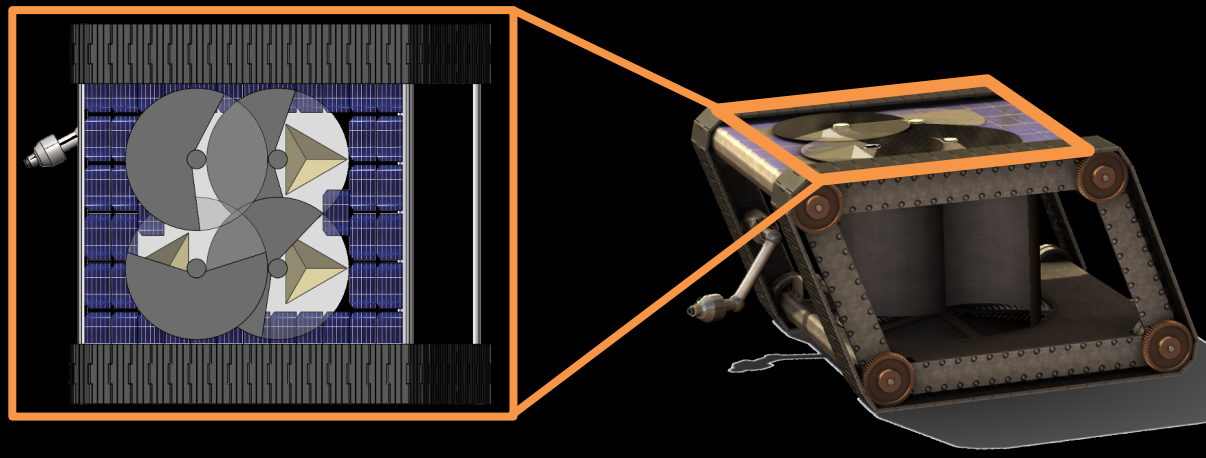
Initial RADAR Target Concept

At the End of Phase I

Four Target Cycling to Increase Data Rate

Issues:

- Orbiter must be directly overhead (10 degree cone width)
- But, directly overhead does not work with regards to SNR.
- Radar targets must be resolved form each other (when a radar pixel is several meters)



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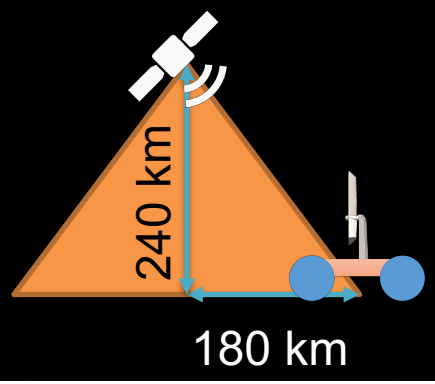
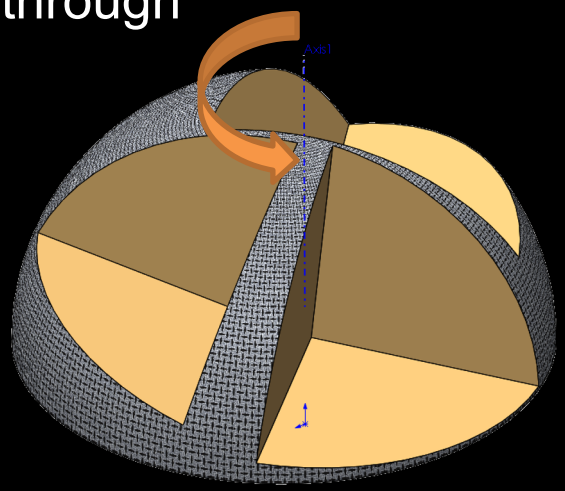
Revised RADAR Target Approach

A Single Target which Spins

- Sweeps the hemisphere, so rover does not need to “point”
- Covers multiple angles as it sweeps.
- For a 240 km orbit, SNR is positive up to 180 km out from the equator
- Each pass is ~8 seconds long, resulting in 11 bits/pass
- Current investigating improving data rates through speed variation





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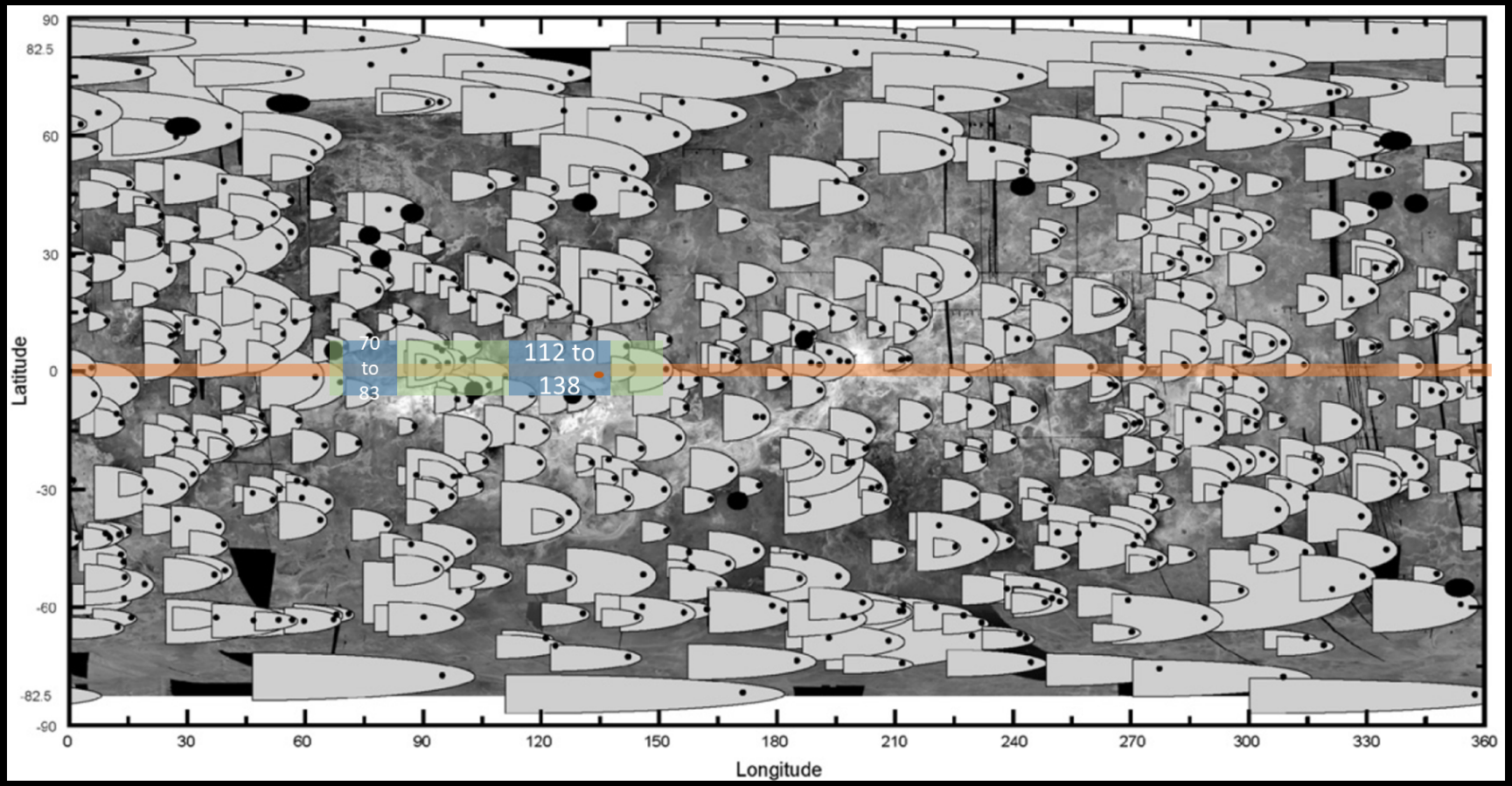
Where to Land on Venus

Driven by Science, Wind and Comms



Background Map from A.T. Basilevsky et al.

Wind Turbines | Locomotion | Rover Prototyping | High Temperature Mechanisms | Radar Targets

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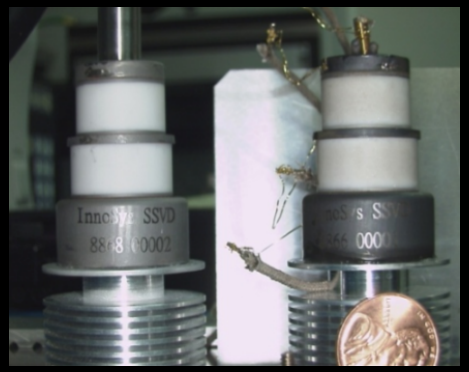
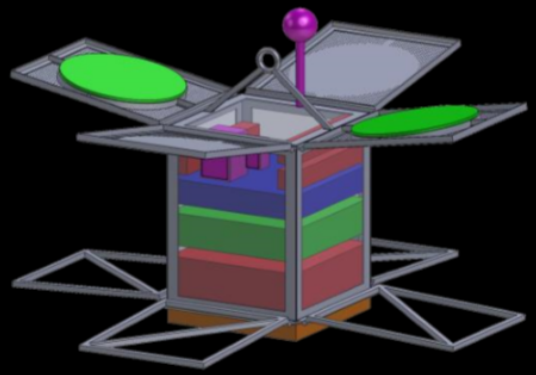
High Temperature Transmitter Technology

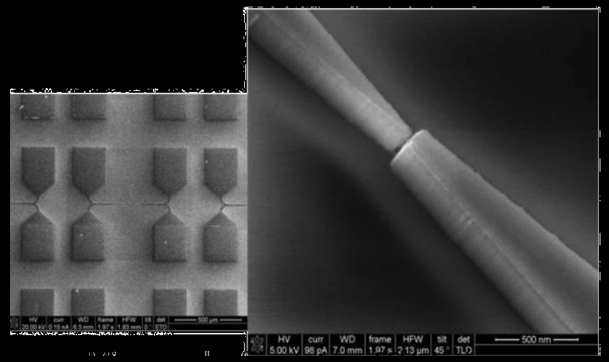
Several Under Development by Hot Tech, Others are Proposed



SSVD, Innosys



LLISSE, Glenn



Field Emission Device, Petz

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Todays Review

Introduction

Topic	Time Allocated	Start Time	End Time
Introduction	20 min	8:30 AM	8:50 AM
Technical Explorations	60 min	8:50 AM	9:50 AM
Break	10 min	9:50 AM	10:00 AM
Technical Explorations	40 min	10:00 AM	10:40 AM
Programmatics	**15 min**	**10:40 AM**	**10:55 AM**
Next Steps	10 min	10:55 AM	11:05 AM
Time for Additional Questions	15 min	11:05 AM	11:20 AM
Lab Tour	30 min	11:20 AM	11:50 AM

Budget/Schedule | Mechanical Maker Challenge | Visibility

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Assessment Against Proposed Tasks

From the Phase II Proposal/Contract

Year 1 Goals:

1. Locomotion trade and prototyping
2. Signaling / control analysis and test
3. High temperature instrument identification*
4. Mechanical design for hot high pressure environment
5. Team-X concept study
6. Prepare the midterm review/ report

Year 2 Goals:

1. Further end to end rover design
2. Design of a representative test rover
3. Fabrication of a representative test rover
4. Environmental test of a representative rover
5. Prepare the final report

= Not Started
= In Progress
= Completed

Budget/Schedule | Mechanical Maker Challenge | Visibility

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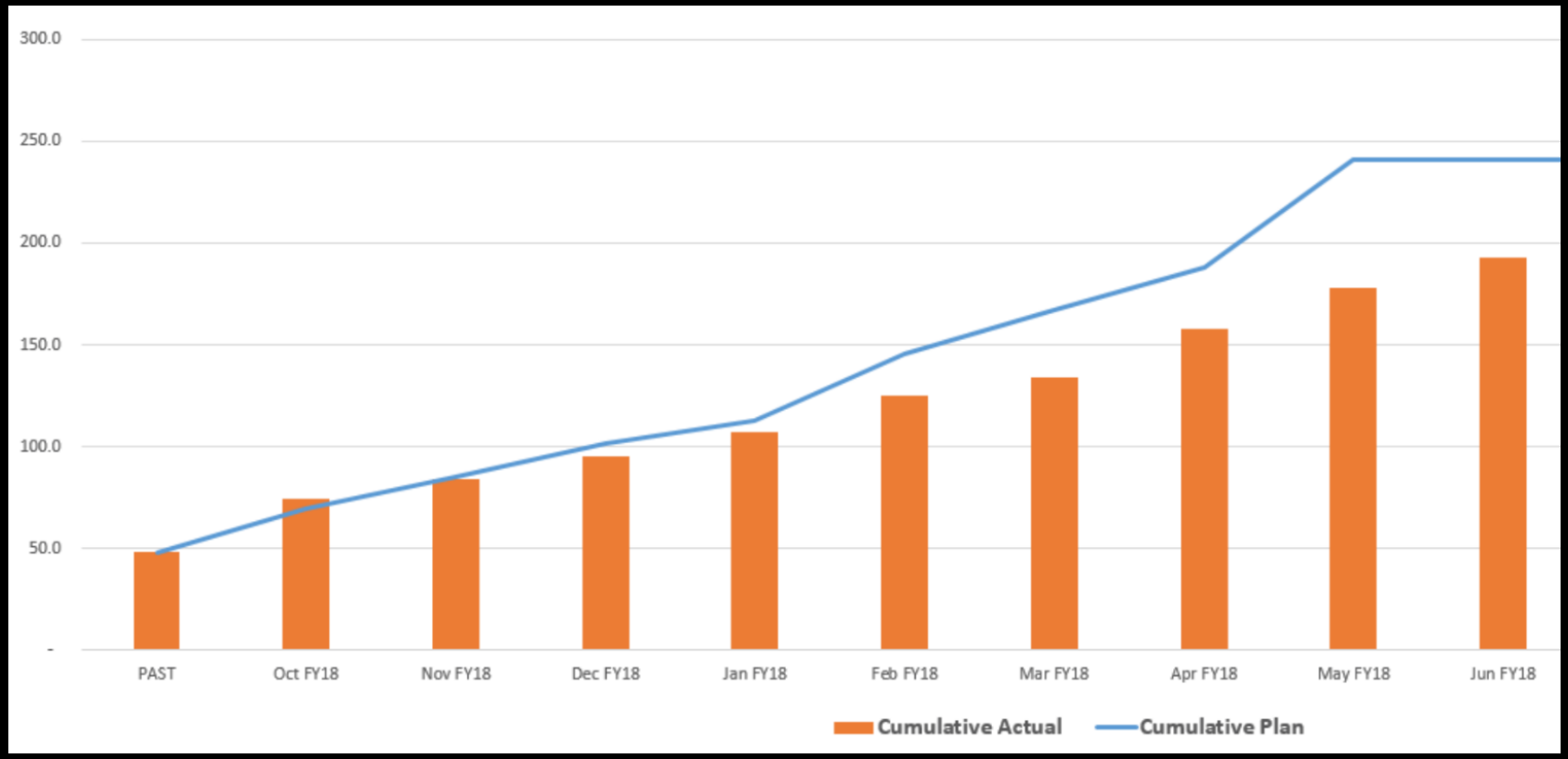
Current Spending

