Briefing to the NRC Panel on Robotics, Communications, and Navigation NASA Technology Roadmaps in the Guidance & Control Area

3/29/11-3/30/11

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Topics to be Covered

- Information about speaker
- Definition of Guidance, Navigation and Control
- Future of Guidance, Navigation and Control as a part of increasingly complex missions and challenging budgetary environment
- Recommendation for the Robotics, Communication and Navigation Roadmaps
  - Key GN&C Technologies
  - Key cross-cutting technologies within GN&C and other disciplines
  - Need for system demonstrations
- Summary

Information about Speaker

- Education
  - B.S., University of Illinois at Urbana-Champaign
  - M.S., University of Illinois at Urbana-Champaign
- With Jet Propulsion Laboratory, Caltech, since 1990
  - Currently manager of the Guidance and Control Section
  - Past experience
    - Guidance & Control sensors group supervisor
    - Formation Flying technology manager for Terrestrial Planet Finder mission
    - Autonomous Formation Flying Sensor manager for StarLight mission
    - Optical Communication Ground Terminal manager for Mars Laser Communication Demonstration
    - Radiometer Instrument cognizant engineer for EOS Microwave Limb Sounder
    - Deep Space Network Signal Processing and Communication engineer
- Briefing Team
  - Dr. Fred Hadaegh, Fellow in AIAA, IEEE, JPL in the area of Guidance & Control
  - Mr. J. Edmund Riedel, Principal Engineer at JPL with extensive experience in Technology and Flight including Deep Space 1, Deep Impact, Stardust and Dawn missions
  - Dr. Alberto Cangahuala, Manager of JPL Mission Design and Navigation Section, extensive experience in Navigation technical analysis and missions, most recently shadow-navigation of Chandraayan-1

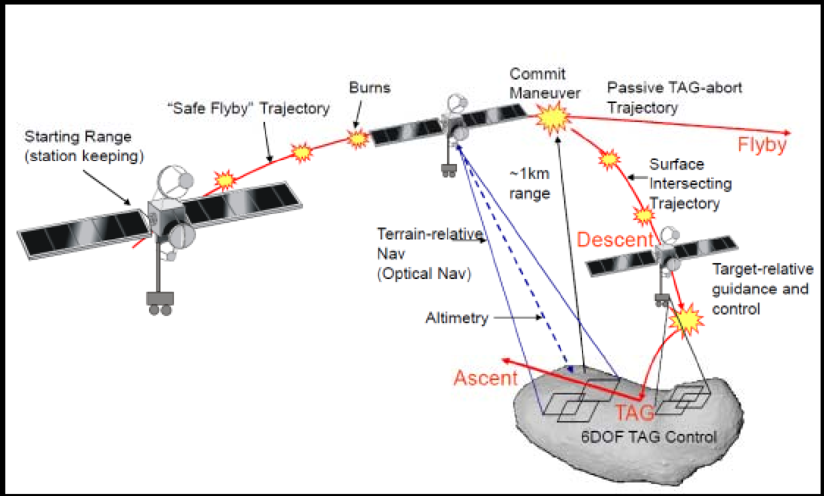
What is Guidance, Navigation & Control (GN&C)?

