Jet Propulsion Laboratory
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Toward Adaptivity by Design: Lessons from Space Mission Operations Beyond the Plan

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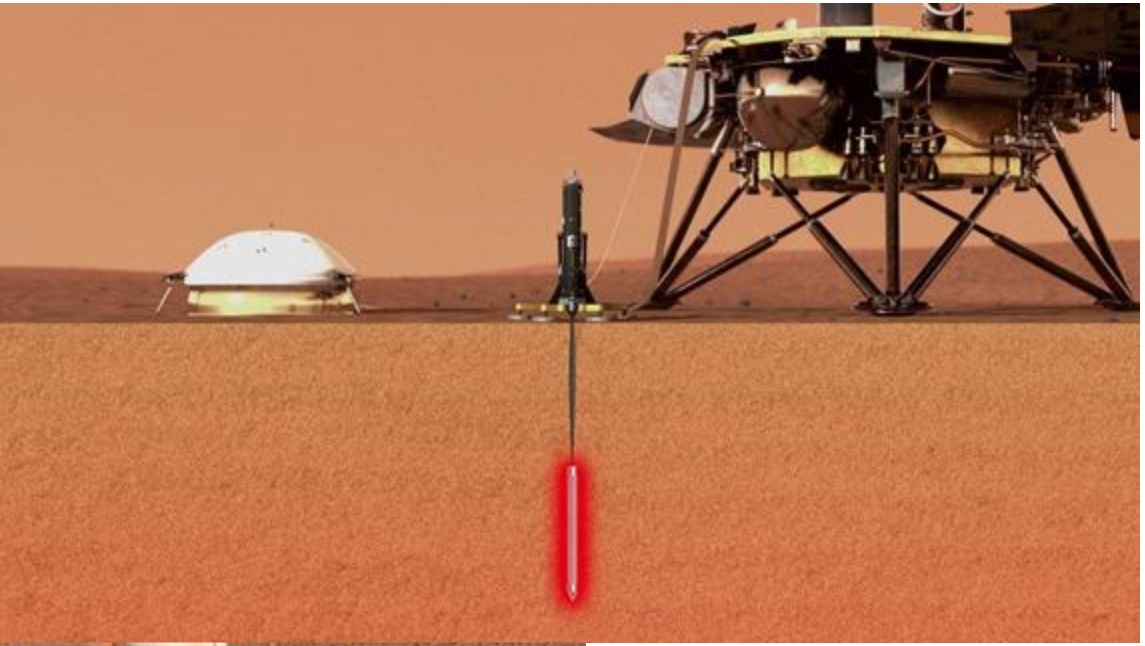
Study Purposes

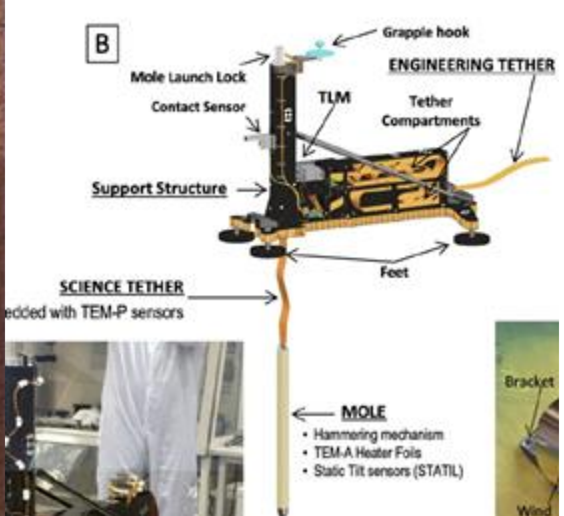
- Spacecraft operation is full of surprises
  - Particularly in planetary missions that go to unvisited destinations
- Mission success often hinged on improvised adaptation using existing resources on the space craft
- Study purposes:
  - Collect examples of successful and unsuccessful adaptations in real mission ops
  - Extract lessons
  - **Derive reusable design principles for improving adaptivity of future space systems**
- Approach
  - Interviews
  - Literature survey
- Funded by JPL's Blue Sky Program