We are currently underrunning by $47.5k



A-team study cost ~$15k instead of ~$50k budgeted
Prototyping expenditures are delayed by about 3 months from original plan
Prototyping and testing of RADAR target has not yet occurred

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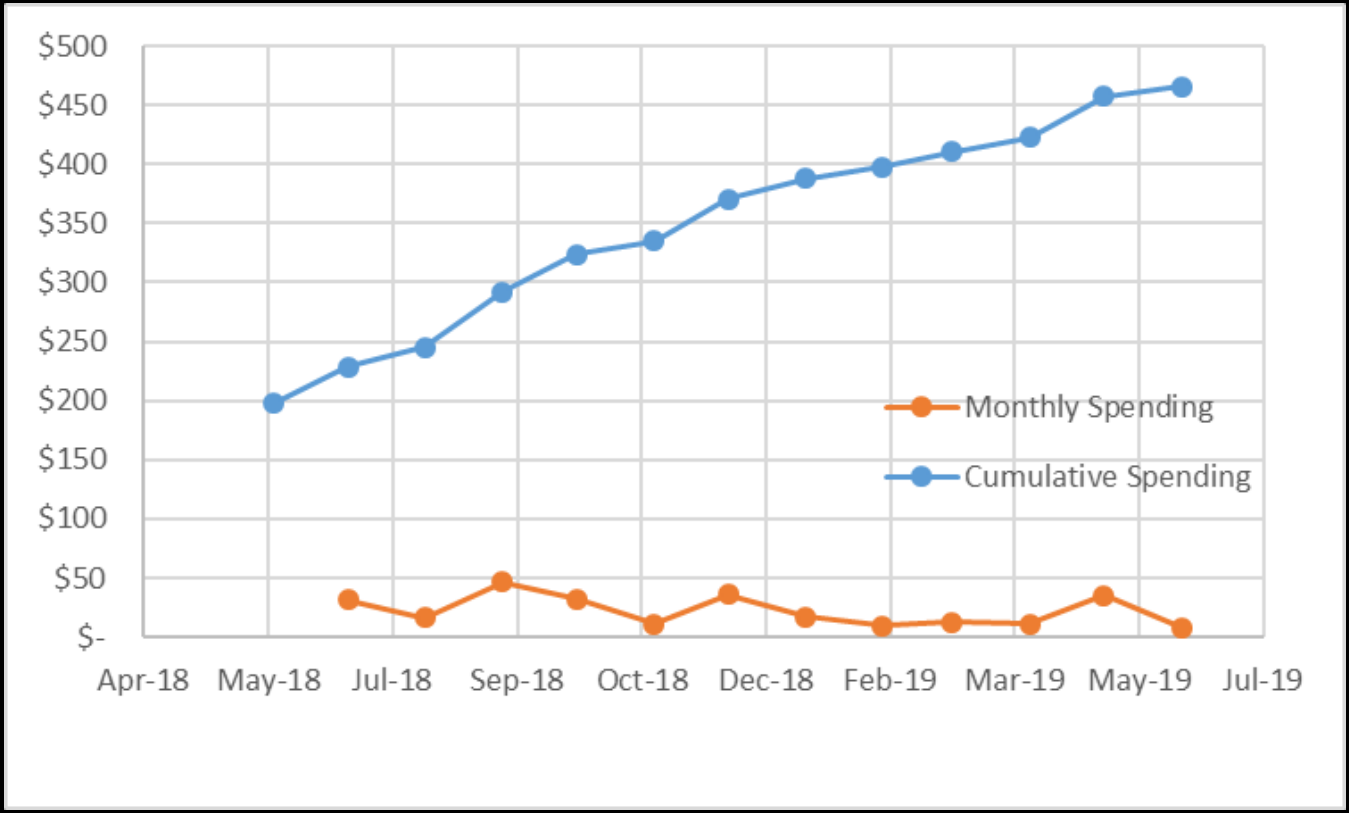
Future Spending Plan

Ending Underrun of ~$27k



Budget/Schedule | Mechanical Maker Challenge | Visibility

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Potential Uses of Underrun

Current amount

We a roughly $20k underspent on radar target and rover prototyping, which we expect to use in the next several months.

Additional $27k under run can be spent by:

1. Pursuing component testing in GEER earlier in piggyback test
2. Mechanical maker challenge investments
3. Pursue more advanced testing options
4. Detailed computer models
5. Investigate a mechanical to electrical interface
6. Firehouse horology investigation

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Mechanical Maker Challenge

Status Update

Structure for First Challenge is Ready

- Legal and contracts has approved challenge details
- Uses Challenge.gov infrastructure
- Running a draft website by JPL communications, education office, and relevant parties
- Currently investigating collaboration with Maker Meetup
- And investigating bringing a ID team member on board
- Challenge.gov is launching a new website in August, and has asked that we wait for that.

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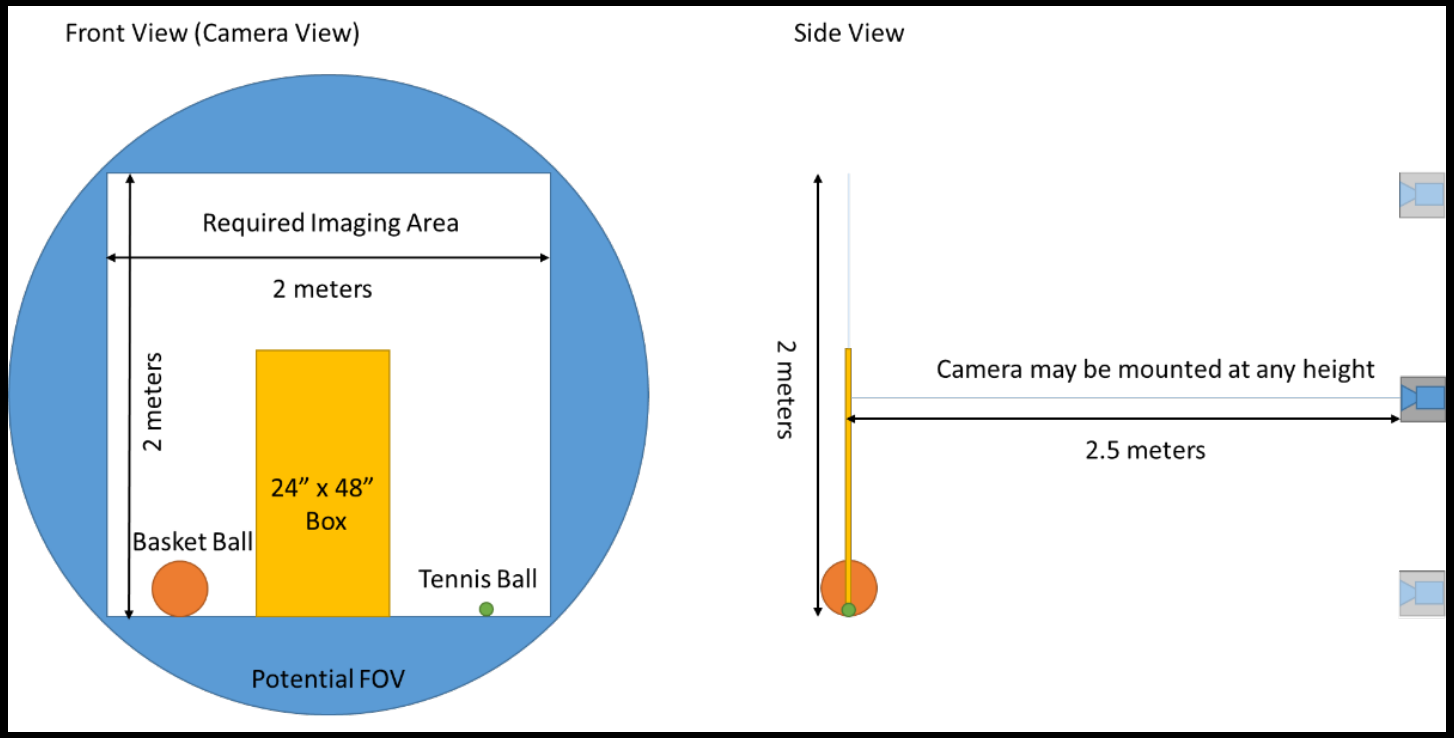
The Challenge

The Mechanical Eye: First in A Series



The Prizes

- First Place: Trip to JPL to demonstrate device
- First, Second and Third Places: A 3D printed commemorative coin

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Mechanical Maker Challenge

The Mechanical Eye Challenge

Challenge.gov
Government Challenges, Your Solutions

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NEWEST CHALLENGES | POST A CHALLENGE | MY CHALLENGES | ANNUAL PRIZE REPORTING

Mechanical Maker Challenge: Mechanical Eye - Draft

National Aeronautics and Space Administration

Challenge Details

Discussions 0

Solutions 0

About the Challenge

Create a Clockwork Mechanical Camera for Venus

Posted By: National Aeronautics and Space Administration
Category: Scientific/Engineering
Skill: Engineering
Interest: Science & Research

Submission Dates: **12 a.m. ET, Jun 11, 2018 - 12 a.m. ET, Sep 04, 2018**

With its sulfuric acid clouds, temperatures over 450°C, and 92 times the surface pressure of Earth, Venus is one of the most hostile planetary environments in the solar system.Prior missions have only survived hours! But an automaton (or clockwork mechanical robot) could solve this problem. By utilizing high temperature alloys, the clockwork rover would survive for months, allowing it to collect and return valuable long-term

Follow this challenge

Prizes

Demonstration at JPL

The first place winner will have the opportunity to demonstrate their device at JPL/Caltech. JPL/Caltech will cover all travel costs up to $1,000.

Commerative Mechanical Maker Challenge Coin

Get serious bragging

Budget/Schedule | Mechanical Maker Challenge | Visibility

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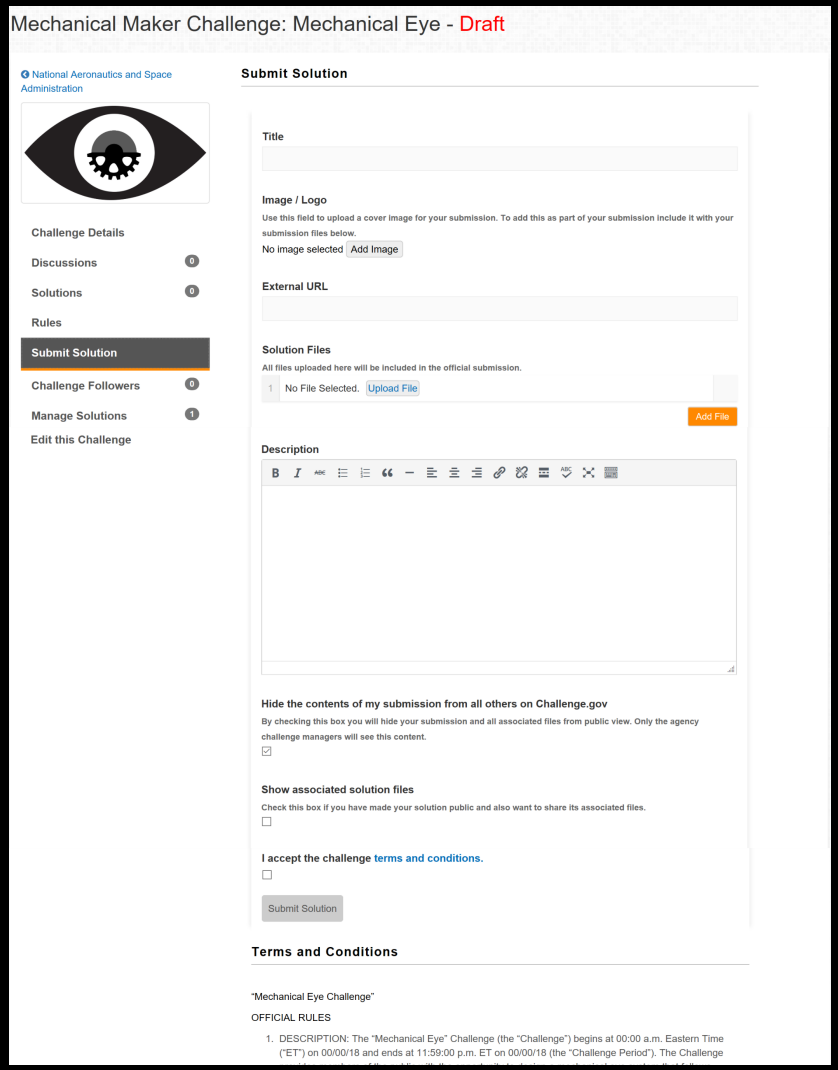
Mechanical Maker Challenge

The Mechanical Eye Challenge



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Future Challenges

My Goal: Run a Total of 3 Challenges

Ideas for Future Challenges

- The Mechanical Geologist
- The Clockwork Memory
- Mechanical Ear and Voicebox

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Featured Articles

DISCOVER

The Next Generation of Robot Explorers

By Steve Murray

Almost all of the explorers of our solar system have been machines. Many of them have been mobile. Rovers, after all, can do more science than stationary landers simply by covering more ground. NASA, the European Space Agency (ESA), India, and China will all launch missions to Mars between 2020 and 2022, and each will include a rover; the Chinese mission may carry up to six.