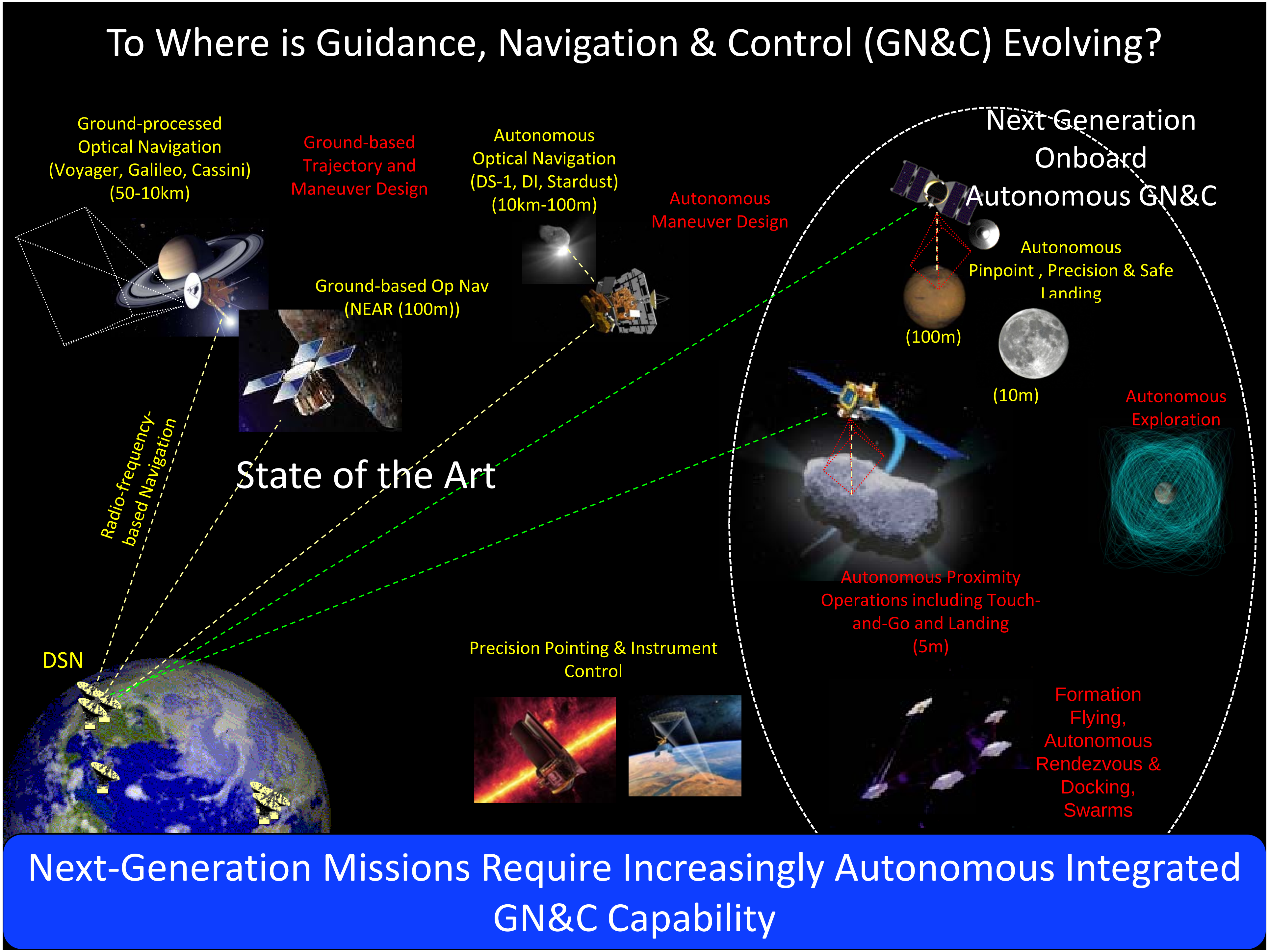
Navigation: Ground-based/aided and onboard determination of the vehicle's position, velocity