List of interviews

Name	Mission	Affiliation	Interview date
Troy Hudson	InSight	JPL	4/8/2025
Travis Brown	Ingenuity	JPL	4/9/2025
Tim Larson	EPOXI, Stardust NEXT	JPL	4/14/2025
Steven Chesley	Stardust NEXT	JPL	4/22/2025
Heidi Becker	Juno	JPL	5/20/2025
Sandy Freund	OSIRIS-Rex	Lockheed Martin	6/10/2025
Linda Spilker	Voyager, Cassini	JPL	6/16/2025
Robert Gounley	Galileo	JPL (retired)	7/23/2025
Tracy Neilson	Galileo	JPL	7/23/2025
Nagin Cox	Galileo	JPL	7/23/2025

InSight Mole

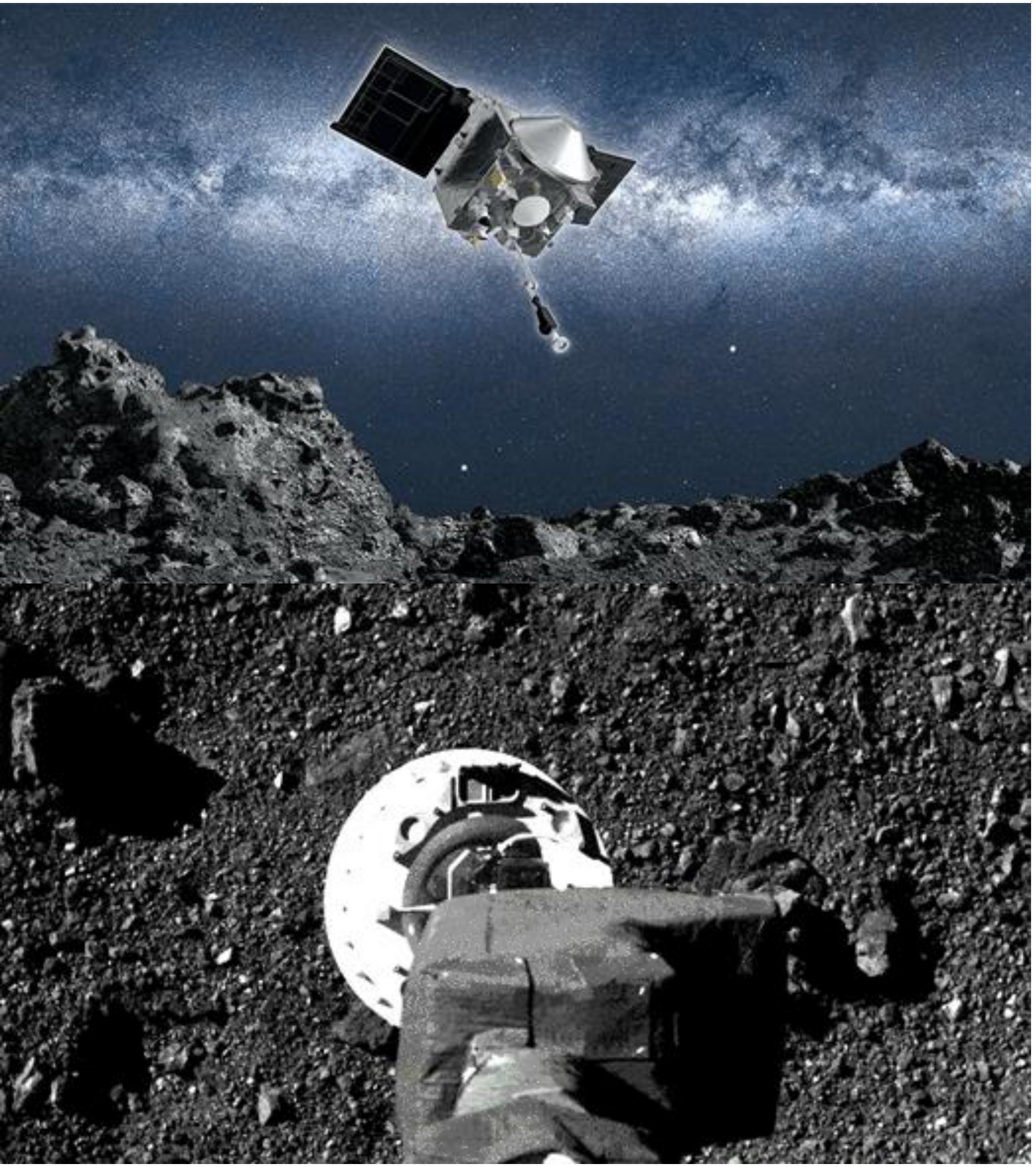




- The heat probe ("mole") of HP3 was required to penetrate >3 m into the soil
- Sol 87: HP3 deployed by the Instrument Deployment Arm (IDA)
  - A refurbished flight spare from cancelled Mars Surveyor 2001
- Sol 92/94: Initial penetration attempt
  - Target depth: 0.7m
  - Failed to reach the target but lacked the ability to measure depth until the mole reaches 0.7m and starts extracting the tether
- IDA happened to have a scoop
  - No planned use for InSight but it was not removed to save cost
- Sol 291/318: Used the scoop to "pin" the mole
  - Successful penetration of ~5 cm, proving that there is no obstructing stone near the surface
- Mole reached full burial but did not reach the required depth

- The InSight-HP3 Mole on Mars: Lessons Learned from Attempts to Penetrate to Depth in the Martian Soil. Spohn et al. (draft)
- Spohn, T., Hudson, T. L., Marteau, E., Golombek, M., Grott, M., Wippermann, T., ... & Banerdt, W. B. (2022). The InSight HP3 penetrator (Mole) on Mars: Soil properties derived from the penetration attempts and related activities. Space Science Reviews, 218(8), 72.

OSIRIS-Rex Touch-and-go Navigation



- OSIRIS-Rex: Sample return mission from Asteroid Bennu
- Ground-based observations suggested Bennu has a smooth regolith surface
- Requirement: sample from 25-m radius patch of loose regolith with lidar-based navigation