Each of these probes will presumably roll on wheels, which have worked well on the Red Planet. NASA, however, has bigger plans for exploring the solar system that include moons and asteroids—places with different gravities, temperatures, and pressures. New approaches to locomotion will be required and, with NASA support, a new generation of rover designs is emerging that move across, over, and under the surfaces of these worlds.

Mechanical movement on Venus

A NASA Jet Propulsion Laboratory (JPL) team has developed the Automaton Rover for Extreme Environments (AREE) for operating on the surface of Venus. Funded by the NASA Innovative Advanced Concepts (NIAC) Program, AREE will move on treads like those of World War I tanks that had to negotiate rough terrain. Its biggest advances, however, will be within.

The high temperatures and pressures of Venus can quickly destroy even protected electronics; the record for data transmission from a Venus lander was just over two hours, set by the Soviet Venera 13. AREE will avoid this fate by avoiding the use of electronics. The craft is built almost entirely with mechanical parts, inspired by the levers and gears of 19th century mechanical computers. Even data communications are handled mechanically: a radar beam from an orbiter is reflected back from AREE, but interrupted to generate Morse code to the spacecraft. An internal turbine powered by Venusian winds cools the rover's minimal components, allowing AREE a planned mission life of up to one year.

Tumbling over asteroids

Gravity is practically nil on comets and asteroids, so without weight for traction surface locomotion requires ingenuity. A team from Stanford University, JPL, and the Massachusetts Institute of Technology is involved in a NASA NIAC project to investigate reaction wheels as a motive force for traveling on small bodies like these.

Cube-shaped robots called "hedgehogs" are equipped with three orthogonal flywheels. Braking a flywheel transfers its momentum to the entire body, causing it to hop or tumble. The amount, suddenness, and sequence of flywheel braking allow the hedgehog to move, if a bit chaotically, in a desired direction. Some space telescopes use reaction wheels for orientation control, although with much gentler changes. The team has successfully tested hedgehog prototypes in zero-g aircraft arcs to demonstrate the effectiveness of the control scheme in reduced gravity.

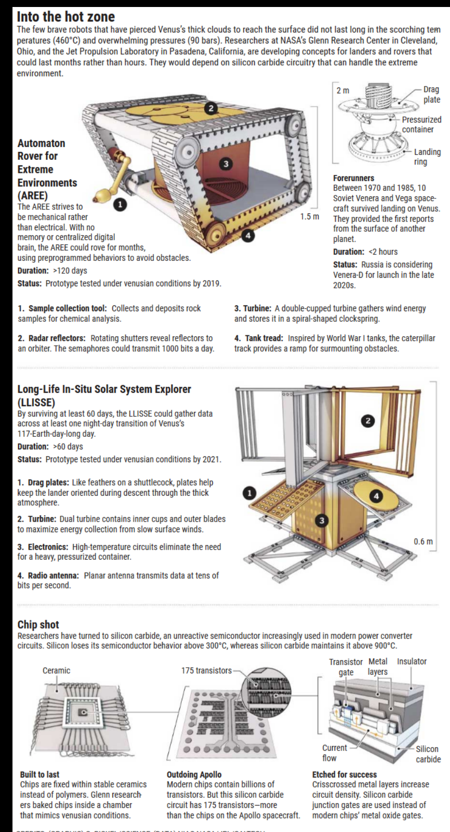
Martian scouts

The track of a ground-based rover is limited by the information it can obtain from onboard sensors or orbiter data. An aerial "scout" platform could boost mission performance by traveling ahead to locate promising sites for exploration and optimal routes for getting there. Flyers could also explore areas that would hazard ground rovers like lava tubes, craters, or canyon walls. NASA is currently considering such a concept for the Mars 2020 mission, which could include a JPL robotic helicopter designed to work in collaboration with the land rover. The drone features two large counter-rotating propellers that would lift a camera-equipped package over short dis-

▲ 1. AREE 3 - Artist's conception of AREE on Venus Credit: NASA / JPL-Caltech
▶ 2. AREE - Artist's conception of AREE on Venus. Credit: NASA / JPL-Caltech
▶ 3. BRUIE - Buoyant Rover for Under-Ice Exploration (BRUIE). Credit: NASA / JPL-Caltech
▶ 4. BRUIE - Alaska field test of the Buoyant Rover for Under-Ice Exploration (BRUIE) Credit: NASA / JPL-Caltech

AD ASTRA | WINTER | 20

Ad Astra



Into the hot zone

The few brave robots that have pierced Venus's thick clouds to reach the surface did not last long in the scorching temperatures (460°C) and overwhelming pressures (90 bars). Researchers at NASA's Glenn Research Center in Cleveland, Ohio, and the Jet Propulsion Laboratory in Pasadena, California, are developing concepts for landers and rovers that could last months rather than hours. They would depend on silicon carbide circuitry that can handle the extreme environment.

Automaton Rover for Extreme Environments (AREE)
The AREE strives to be mechanical rather than electrical. With no memory or centralized digital brain, the AREE could rove for months, using preprogrammed behaviors to avoid obstacles.
Duration: >120 days
Status: Prototype tested under venusian conditions by 2019.

Forerunners
Between 1970 and 1985, 10 Soviet Venera and Vega spacecraft survived landing on Venus. They provided the first reports from the surface of another planet.
Duration: <2 hours
Status: Russia is considering Venera-D for launch in the late 2020s.

1. **Sample collection tool:** Collects and deposits rock samples for chemical analysis.
2. **Radar reflectors:** Rotating shutters reveal reflectors to an orbiter. The semaphores could transmit 1000 bits a day.
3. **Turbine:** A double-cupped turbine gathers wind energy and stores it in a spiral-shaped clockspring.
4. **Tank tread:** Inspired by World War I tanks, the caterpillar track provides a ramp for surmounting obstacles.

Long-Life In-Situ Solar System Explorer (LLISSE)
By surviving at least 60 days, the LLISSE could gather data across at least one night-day transition of Venus's 117-Earth-day-long day.
Duration: >60 days
Status: Prototype tested under venusian conditions by 2021.

1. **Drag plates:** Like feathers on a shuttlecock, plates help keep the lander oriented during descent through the thick atmosphere.
2. **Turbine:** Dual turbine contains inner cups and outer blades to maximize energy collection from slow surface winds.
3. **Electronics:** High-temperature circuits eliminate the need for a heavy, pressurized container.
4. **Radio antenna:** Planar antenna transmits data at tens of bits per second.

Chip shot
Researchers have turned to silicon carbide, an unreactive semiconductor increasingly used in modern power converter circuits. Silicon loses its semiconductor behavior above 300°C, whereas silicon carbide maintains it above 900°C.

Built to last
Chips are fixed within stable ceramics instead of polymers. Glenn researchers baked chips inside a chamber that mimics venusian conditions.

Outdoing Apollo
Modern chips contain billions of transistors. But this silicon carbide circuit has 175 transistors—more than the chips on the Apollo spacecraft.

Etched for success
Crisscrossed metal layers increase circuit density. Silicon carbide junction gates are used instead of modern chips' metal oxide gates.

CREDITS: (GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) NIAC NASA/JPL/CALTECH

Science

THE CRUX

BIG IDEA

Walking With Venus' Wind

The hellishly hot planet fries spacecraft electronics, so NASA scientists devised a machine inspired by ancient technology.

VENUS IS NOT A FORGIVING PLANET. The longest that any machine has survived there is 127 minutes. Surface temperatures surpassing 800 degrees Fahrenheit and clouds of sulfuric acid are a perfect recipe for frying circuits. So Jet Propulsion Lab engineer Jonathan Sauder and his team designed a futuristic Venus rover that doesn't need electronics. Instead it uses mechanical systems that would have been familiar to Leonardo da Vinci.

The Automaton Rover for Extreme Environments (AREE) — which recently received a NASA Innovative Advanced Concepts grant — is built entirely of hardened metals and guided by a clockwork computer. The rover is still far from a planned mission, but it would be able to collect weeks' worth of climate and seismic data from Venus' surface, all recorded on phonograph-style records that periodically would be lifted by balloon to an overhead drone. Then NASA just needs to salvage an old Victrola. —JONATHON KEATS

RELAY DRONE
A solar-powered drone could safely fly dozens of miles over the surface, where temperatures and pressure are Earth-like. Gas-filled balloons would tote rock samples and phonograph records up to the drone, which would record the findings and relay it to an orbiting spacecraft. That craft would then beam data back to Earth.

PHONOGRAPHS
Designers are exploring several ways to send information to Earth, but the base concept has seismic data cut into records that are subsequently launched above the clouds by gas balloons. A simpler approach would involve retro-reflectors bouncing signals from Venus' surface.

INTERNAL COMPUTER
History provides many examples of mechanical computers, like the Greek Antikythera mechanism, which calculated eclipse dates more than 2,000 years ago. AREE's computer would need to track temperature, pressure, winds and seismic events.

SAMPLE DRILL
Like the Mars Curiosity rover, AREE's drill would let scientists see into Venus' interior — and past.

WIND TURBINE
Venus' winds would spin AREE's fan blades, generating energy that's stored in a spring.

SEISMOMETER
Astronomers know little about Venus' interior, and that impedes our understanding of how planets form. So one prime objective is to set up "Earth's Twin" with a seismometer, which measures geologic activity.

JANSEN MECHANISM WALKING LEGS
Kinetic sculptor Theo Jansen designed a system of legs that walk naturally, powered only by the wind. His autonomous Strandbeests gained fame roaming Earth's beaches. His legs inspired those used by AREE.

10 DISCOVERMAGAZINE.COM

April 2017 DISCOVER 11

Discover Magazine

Budget/Schedule ❯ Mechanical Maker Challenge ❯ **Visibility**

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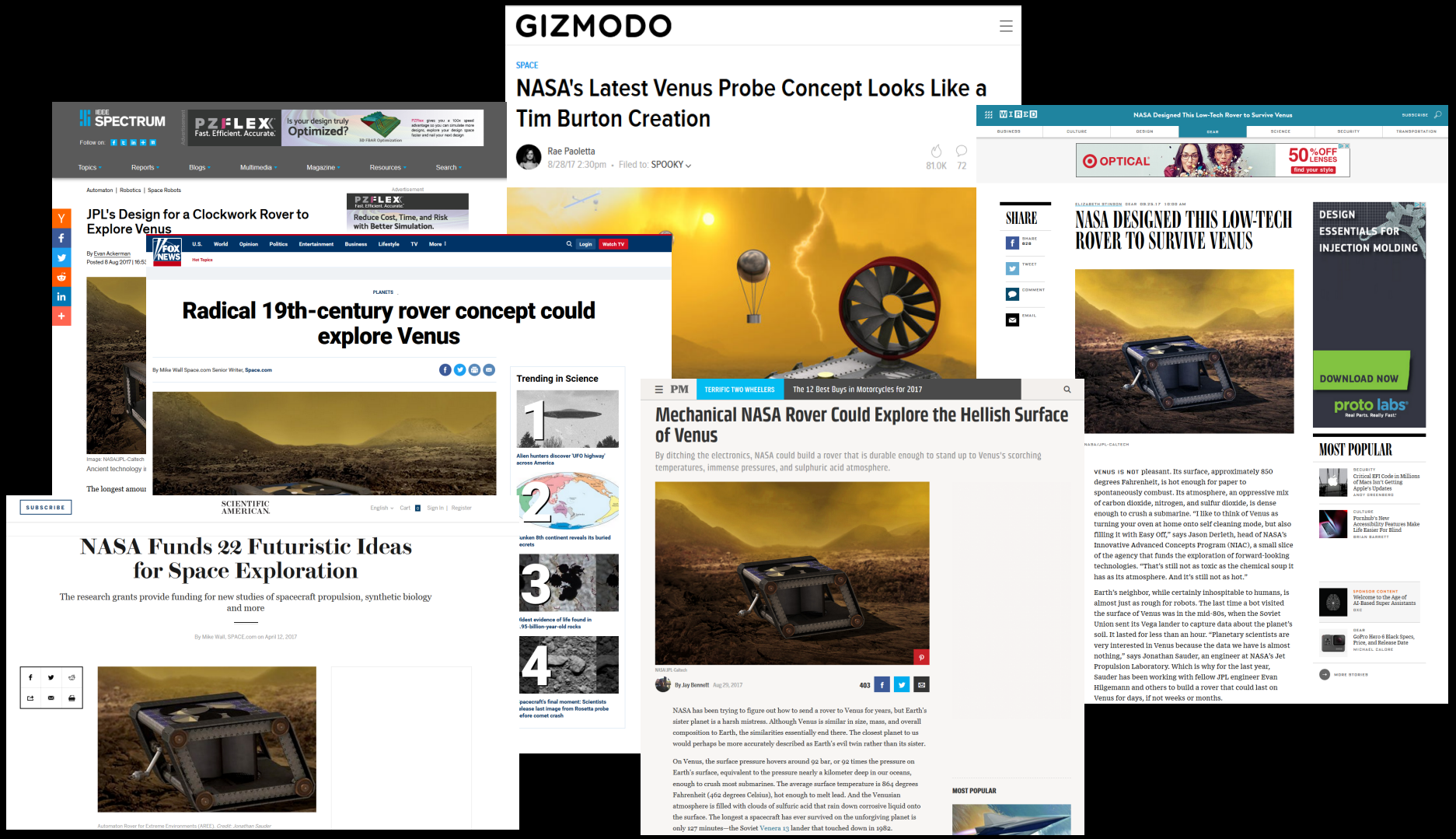
Selected Online Articles



Budget/Schedule → Mechanical Maker Challenge → Visibility

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Visibility

Within the Venus Community

Venusian Acceptance is Critical

- Presented concept at the last two VEXAG's
- Chairing the technology panel for the Venus Landed Platform Study
- Participating in JPL Venus mission concepts and workshops.