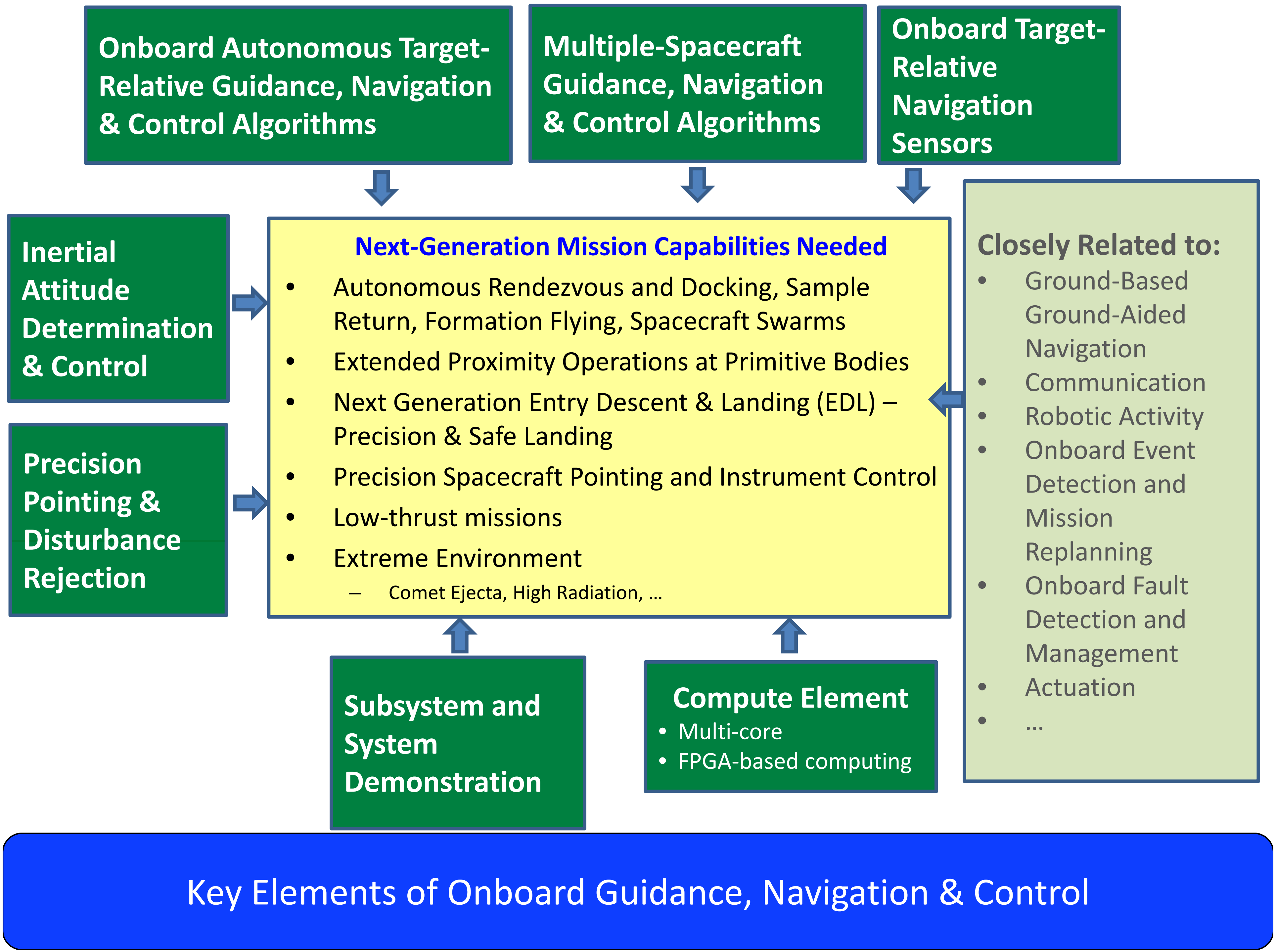
Guidance: Ground-based/onboard determination of the desired path of travel from the vehicle's current location to a designated target