- However, when OSIRIS-Rex arrived Bennu, it turned out to be far rockier than the assumption
  - Best available landing site: 8 m radius
  - Lidar resolution was not sufficient
  - Concern of incorrect estimation of surface elevation due to reflection from nearby boulders
- The mission added vision-based natural feature tracking (NFT) as a back-up
  - Due to the development risk of lidar
  - Navigation cameras added at PDR
  - NFT added at CDR based on internal R&D at Lockheed Martin
- Eventually, NFT was used for touchdown navigation; achieved <1 m accuracy

- Leonard, Jason M., et al. "Cross-calibration of GNC and OLA LIDAR systems onboard OSIRIS-REx." Proceedings of the 44th Annual American Astronautical Society Guidance, Navigation, and Control Conference, 2022. Cham: Springer International Publishing, 2022.
- Lauretta, D. S., DellaGuistina, D. N., Bennett, C. A., et al. 2019, Nature, 568, 55
- Lauretta, D. S., Enos, H. L., Polit, A. T., et al. 2021, in Sample Return Missions: The Last Frontier of Solar System Exploration, ed. A. Longobardo (Amsterdam: Elsevier), 163

Galileo HGA

- HGA failed to deploy, severely limiting downlink data volume
- Solution: Update FSW and add data compression capability
  - Issue: C&DH computer didn't have enough memory
- Galileo had a separate computer for attitude control
  - Added data compression to attitude control computer
- Launch delay required Venus flyby, imposing new attitude requirements
  - Mission added a sun sensor (*sun gate*) to orient the rotation axis toward the sun
  - Sun gate used for sensing how much HGA opened
- During the design time the mission decided not to add capability to re-close HGA
  - Ran out of switches
  - Closing/opening multiple times would *increase* the risk of getting stuck
  - In retrospect – had it had the ability to re-close, it could have de-stuck