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Todays Review

Next Steps

Topic	Time Allocated	Start Time	End Time
Introduction	20 min	8:30 AM	8:50 AM
Technical Explorations	110 min	8:50 AM	10:40 AM
Programmatics	15 min	10:40 AM	10:55 AM
Next Steps	**10 min**	**10:55 AM**	**11:05 AM**
Time for Additional Questions	15 min	11:05 AM	11:20 AM
Lab Tour	30 min	11:20 AM	11:50 AM

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Future/Ongoing Work

- Prototype Rovers
  - Prototypes through Summer/Fall 2018
- High temperature mechanical clock
  - Prototype through Summer 2018
- RADAR Target Signaling System
  - Analysis to complete in Summer 2018
  - Test in Fall 2018 (if beneficial)
- Wind Turbine Design for Venus and Test Methods
  - Prototype in Spring 2018 and 2019 (University Teams)
- Mechanical Maker Challenge
  - Mechanical Eye, Mechanical Geologist, Clockwork Hard Drive
- Representative Model AREE Rover
  - Prototype in Spring 2019 test in Venus Environment (pressure and temperature).

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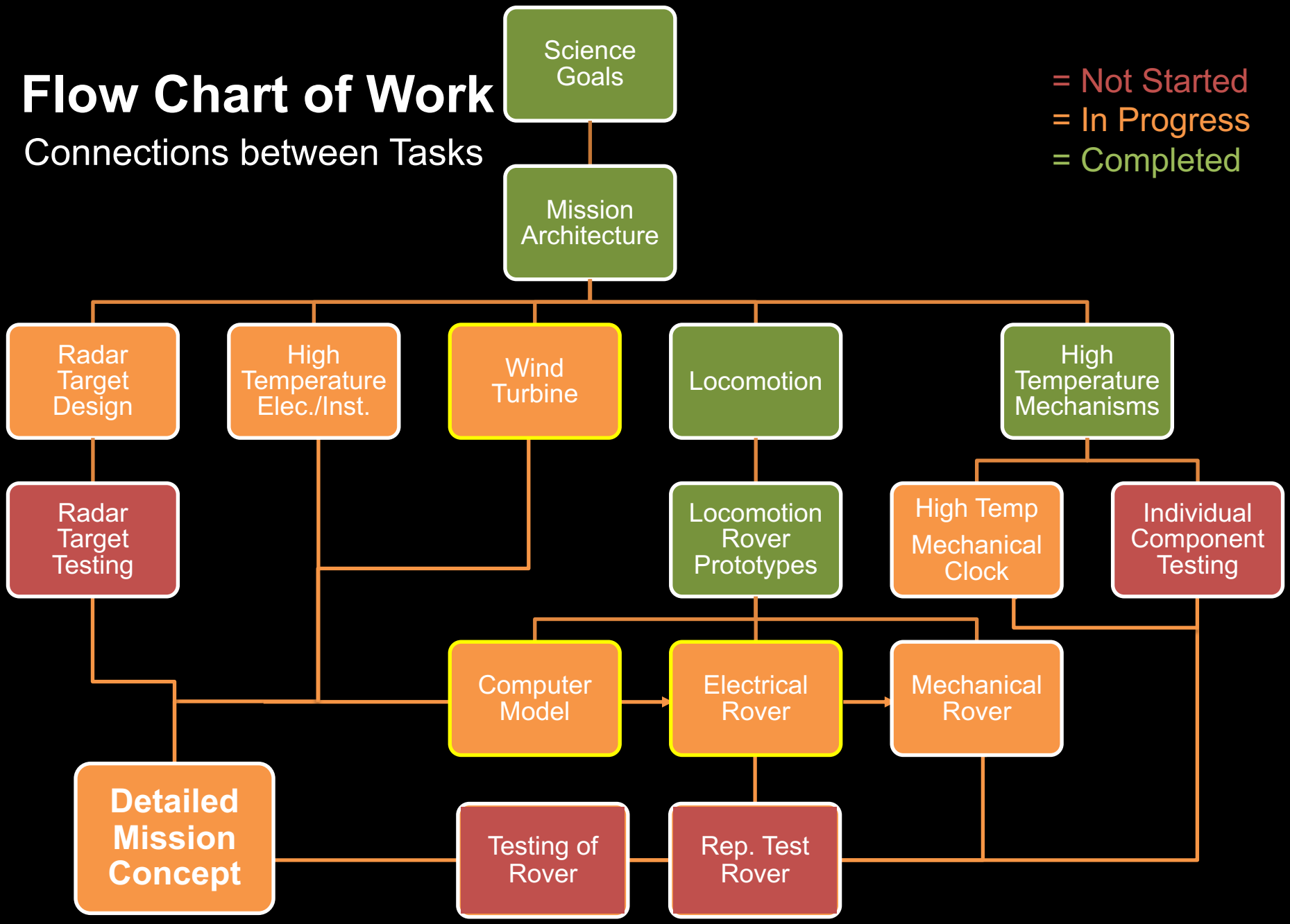
Flow Chart of Work

Connections between Tasks

= Not Started
= In Progress
= Completed



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Environmental Testing

Three potential opportunities

	Kittyhawk Products HIP	JPL Venus Chamber	Glenn GEER
Cost	$11.5k/day	$15k/test	$50-100k/test
Test Length	2 days	2 days	2 months
Chemicals	Neutral Gases Only (Argon)	CO^2 and N^2	Venus Simulated
Diam.	33 in	6 in and 12 in	36 in
Length.	7’	~6’ and 12’	4’
Orientation	Vertical	Horiz. or Vert.	Horiz.
Notes	Venus Pressure is low		Low Cost Piggyback Opportunities

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Concept Potential Challenges

- Is there enough wind for a wind powered rover on Venus?
    - We only have 4 data points
- Need for high temperature images and geologic instruments.
    - But ongoing research at Glenn
- Venus missions have not be selected in the past
    - Exoplanets will drive new interest in Venus
    - A long lived mobile platform makes a Venus mission much more compelling than current proposed concepts.

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Potential Funding Opportunities

After NIAC Phase 2

Full Mission Concept:

JPL IRAD – For Low Cost Rover Version

PSTAR - Planetary Science and Technology from Analog Research

NASA Game Changing

Component Funding:

Glenn Venus Projects

JPL IRAD and Venus Projects

Sponsoring work (Firehouse Horology) via SBIR

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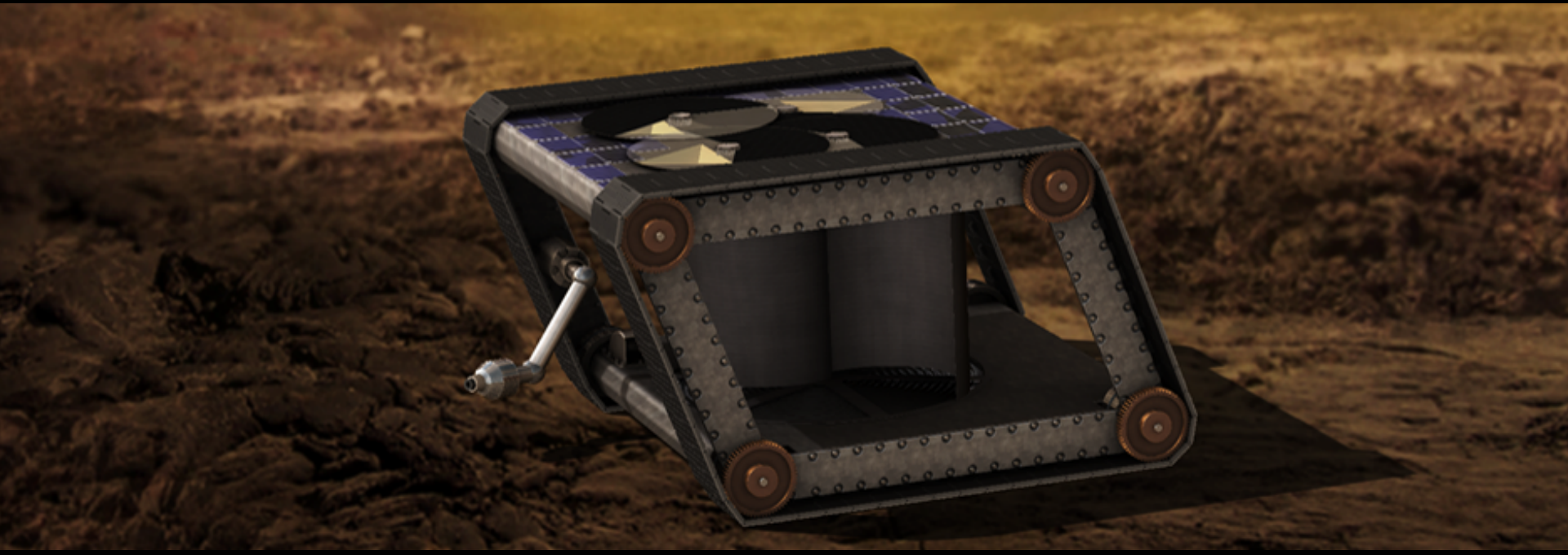

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NIAC
NASA Innovative Advanced Concepts

Todays Review

Next Steps

Topic	Time Allocated	Start Time	End Time
Introduction	20 min	8:30 AM	8:50 AM
Technical Explorations	110 min	8:50 AM	10:40 AM
Programmatics	15 min	10:40 AM	10:55 AM
Next Steps	10 min	10:55 AM	11:05 AM
Time for Additional Questions	**15 min**	**11:05 AM**	**11:20 AM**
Lab Tour	30 min	11:20 AM	11:50 AM

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Backup Slides

Systems

Option 1: Conventional New Frontiers

- **Based on analogy from previous Team X studies, a New Frontiers-class multi-element mission to Venus typically has a total wet mass of ~2950 kg**
  - Based on Architecture B → orbiter carries (ES+R) into Venus Orbit
  - ~900 kg for an orbiter flight system without a payload
  - Add 100 kg to the orbiter for the radar system
  - Aeroshell ~100 kg, parachute ~50 kg
  - ~1600 kg propellant required for orbit insertion
    - Can potentially save propellant if the delivered mass (entry system + lander) is separated before Venus Orbit Injection (VOI) (Architecture C with associated risk)
  - Leaves ~200 kg for landed mass, which must include the Rover and landing system (legs, crush plates, etc.)
  - Cost of orbiter (capable of carrying lander) + radar is ~$270M by analogy. Using rules of thumb and applying $850M cost cap yields a cost allocation for ES+R of ~$190M. Estimate by analogy that the entry system is about 1/3 of that cost, leaving $126M for the Rover

Mass in kg

Orbiter dry mass	900
Radar	100
Propellant	1600
Entry system	150
Rover	200
Total stack mass	2950

Cost in $M

Total mission cost	NA
Launch vehicle	NA
Total mission cost without LV	$ 850
Total A-D cost	$ 850
WBS 5+6 fraction of total	54%
WBS 5+6 total	$ 459
Orbiter FS + PL	$ 270
Allocation for Rover+entry FS	$ 189
Rover Allocation	$ 126

Size

Orbiter	2.5 m x 2 .5 m x 4 m
Heat shield diameter	< 3.7 m
Entry System + Rover	Constrained by fairing volume

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Option 2: New Frontiers with Architecture A

- **If Architecture A is employed, the entire stack is not inserted into Venus Orbit, saving propellant, but requiring a carrier for the Rover**
  - Estimated propellant mass reduced to 1200 kg and orbiter reduced to 850 kg (structure resized for less propellant)
  - Maintaining 2950 kg launch mass and 1000 kg for orbiter + radar leaves 800 kg for C+ES+R mass. Note that propellant mass for the carrier is small (just TMCs, no VOI)
  - Estimated ratio of C+ES mass to R mass is ~48:52
  - Thus Rover allocation is 370 kg *based on LV capability alone*
- **With $850M cap and $270M orbiter, have ~$190 allocation for C+ES+R**
- **By analogy from other New Frontiers-class Venus C+ES+R designs, the Rover cost is 53% of the flight system cost, leaving an approximate allocation of ~$100M for the Rover**
  - By the same analogy, the cost per kilogram is about $0.3M, and thus an approximate mass allocation for the Rover *based on cost* is 330 kg (again must include landing legs and/or crush plates)
  - THIS IMPLIES THAT THE MASS IS COST CONSTRAINED IN THIS ARCHITECTURE. Scaling the carrier + entry system by the Rover mass of 330 kg yields a total *affordable* stack mass of 2520 kg

Mass in kg

Orbiter dry mass	850
Radar	100
Propellant	1200
Carrier + entry system	350
Rover	330
Total stack mass	2500

Cost in $M

Total mission cost without LV	$ 850
Total A-D cost	$ 850
WBS 5+6 fraction of total	54%
WBS 5+6 total	$ 459
Orbiter FS + PL	$ 260
Allocation for Rover+carrier+entry FS	$ 199
Rover Allocation	$ 106

Size

Orbiter	2.5 m x 2 .5 m x 4 m
Heat shield diameter	< 3.7 m
C + ES + R	Constrained by fairing volume

Option 3: Smallsat-based New Frontiers

- **If high-temperature electronics are available, then the Rover could be equipped with a radio, eliminating the need for radar on the relay orbiter and reducing the orbiter to smallsat-class**
  - Assuming Architecture A → orbiter and C+ES+R are independent
  - By analogy a smallsat Venus orbiter would have a WBS 6 cost of ~$100M.
  - Using the same assumptions listed for Option 2, the approximate cost allocation for the Rover is ~$190M
  - By the same analogy, the cost per kilogram is about $0.3M, and thus an approximate mass allocation for the Rover is 630 kg. As with Option 2, the mass is constrained by cost.