Control: Onboard manipulation of vehicle steering controls to track guidance commands while maintaining vehicle pointed with the required precision

Tightly Related Functions

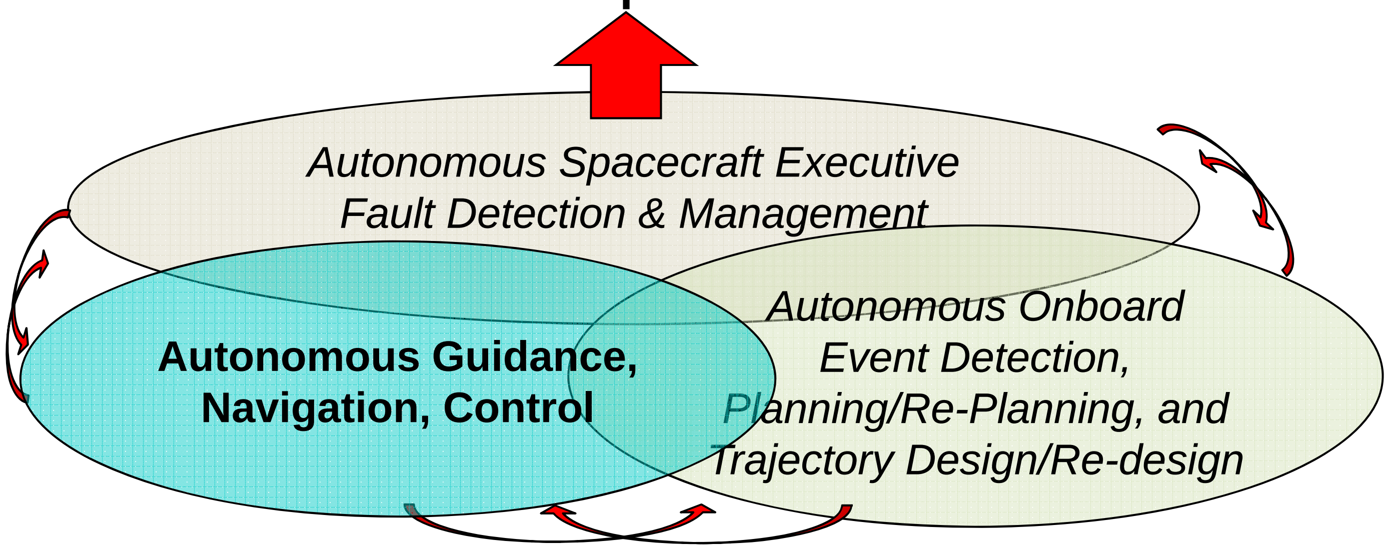


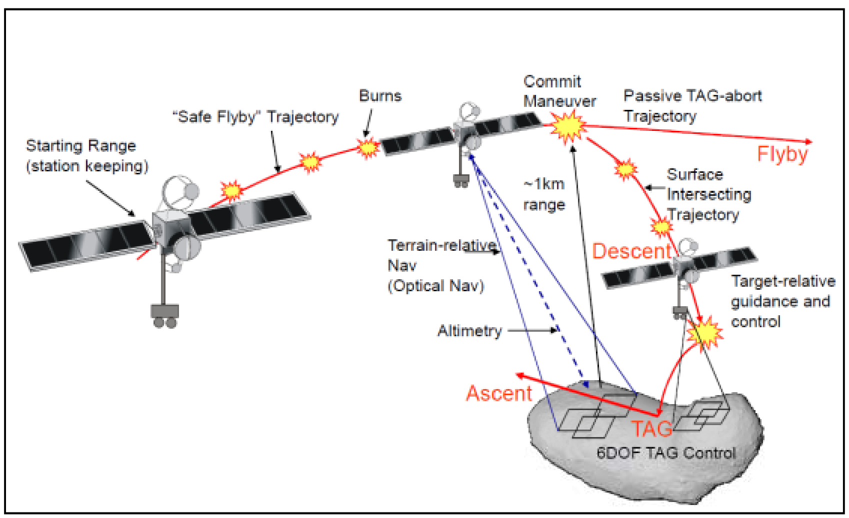

To Where is Guidance, Navigation & Control (GN&C) Evolving?
Ground-processed Optical Navigation (Voyager, Galileo, Cassini) (50-10km)
Ground-based Trajectory and Maneuver Design
Autonomous Optical Navigation (DS-1, DI, Stardust) (10km-100m)
Autonomous Maneuver Design
Next Generation Onboard Autonomous GN&C
Autonomous Pinpoint , Precision & Safe Landing
(100m)
(10m)
Ground-based Op Nav (NEAR (100m))
Radio-frequency-based Navigation
State of the Art
Autonomous Exploration
Autonomous Proximity Operations including Touch-and-Go and Landing (5m)
DSN
Precision Pointing & Instrument Control
Formation Flying, Autonomous Rendezvous & Docking, Swarms
Next-Generation Missions Require Increasingly Autonomous Integrated GN&C Capability


Onboard Autonomous Target-Relative Guidance, Navigation & Control Algorithms
Multiple-Spacecraft Guidance, Navigation & Control Algorithms
Onboard Target-Relative Navigation Sensors
Inertial Attitude Determination & Control
Precision Pointing & Disturbance Rejection
Next-Generation Mission Capabilities Needed
• Autonomous Rendezvous and Docking, Sample Return, Formation Flying, Spacecraft Swarms
• Extended Proximity Operations at Primitive Bodies
• Next Generation Entry Descent & Landing (EDL) – Precision & Safe Landing
• Precision Spacecraft Pointing and Instrument Control
• Low-thrust missions
• Extreme Environment
– Comet Ejecta, High Radiation, …
Closely Related to:
• Ground-Based Ground-Aided Navigation
• Communication
• Robotic Activity
• Onboard Event Detection and Mission Replanning
• Onboard Fault Detection and Management
• Actuation
• …
Subsystem and System Demonstration
Compute Element
• Multi-core
• FPGA-based computing
Key Elements of Onboard Guidance, Navigation & Control

Onboard GN&C Will Enable Future Onboard Autonomous Missions

Autonomous Spacecraft Actions





Challenging Mission Scenarios Require Autonomous Real-time Integrated Guidance, Navigation and Control, and Autonomous Operation, with Reduced Cost

Recommendation for the Roadmaps

- We recommend that a section dedicated to Autonomous Integrated Guidance, Navigation & Control (GN&C) be added to the roadmaps

- Contents of the recommended section
  - Key onboard autonomous integrated GN&C capabilities needing advancement to enable next-generation missions

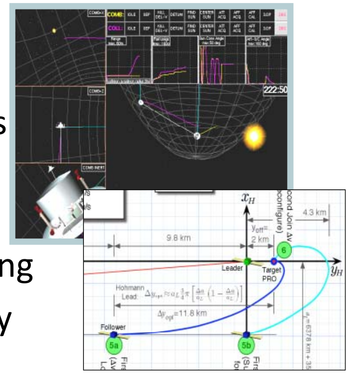
  - Synergistic technologies and inter-play across integrated GN&C, Navigation, Communications and Robotics in enabling increasingly autonomous missions