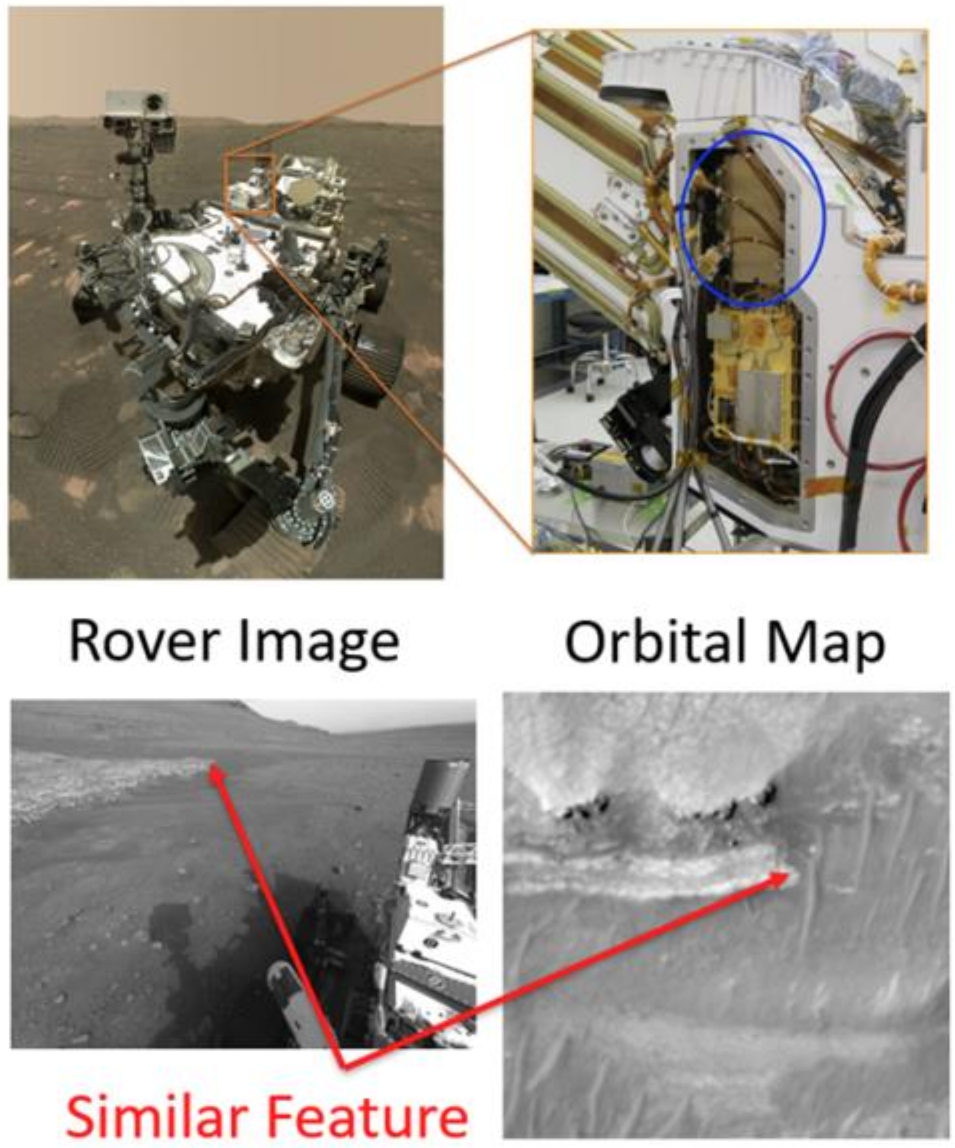
- Mobasser, Sohrab, and David Weisenberg. "A sun gate for Galileo spacecraft attitude control." *IEEE Conference on Aerospace Applications*. IEEE, 1990.
- O'Neil, W. J., et al. "Project galileo at jupiter." Acta astronautica 40.2-8 (1997): 477-509.
- Johnson, Michael R. "The Galileo high gain antenna deployment anomaly." NASA. Lewis Research Center, The 28th Aerospace Mechanisms Symposium. 1994.
- Jansma, P. A. "Open! Open! Open! Galileo high gain antenna anomaly workarounds." 2011 Aerospace Conference. IEEE, 2011.
- Marr, James C. "Performing the Galileo mission using the S-band low-gain antenna." Proceedings of 1994 IEEE Aerospace Applications Conference Proceedings. IEEE, 1994.