Mass in kg

Orbiter + payload wet mass	340
Carrier + entry system	675
Rover	630
Total stack mass	1645

Cost in $M

Total mission cost	NA
Launch vehicle	NA
Total mission cost without LV	$ 850
Total A-D cost	$ 850
WBS 5+6 fraction of total	54%
WBS 5+6 total	$ 459
Orbiter FS + PL	$ 100
Allocation for Rover+carrier+entry FS	$ 359
Rover Allocation	$ 191

Size

Orbiter	1 m x 1 m x 1 m
Heat shield diameter	< 3.7 m
Entry System + Rover	Constrained by fairing volume

Systems

Option 4: Conservative Flagship

- **Most conservative and capable option based on architecture A: orbiter with radar, and Rover delivery system (carrier + entry system + lander). Launch together, then separate and operate independently**
- **Based on previous Team X studies, a Discovery-class Venus orbiter with radar is ~2150 kg wet**
  - Radar is ~140 kg
  - Spacecraft with payload dry mass is ~950 kg
  - Flight system + radar cost ~$300M development only
- **A 500 kg carrier (dry) + 1000 kg entry system can land a 1400 kg Rover (total wet mass of 2800 kg)**
  - Carrier + entry system cost ~$225M development only
  - The aeroshell is assumed to be 3.2 m in diameter
- **Thus, the total stack can be launched with the Falcon 9 Heavy (expendable) with 87% wet margin or a Atlas V 551 with only a 10% wet margin**
- **Note that the Falcon 9 Heavy fairing has a diameter of 5.2 m and a height of 13.9 m. By analogy, the Discovery-class orbiter and C+ES+R would each be designed for a 4 m fairing and 5 m height. Thus the elements should also fit in the launch vehicle volumetrically.**
- **Using cost rules of thumb for interplanetary landers, flight system + payload (WBS 5+6) is around 54% of *development* cost**
  - Assume 85:15 split between phase A-D cost and E-F cost
  - Assume $300M for launch vehicle + services
  - $300M for launch vehicle
  - Thus, with $2B total mission cost, allocation for Rover is $255M

Mass in kg

Orbiter + payload wet mass	2150
Carrier + entry system dry mass	1400
Rover	1400
Propellant for carrier	100
Total stack mass	5050

Cost in $M 2015

Total mission cost	$ 2,000
Launch vehicle	$ 300
Total mission cost without LV	$ 1,700
Total A-D cost	$ 1,445
WBS 5+6 fraction of total	54%
WBS 5+6 total	$ 780
Orbiter FS + PL	$ 270
Carrier + Entry FS	$ 225
Rover Allocation	$ 285

Size

Orbiter	2.5 m x 2 .5 m x 4 m
C + ES + R	3.5 m diameter x 5 m height
Heat shield diameter	3.2 m

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Option 5: SPECULATIVE Flagship

- **There is another option of a Flagship mission with Architecture B (direct entry), which would only include an orbiter, entry system, and rover.**
- **There is no direct analogy this option. A very rough mass allocation can be obtained by scaling Option 1 by the increased launch mass of 9850 kg over 2950 kg.**
  - The propellant scales directly → 1600 kg becomes 5340 kg
  - Increasing the propellant and carried mass will increase the orbiter structure, thermal mass, and possibly the reaction wheel size. By analogy, about 75% of the orbiter dry mass would scale with the increased launch mass → 900 kg becomes 2500 kg
  - The radar is the same 100 kg
  - This leaves 1930 kg for the Entry System + Rover. By analogy, the Entry System is about 75% of the mass of the Rover, leaving 1100 kg for the Rover.
- **Structural and propellant mass tend to be less expensive per kilogram than the avionics and telecom subsystems, and thus a direct cost scaling of $/kg would likely be too conservative. Based on very little information, one could speculate that the Orbiter cost may only increase by $60M. Using the same methodology outlined for Option 4, this would leave $390M for the Rover.**
- **<u>Team X has very little confidence in the assumptions and scaling rules applied to this option.</u> Option 1 is in a completely different mass and cost regime and thus scaling from it is likely not appropriate or realistic.**

Cost in $M

Total mission cost	NA
Launch vehicle	NA
Total mission cost without LV	$ 2,000
Total A-D cost	$ 1,700
WBS 5+6 fraction of total	54%
WBS 5+6 total	$ 918
Orbiter FS + PL	$ 330
Allocation for rover+entry FS	$ 588
Rover Allocation	$ 392

Mass in kg

Orbiter dry mass	2479
Radar	100
Propellant	5342
Entry System + Rover	1929
Rover	1102
Total stack mass	9850

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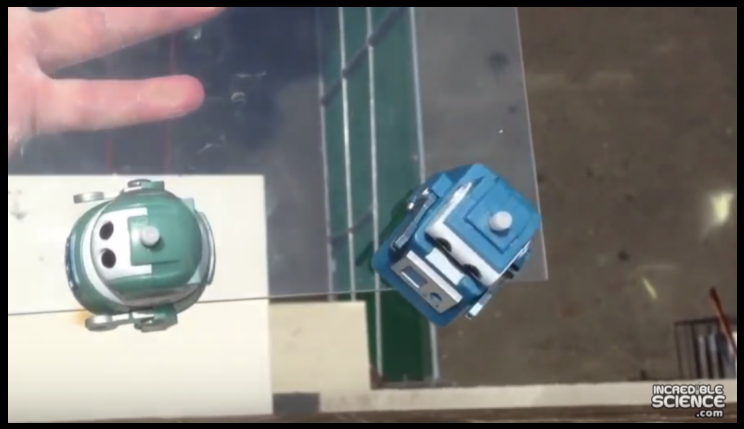
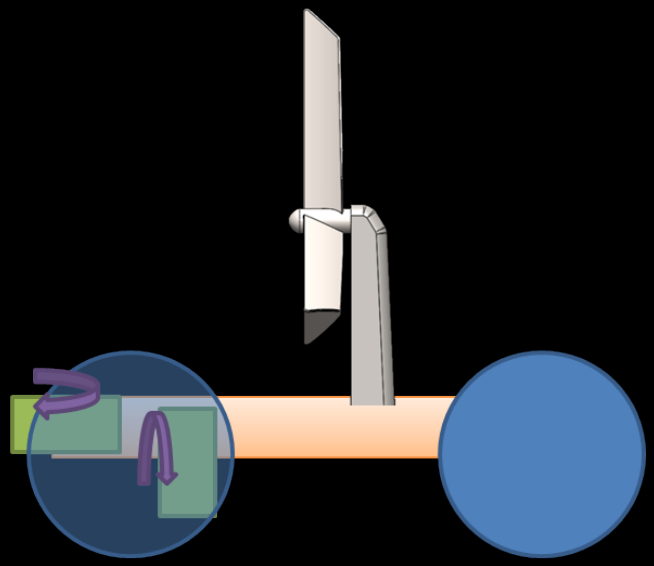
Always Active Avoidance

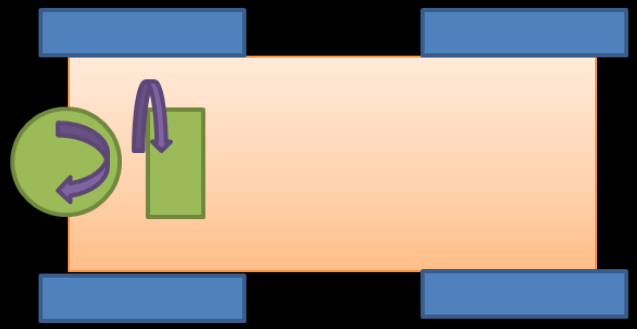
Inspired by the Never Fall Robots



Side View



Top View



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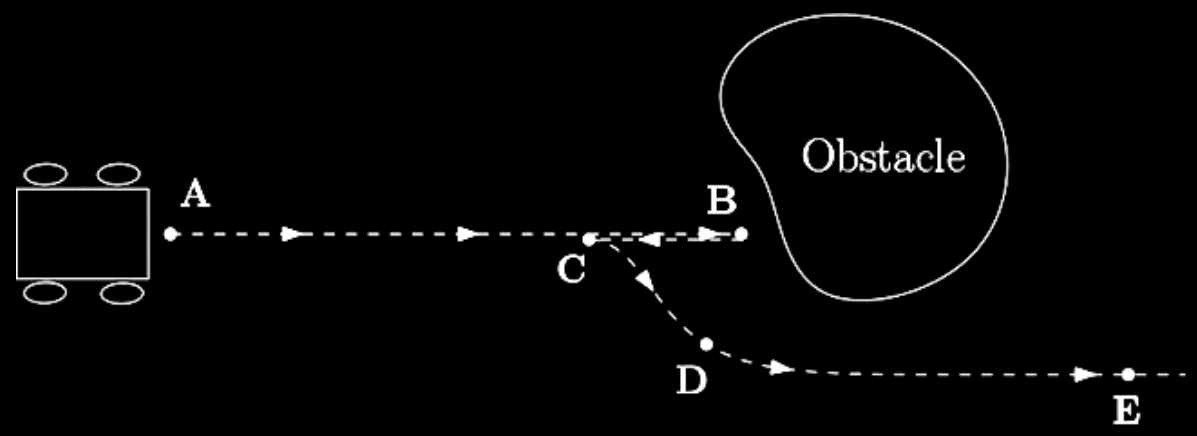
Bumper/Roller/Whisker

Obstacle Avoidance Goal



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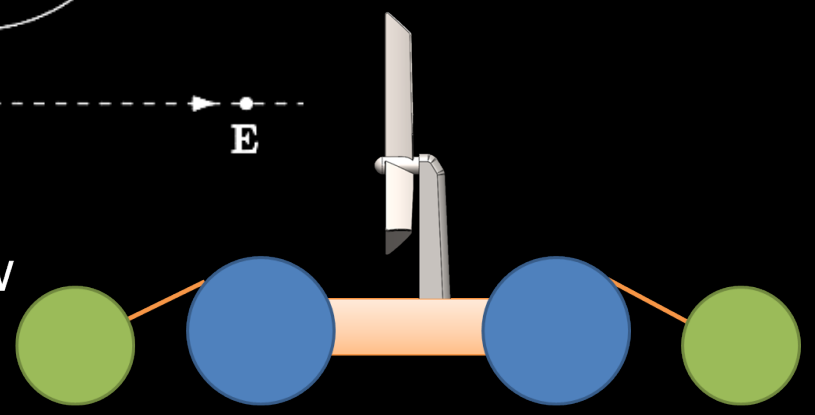
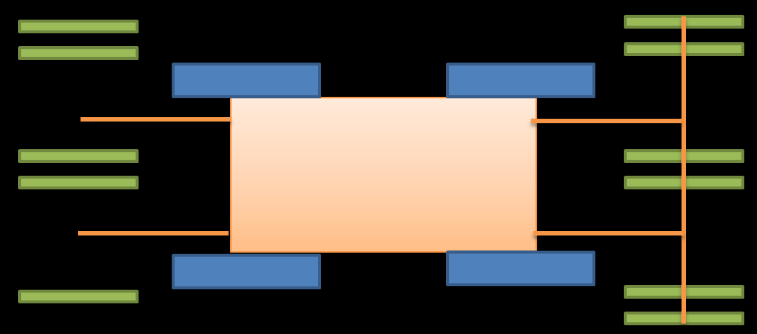