  - Need for System-Level Demonstration

Key Component Technologies for Formation Flying, Autonomous Rendezvous & Docking, Swarms

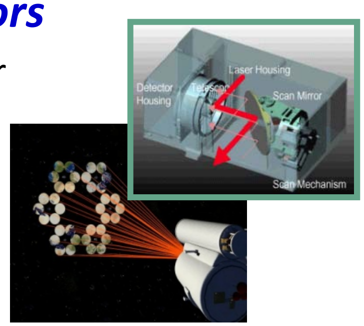
– ***Guidance, Estimation, and Control***

- Architectures & algorithms for estimation with variable sensor and comm. topologies
- Relative orbit designs & collision avoidance with onboard relative path-planning
- Stable control for dynamically sized formations



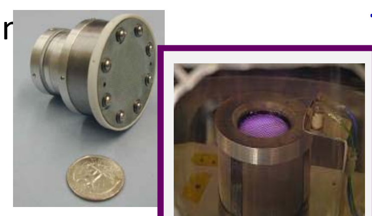
– ***Inter-Spacecraft Sensors***

- Inter-spacecraft RF sensor for deep-space
- Sub-nm, absolute laser metrology systems for precision formations
- Scanning and flash lidars, laser-augmented visual targets, feature-recognition systems



– ***Propulsion***

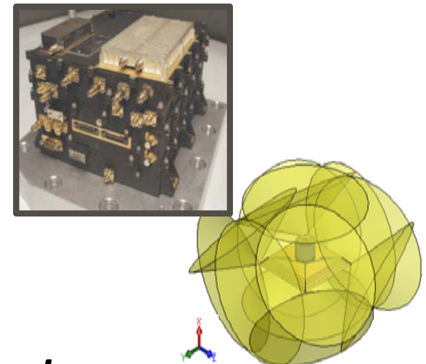
- Non-contaminating, high-efficiency electric propulsion



Hollow Cathode Discharge (in MiXI Test Facility)

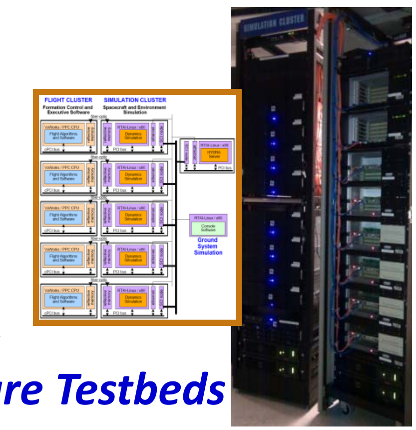
– ***Inter-Spacecraft Communication***

- Low-bandwidth RF-comm over sensor links
- High-bandwidth RF and Optical communication systems
- TDMA schemes scalable to several s/c



– ***Software and Distributed Simulation***

- StarLight formation software to PDR and TPF formation software to Level 1 Milestone
- Distributed real-time simulation environments



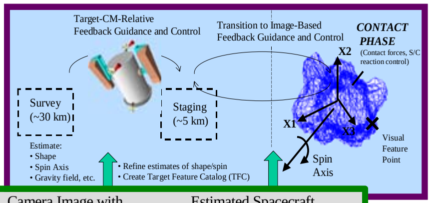
– ***System-Level Hardware Testbeds***

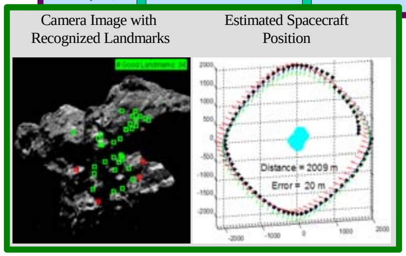
- **6DOF dynamics multiple robots**

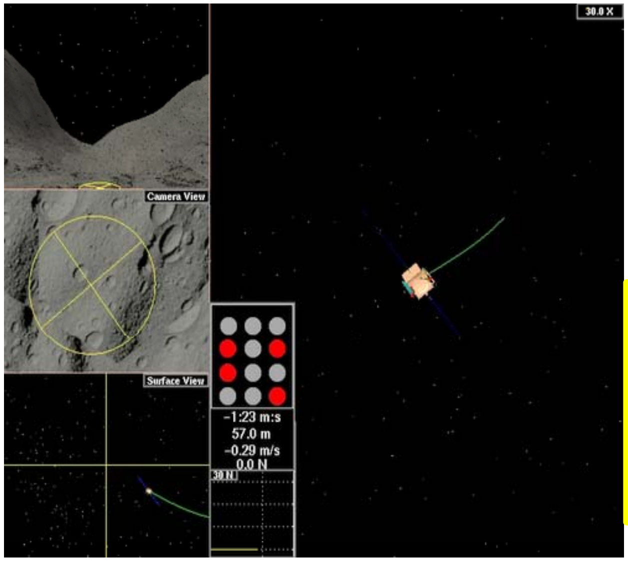
Requires New Technologies Working Together at System-Level