Deep Space 1 / Juno Star Tracker

- Deep Space 1
  - Star tracker failed
  - Reprogrammed the science camera (MICAS: Miniature Integrated Camera And Spectrometer) to function as a star tracker
- Juno
  - Used star tracker (SRU) for scientific observations
    - SRU was designed to be able to downlink images for housekeeping and testing purposes
    - Designed for imaging dark objects
      - JunoCam was for bright objects
  - Scientific achievements:
    - First imaging of Jupiter lightening
    - Dark side images of the moons
    - Investigation of the rings
  - Limitation: slow data bus speed; takes 15 min to transfer an image to C&DH

- Becker, Heidi N., et al. "A complex region of Europa's surface with hints of recent activity revealed by Juno's Stellar Reference Unit." Journal of Geophysical Research: Planets 128.12 (2023):
- Becker, Heidi N., et al. "Surface features of Ganymede revealed in Jupiter-shine by Juno's Stellar Reference Unit." Geophysical Research Letters 49.23 (2022)
- Channelized Thermal Emission, Promethean-Type Jets and Surface Changes on Io From Juno Stellar Reference Unit Imagery
- Becker, Heidi N., et al. "Small lightning flashes from shallow electrical storms on Jupiter." Nature 584.7819 (2020): 55-58
- Becker, Heidi N., et al. "Observations of MeV electrons in Jupiter's innermost radiation belts and polar regions by the Juno radiation monitoring investigation: Perijoves 1 and 3." Geophysical Research Letters 44.10 (2017): 4481-4488.

Mars 2020 Global Localization



- Mars 2020 Rover Perseverance originally did not have ability to localize herself against orbital map coordinate
- Growing positional uncertainty occasionally interrupted drives prematurely
- Experimentally implemented global localization capability on the Snapdragon 801 processor of the Helicopter Base Station (HBS)
  - Added later in the mission to support Ingenuity
  - Unused after the end of Ingenuity mission
- Successfully demonstrated on Mars
  - Takes only 32 sec on Snapdragon
- Limitation:
  - Slow serial link between HBS and the main computer (RCE) - ~10 kbps
  - Takes ~30 min to transfer images to HBS

Verma, Vandi, et al. "Enabling long & precise drives for the perseverance mars rover via onboard global localization." *2024 IEEE Aerospace Conference*.

Ingenuity (Mars Heli)

- Inclinometer was found broken after the first winter
- Luckly, Ingenuity had a separate IMU
  - Inclinometer intended for high-accuracy measurement before flight
  - IMU used during flights
- Changed FSW to use inertial measurement unit (IMU) instead
  - COTS sensor - Bosch BMI-160
- Color 4K camera (RTE camera) was not required but added “just because they could”
  - The only required camera was black/white NAV camera
  - It was later used for scientific observations