Top View



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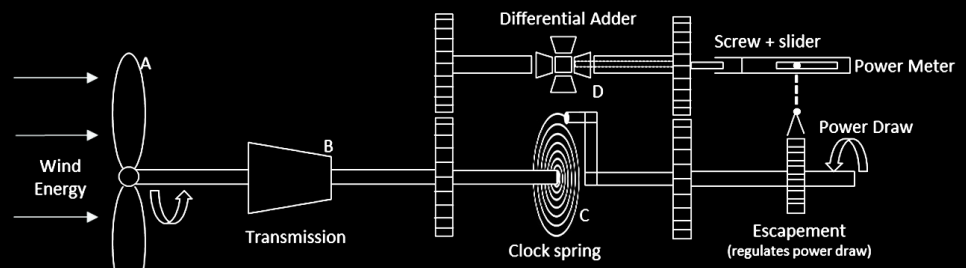
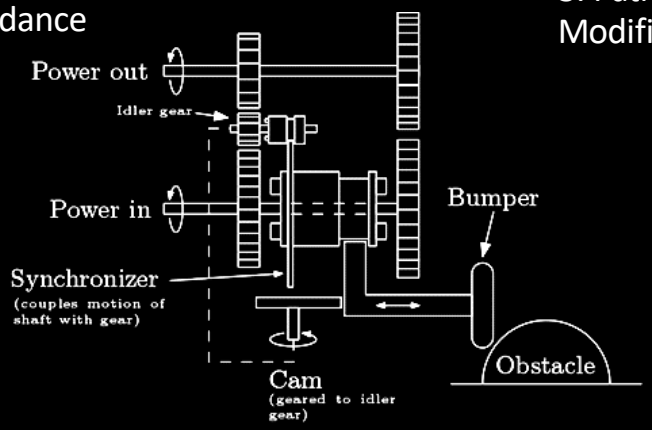
Bumper/Roller/Whisker

Obstacle Avoidance Mechanisms

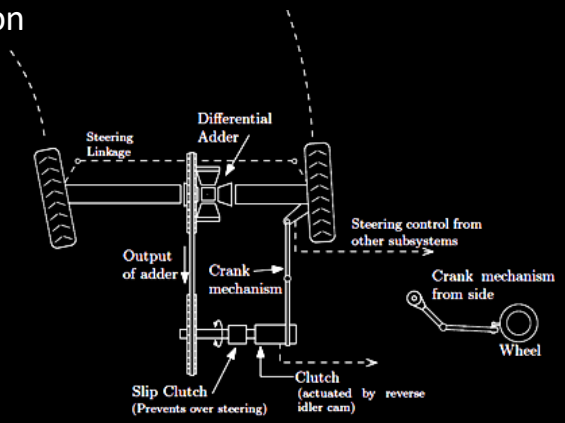
1. Energy Management



2. Obstacle Avoidance



3. Path Modification



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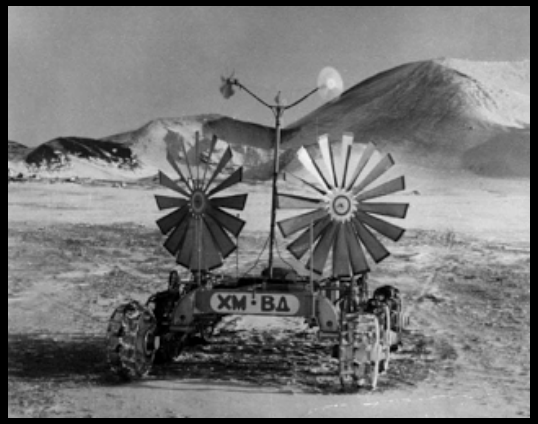
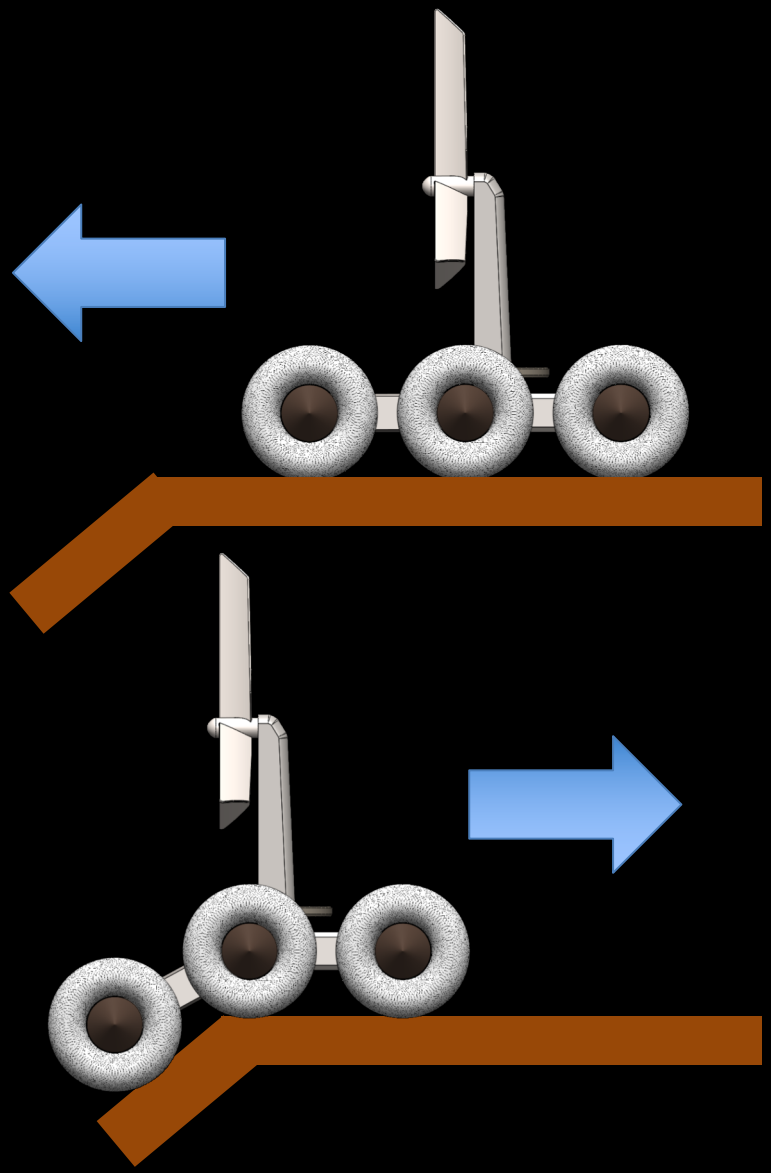
Internal Obstacle Avoidance

Draws from the Soviet Venerokhod and Marsokhod



https://www.youtube.com/watch?v=0IfpwkQ2598&t=3m18s



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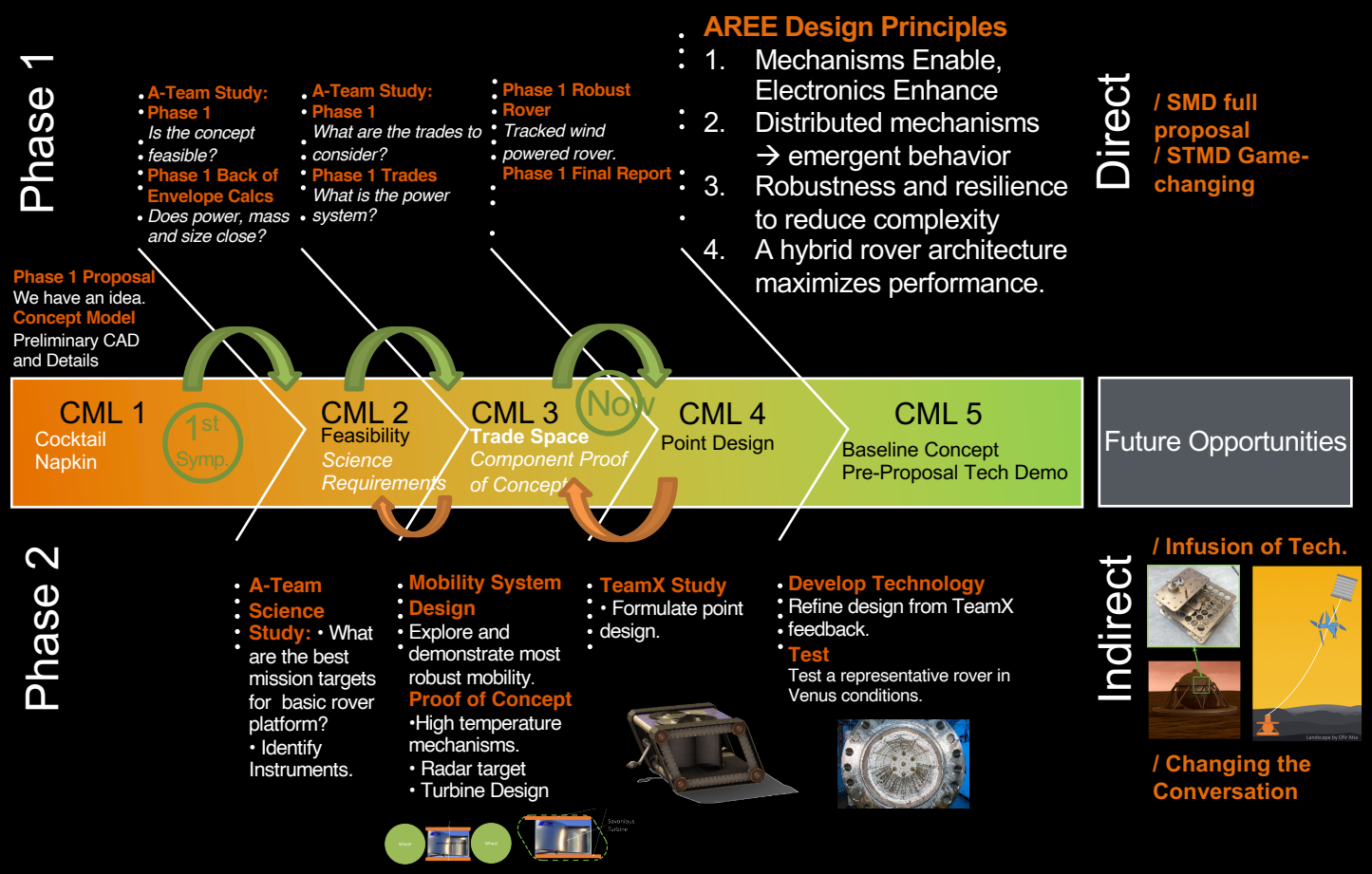

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Mass, Power, and Size Estimates

Item	Energy CBE (W-h)	Contingency	Energy w/ Margin (W-h)	Charge Time from Wind Turbine (Hours)	Charge Time from Solar Panels (Hours)
Move 100 Meters	10.68	30%	13.88	7.9	N/A
Signaling	0.31	30%	0.41	Continuous	N/A
Collect Sample (1)	77.50	30%	100.75	57.5	9.9
Analyze Sample (1)	252.50	50%	378.75	216.1	37.1
Weather Data (1 hr)	1.40	50%	2.10	1.2	0.2
Other Science (5 hr)	52.90	50%	79.35	57.5	7.8

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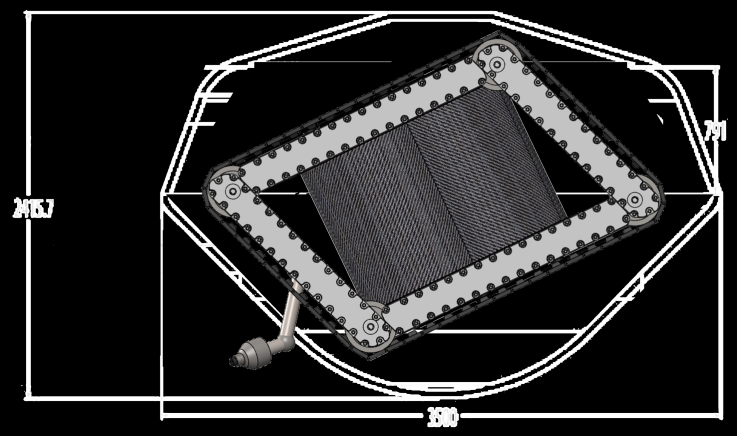
Mass and Size Estimates



Item	Mass CBE (kg)	Contin-gency	Mass Estimate Value (kg)
Power Generation	30.03	30%	42.90
Power Storage	25.52	30%	36.46
Locomotion	326.69	30%	466.70
Communication/ Signalling	78.62	30%	112.32
Control/Sensing Mechanisms	45.50	30%	65.00
Structure	147.32	30%	210.46
Science Payload	150.00	30%	195.00
Total Mass	**804**		**1129**