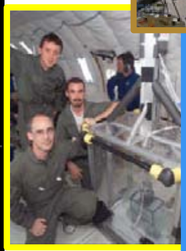
Key Component Technologies for Proximity Operations

- Ground-based Shape, Dynamics and Surface Modeling
  - Eros, Itokawa modeling; Dawn at Vesta upcoming
- Onboard Terrain Relative Navigation
  - With Registered Landmarks
  - With Stereo Odometry
- **AutoGNC**
  - On-board translational and attitude trajectory design, target-relative navigation, and control for descent, contact, and ascent
- Brushwheel Sampler
  - Collects kg’s in seconds of contact
- Sampling Arm and Vault
  - Sample acquisition, transfer
  - Robotic manipulation
  - Drilling





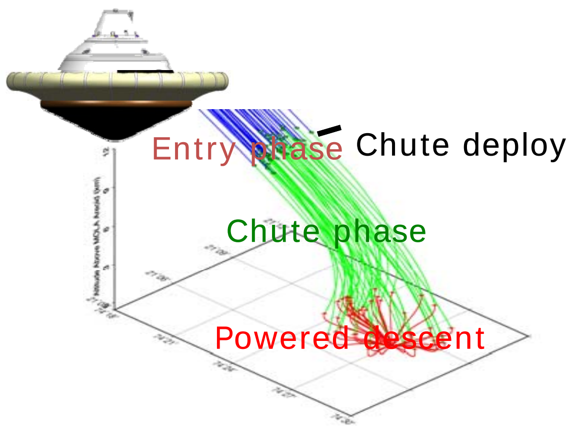




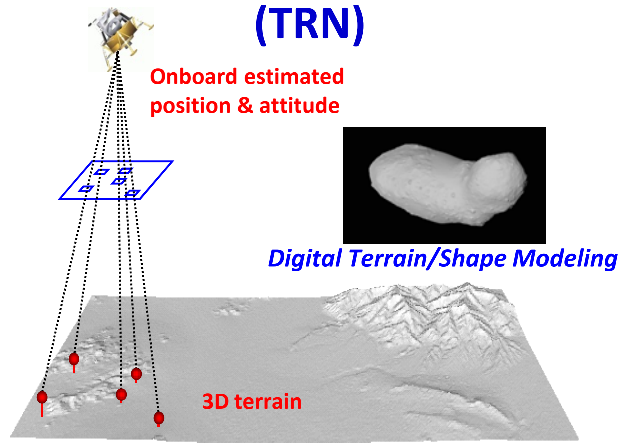
Requires Integrated System-Level Demonstration of Primitive Body Sampling

Key Component Technologies for Next-Generation Entry, Descent & Landing (Precision and Safe Landing)