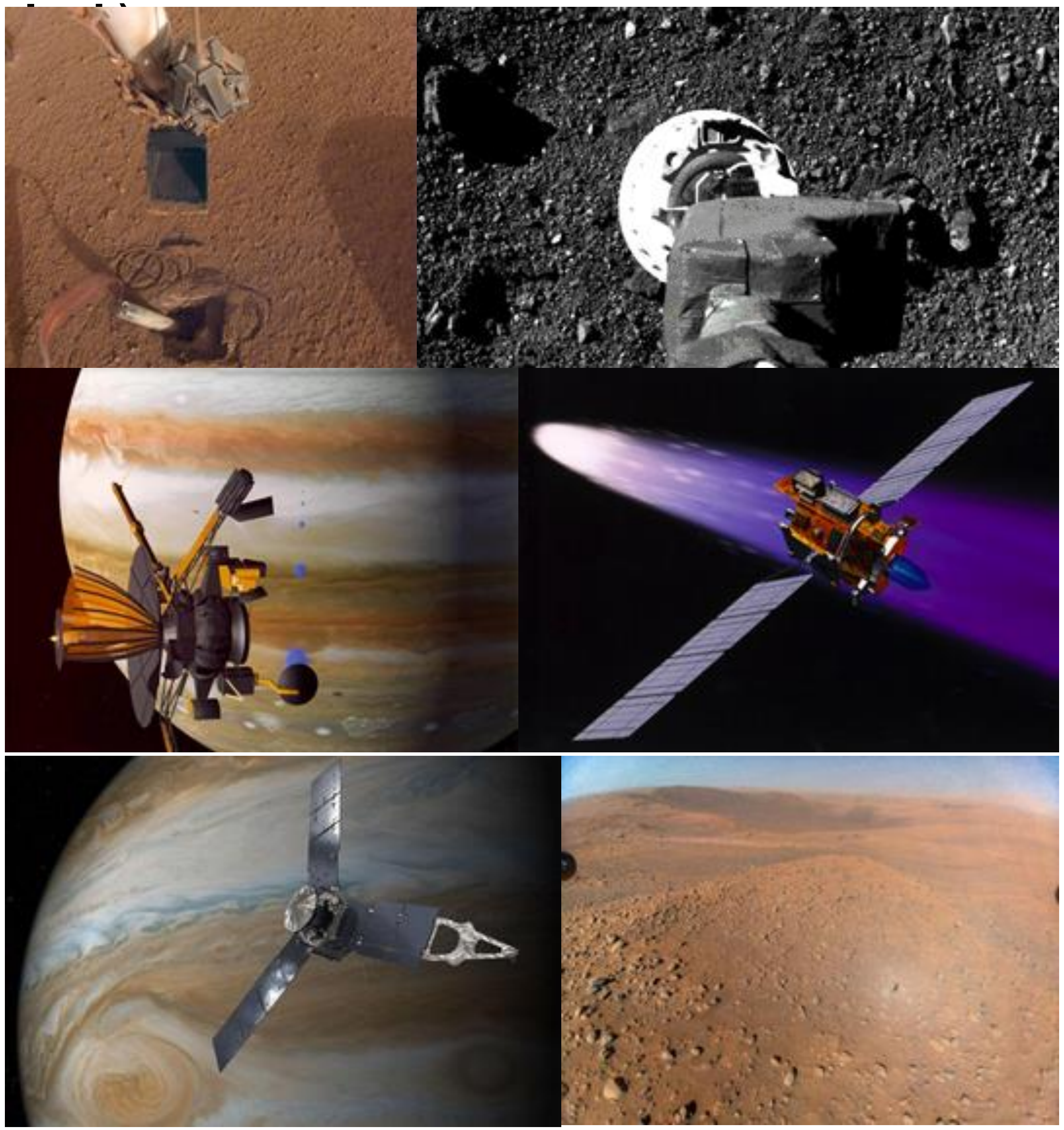
- Anderson, Joshua L., et al. "Ingenuity, one year of flying on mars." 2023 IEEE Aerospace Conference. IEEE, 2023.
- Grip, H. et al. "Flying a helicopter on Mars: How ingenuity's flights were planned, executed, and analyzed." 2022 IEEE Aerospace Conference (AERO). IEEE, 2022.

Design Principles for Adaptability

- Design HW-level flexibility
  - InSight scoop on IDA
  - Galileo HGA re-close capability
- Make spacecraft sensor-rich
  - Galileo sun gate
  - InSight - lack of mole depth measurement
- Design generous margins
  - Memory size (Galileo)
  - Data bus speed (Perseverance, Juno)
- Make components multi-purposed
  - Ingenuity IMU
  - Juno star tracker, Deep Space 1 science camera
- Don’t remove redundancies even if there is no use
  - InSight scoop
  - OSIRIS-Rex Navigation Camera
  - Ingenuity RTE cam