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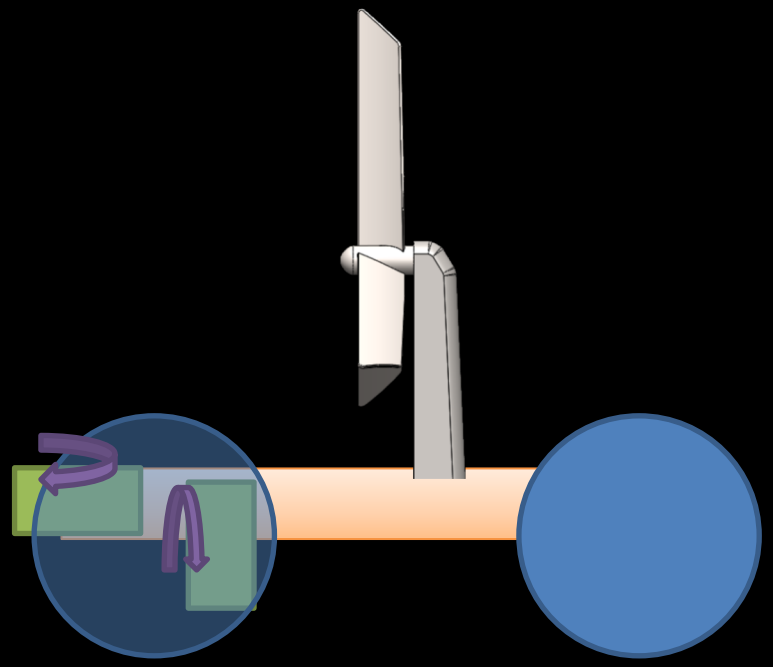
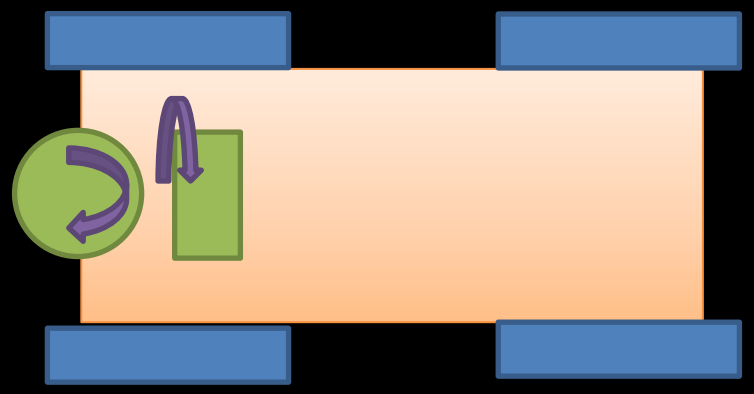
Another Variant

Side View



Top View



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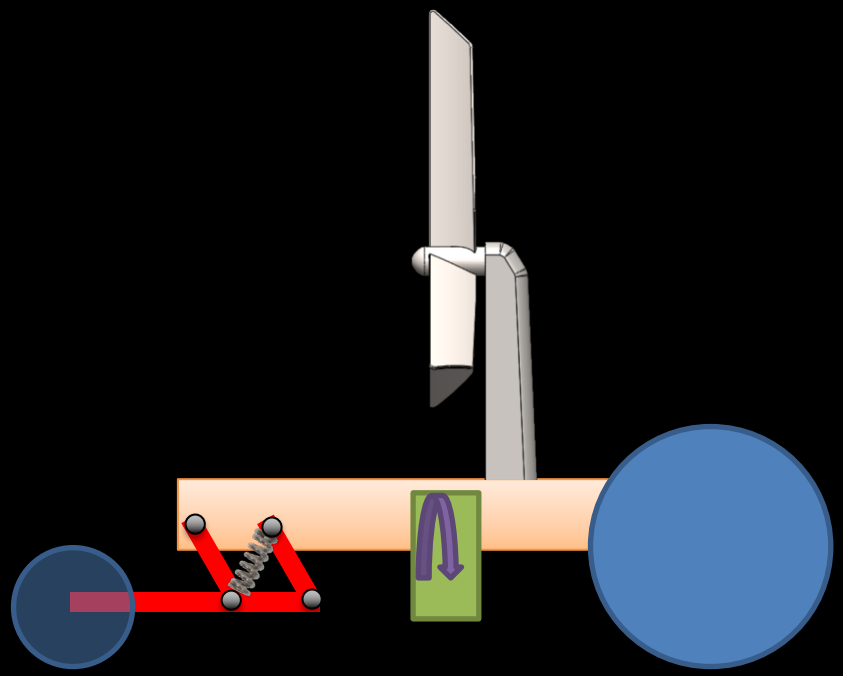

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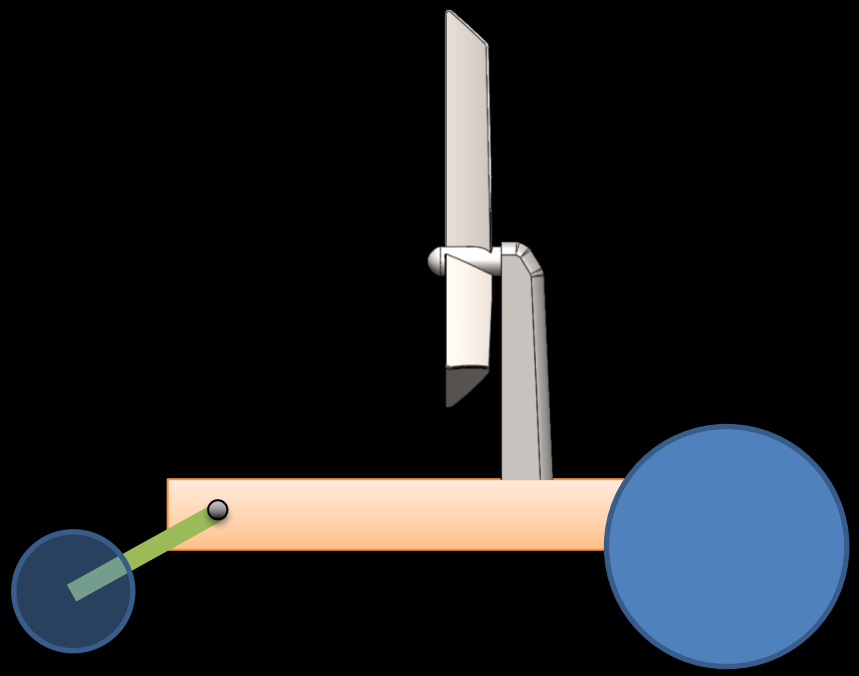

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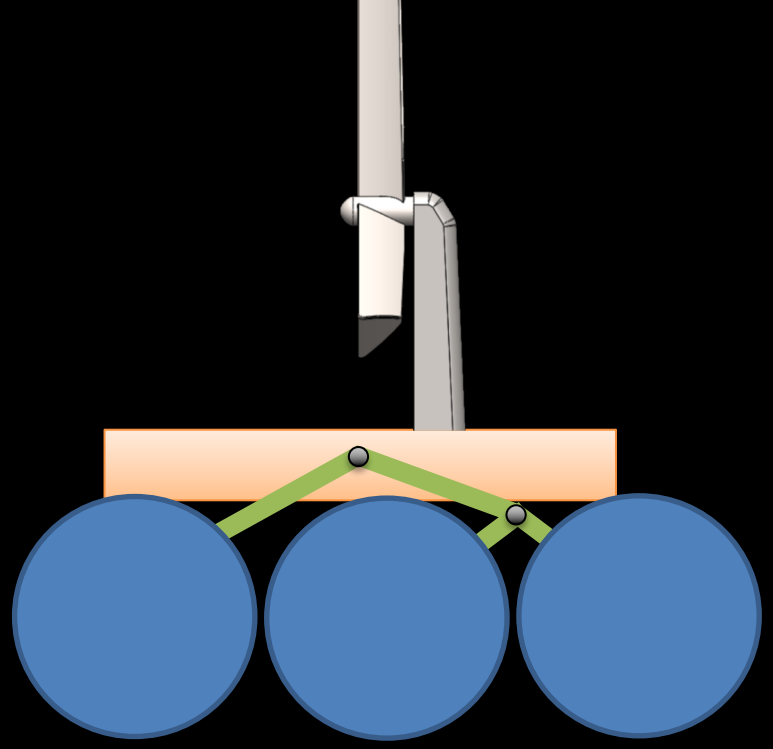

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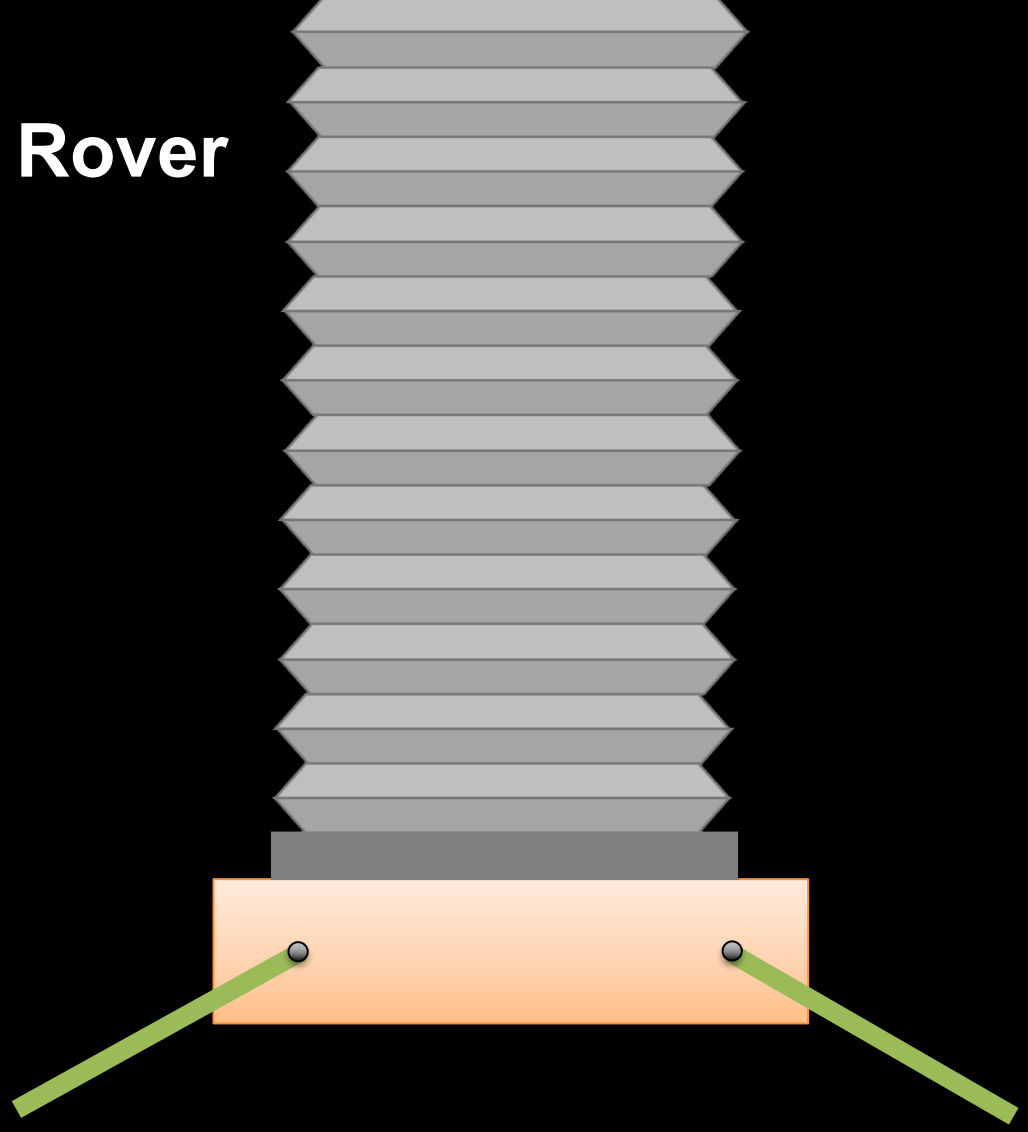
Mobile Rover



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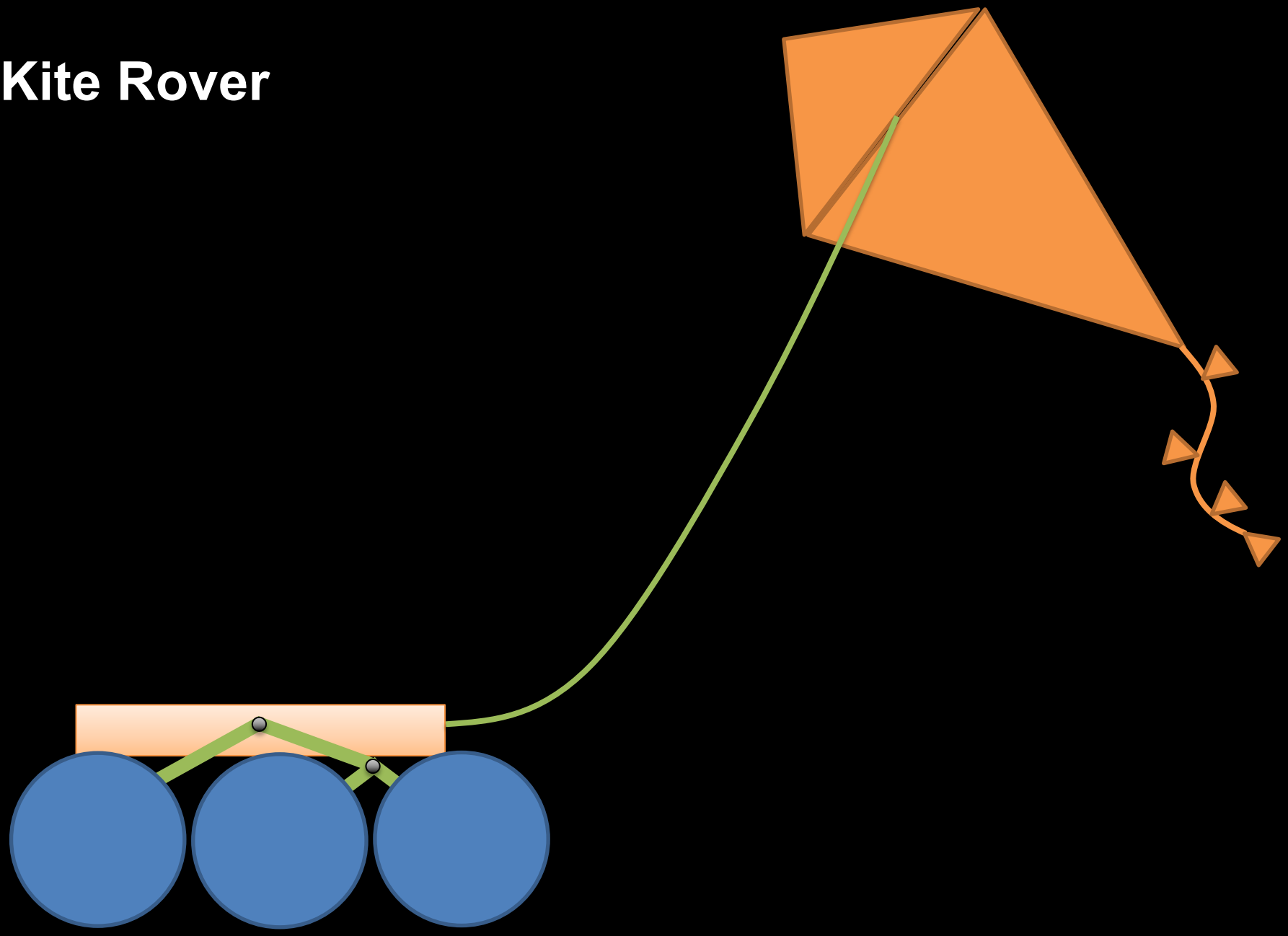
Kite Rover