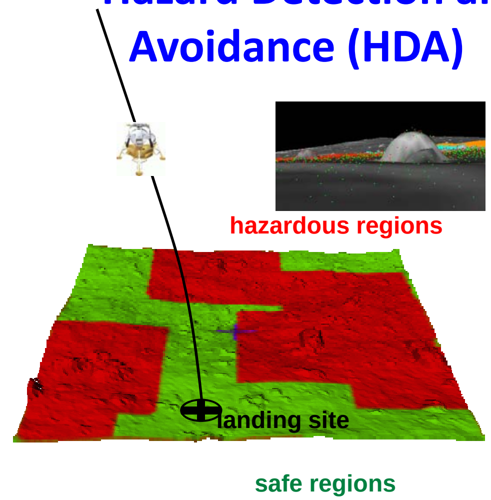
- Advanced Entry Guidance Algorithms



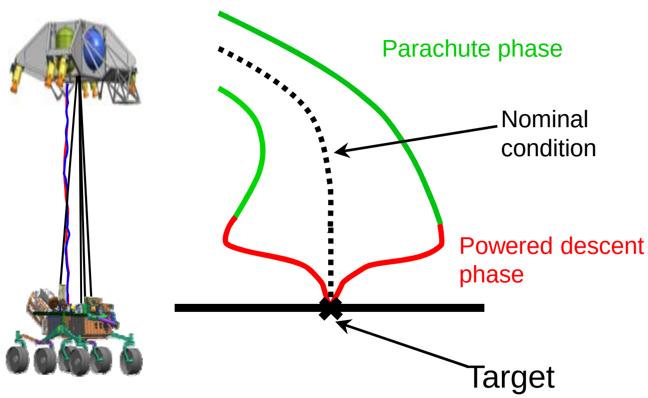
- **Terrain Relative Navigation (TRN)**

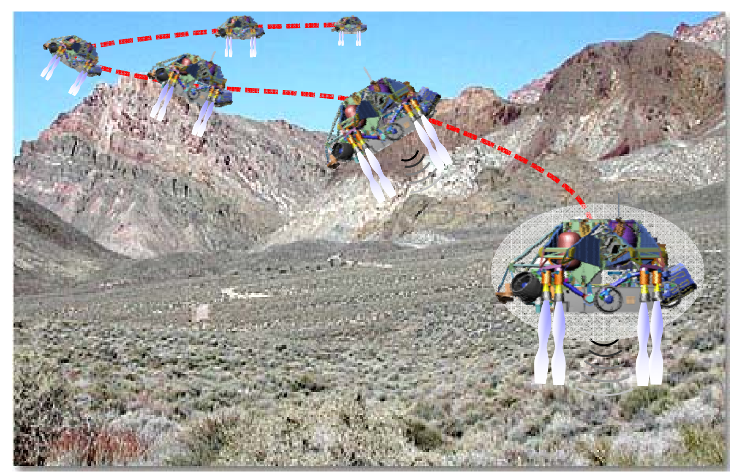


- **Hazard Detection and Avoidance (HDA)**



- Fuel-Efficient, Optimal Powered Descent and Soft Landing Algorithms

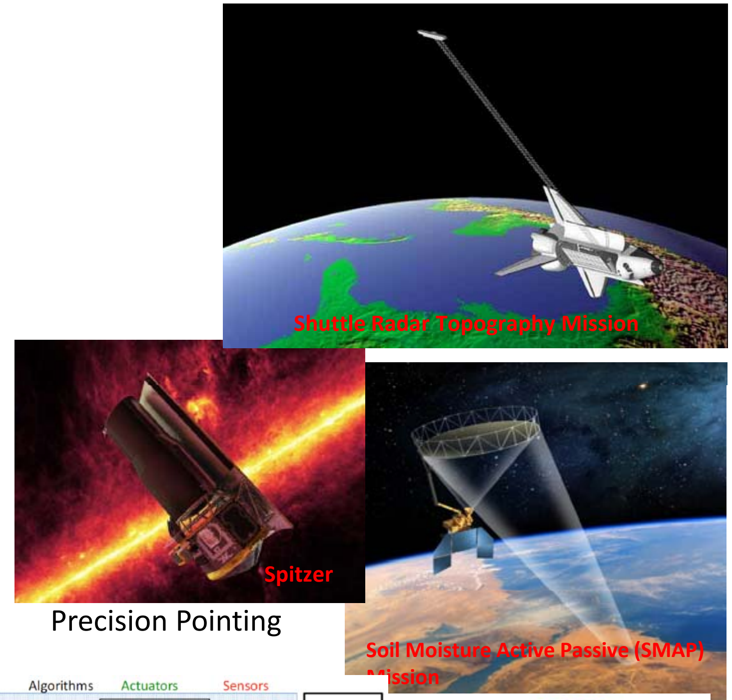




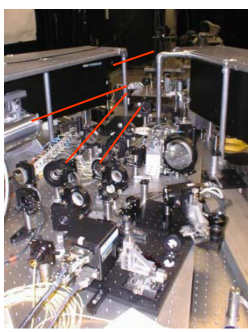
Requires Earth-Based System-Level Demonstration of Terminal Descent

Key Technologies for Precision Spacecraft Pointing and Instrument Control

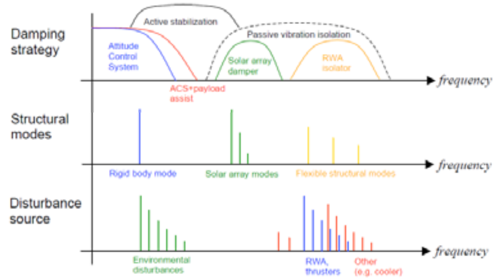
- Multi-stage control systems
- Modeling and Analysis
- Precision sensors and actuators
- Advanced calibration methods
- Disturbance rejection
- Integrated modeling
- Precision Testbed