Open Question: Toward Adaptivity by Design

RSE 2.0: Adaptivity by improvisation (or by



RSE 3.0: Adaptivity by Design

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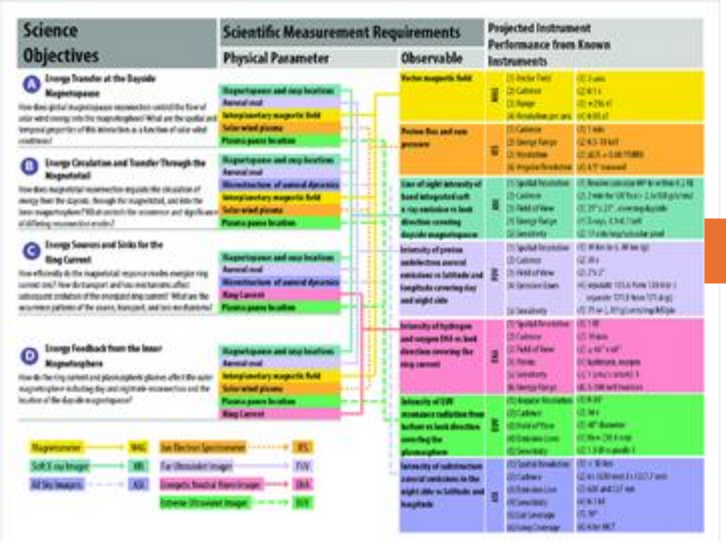
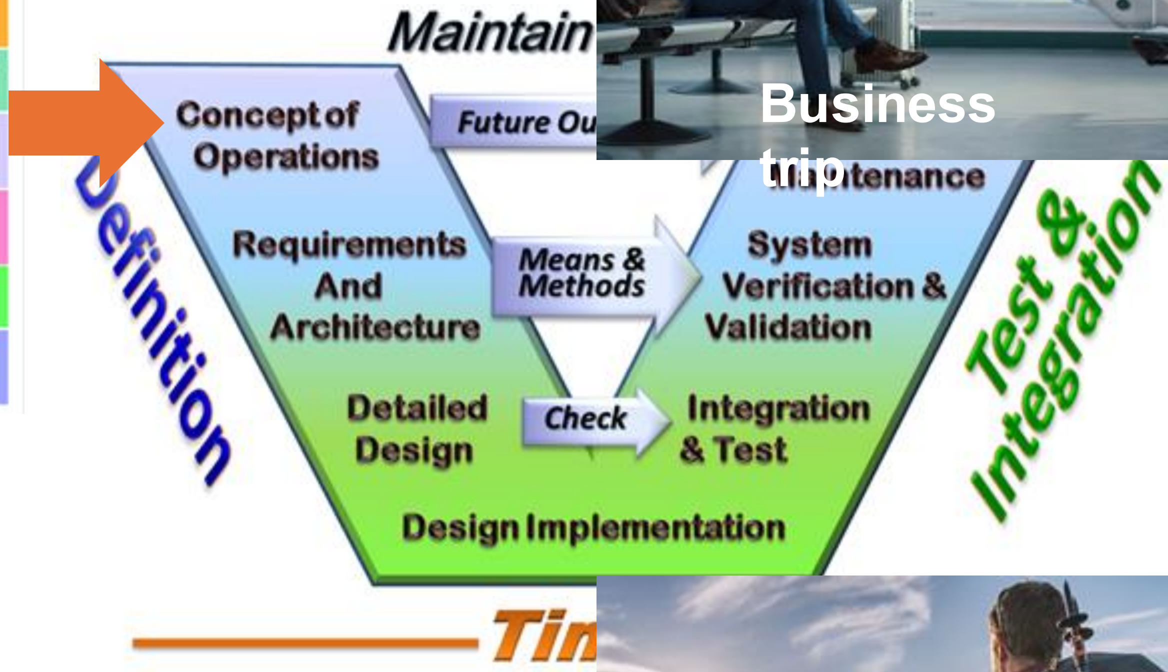
- Flexible hardware
  - High-DOF
  - Modularity
  - Reconfigurability
  - Multi-agent
- Intelligent software
  - Adaptive autonomy
  - On-board learning
  - Real-to-sim-to-real?
  - Foundation models?

New Space Systems Engineering Approach?



Requirement-driv



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