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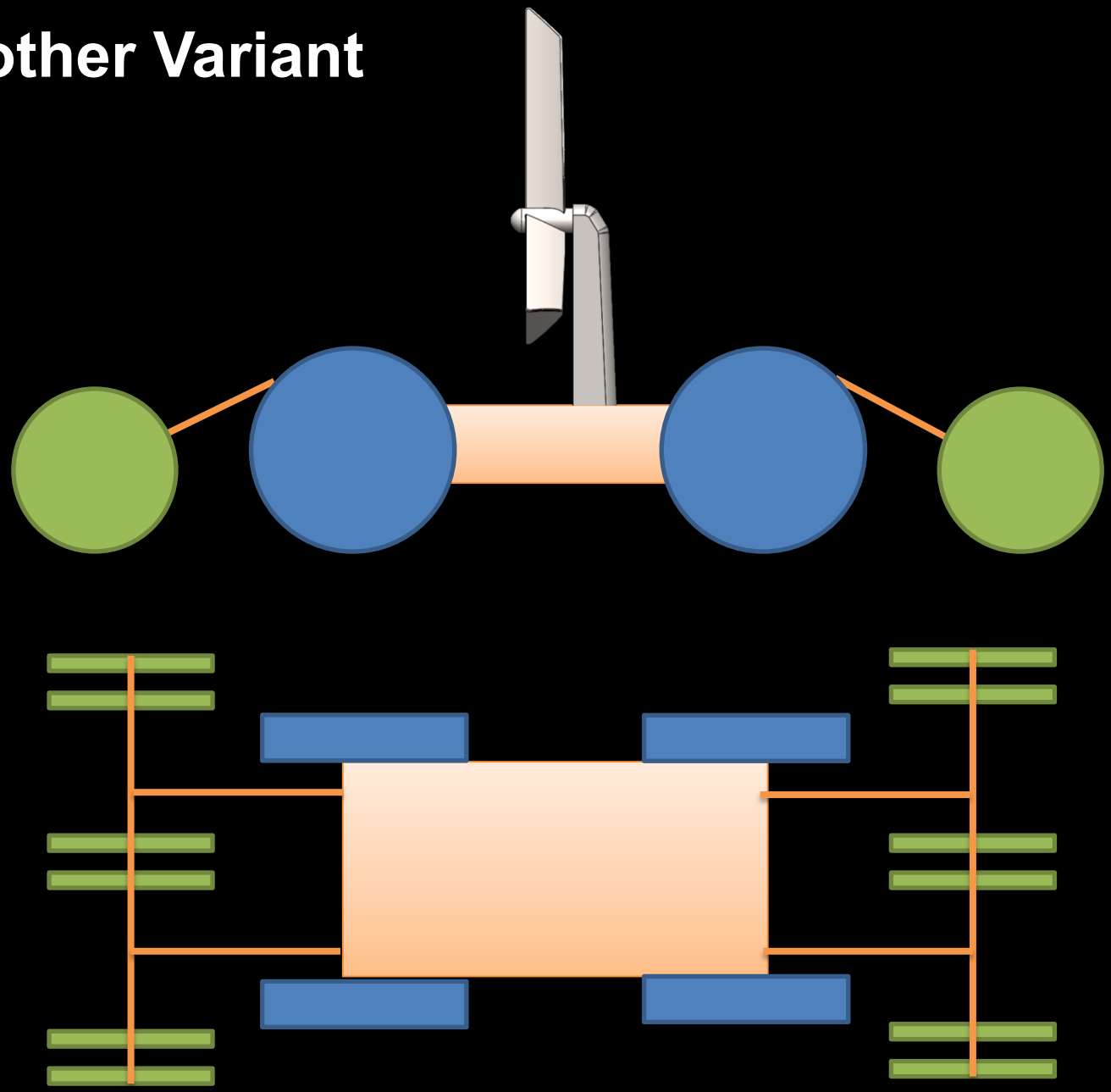

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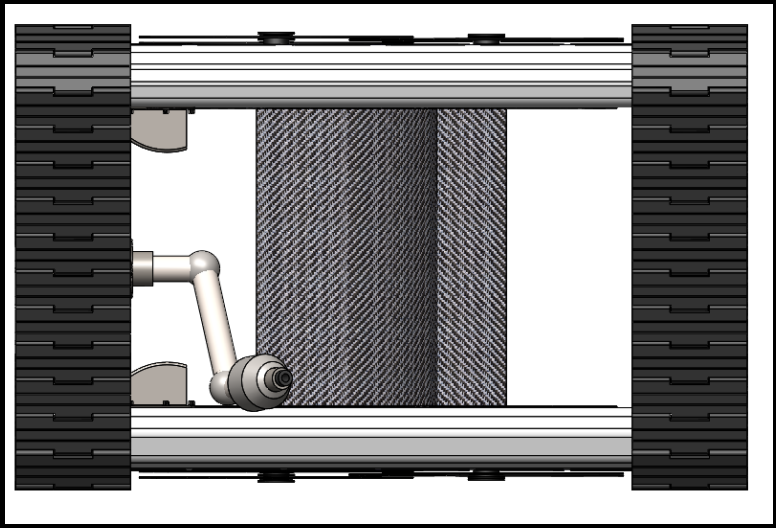

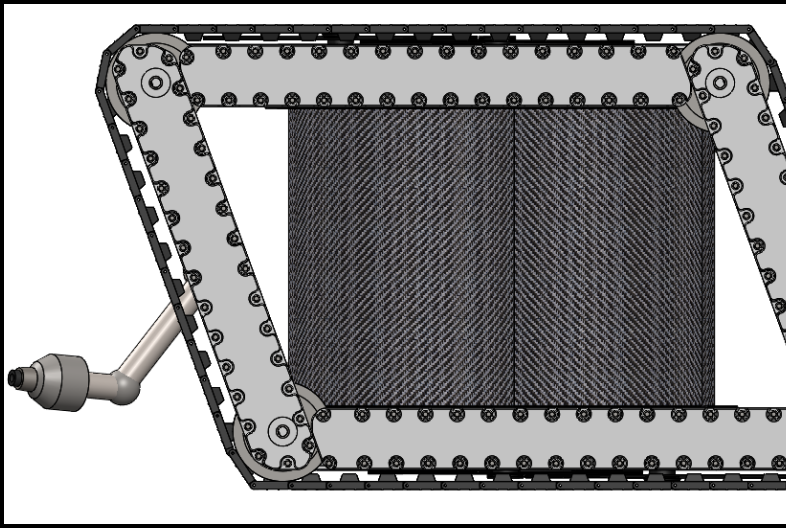

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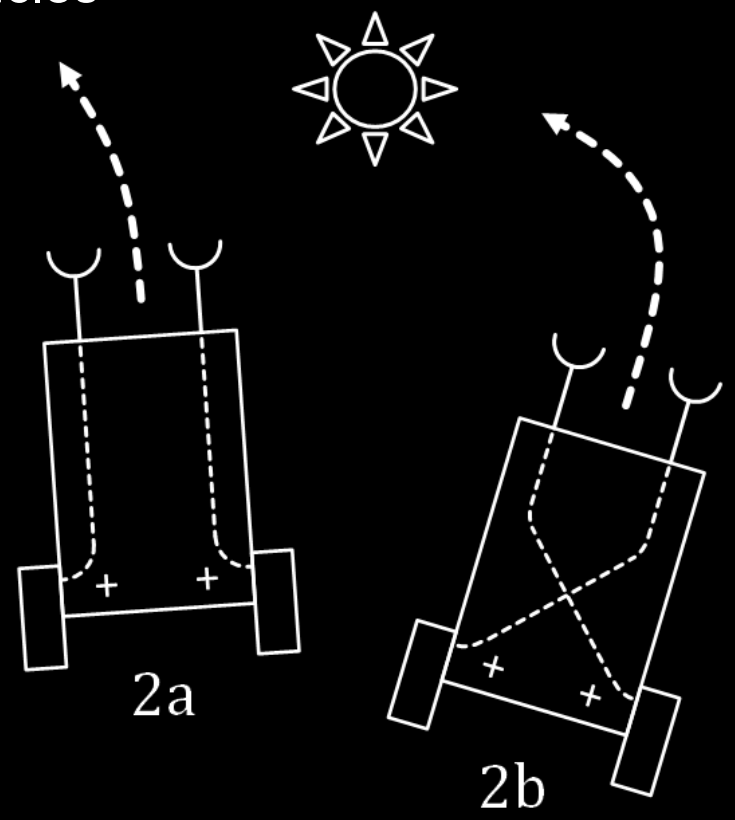
State Machines

- Leverage work of behavioral robotics and emergent systems to generate “intelligent” behavior from basic rules

Classic Example: Braintenburg Vehicles

By linking sensors directly with actuators, the vehicles exhibit basic behaviors such as light attraction or repulsion



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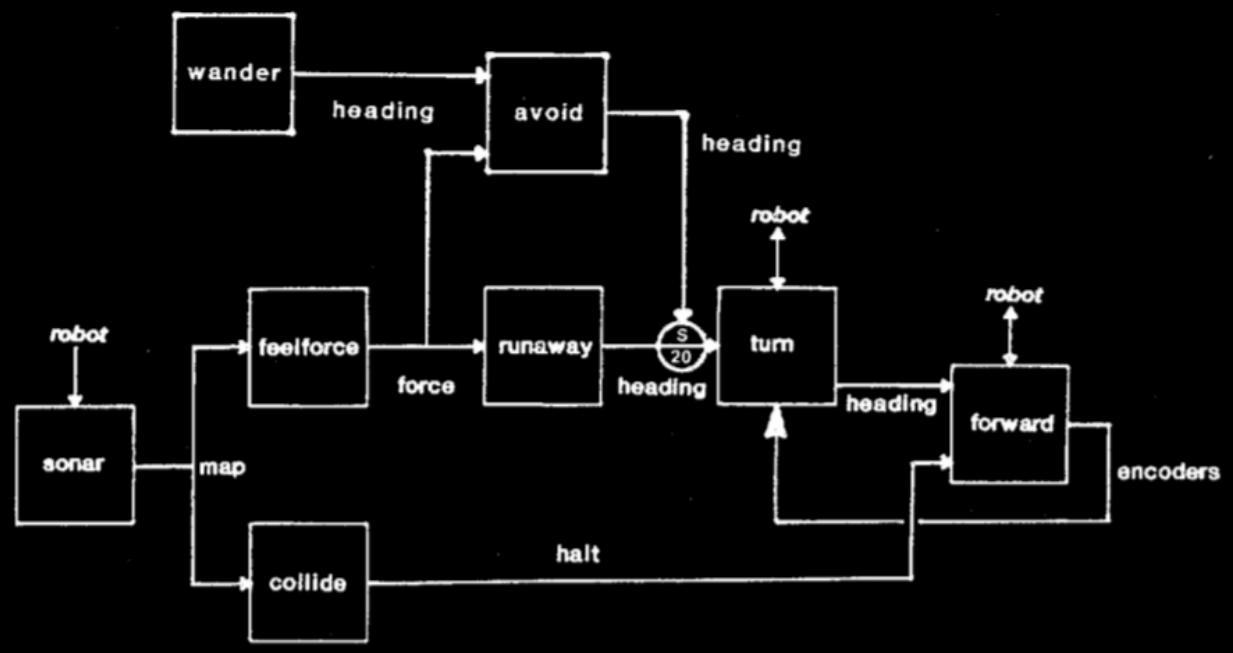
State Machines

- Significant prior work done in behavioral robotics
  - Emphasizes moving in a dynamic environment, and elimination of a central computer and symbolic processing
- Next step: can we leverage existing work by converting existing state machines from an electrical paradigm to a mechanical

State machine for a robot that can “wander” in its environment and avoid obstacles
(Brooks, Intelligence without representation)



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Potential Opportunity: Combustion/Steam Engines

A Recent Trade Opportunity

Gas has an energy density of 12900 kW/kg

Need to carry and oxizer.

Steam energy (stored in water)

Vacuum to the surface of Venus (using external pressure)

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