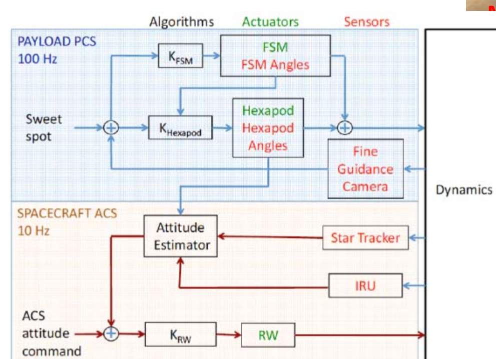
Precision Pointing



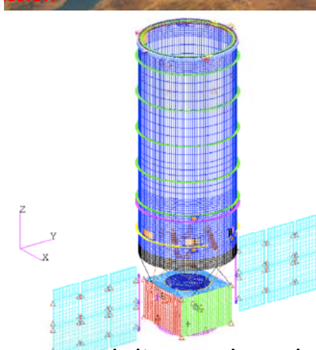
Precision Testbed



Disturbance Rejection



Multi-stage controls



Modeling and Analysis

Requires Integrated, System-Level Open-Architecture Adaptable Hardware-in-the-Loop Pointing System Demonstration

Examples of Key Cross-Cutting Technologies within GN&C and other Disciplines

Flash Lidar

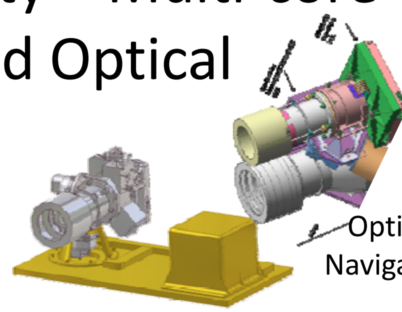
Camera

IMU

Gimbal

- Flash lidar
- Integrated sensors
  - E.g. integrated multi-sensor system of flash lidar, camera, IMU, altimeter, gimbal integrated for terrain relative navigation and hazard detection
- High-precision Star Tracker for beaconless precision pointing
- High-precision Inertial Measurement Unit
- Advanced onboard computing capability – Multi-core
- Shared optical front-end for GN&C and Optical Communication

Multi-core processor



Optical Communication

Optical Navigation

Requires Multi-Disciplinary Demonstration (e.g. communications, GN&C, computation and data handling)

The Need for System Demonstration

System complexity and unprecedented performance requirements lead to the need for System Demonstrations

- Multiple autonomous GN&C capabilities can be demonstrated in a demonstration mission
  - AR&D, Formation Flying, Extended Proximity Operations, Autonomous GN&C
- Multiple functions of integrated sensor capabilities can be demonstrated in a demonstration mission
- Proper combination of Simulations, Ground testbeds, Field-tests, Sub-Orbital and Space-based Flight Test are needed
- Build upon existing GN&C test facilities and establish future space flight opportunities for System Demonstration

System Demonstrations are required to achieve unprecedented system complexity and meet unprecedented performance requirements

Summary

- (Game Changing Nature) Future NASA missions require challenging mission scenarios that will be enabled by Autonomous Real-time Integrated Guidance, Navigation and Control and Autonomous Operation with Reduced Cost
  - Control of spacecraft in reaction to environmental uncertainties
- (Tipping Point) We believe system demonstration will ensure infusion of advanced technologies into future missions
  - Reduces failure risk of technology and increases chance of infusion into missions
- We recommend that a dedicated section summarizing *Autonomous Integrated GN&C* be added to the roadmaps
  - *The GN&C community is enthusiastic to be of service to provide this section*
- (Time Horizon) Roadmaps should include a 10-year development and demonstration plan
  - Key component GN&C technologies were identified for various mission types

THANK YOU

Back-Up

Contents of GN&C Aspects in *Communications & Navigation Roadmap* and *Robotics, Telerobotics, and Autonomous Systems Roadmap*

- **Communications and Navigation Roadmap**
  - **Optical Communications and Navigation**
  - **(Radio-metric-based) Position Navigation and Timing (PNT)**
  - **On-Board Autonomous Navigation and Maneuvering Systems**
    - **Relative and Proximity Navigation:**
    - **Autonomous Precision Formation Flying**
    - **Autonomous Approach and Landing**
- **Robotics, Tele-Robotics and Autonomous Systems Roadmap**
  - **Sensing**
  - **Autonomy**
  - **Autonomous Rendezvous and Docking**
  - **(GN&C-Challenging) Missions**
    - **SOMD/HEOMD Missions, Robonaut, ISS service, Fuel Stations**
    - **ESMD Missions: NEA Precursor, CTV, MMSEV, Humans to HEO, Crewed NEO, Crewed Mars/Phobos**
    - **SMD Missions: MSL/Extended, MSR, Venus-bots, Titan-bot**