The Future of Aerospace Control: Opportunities and Challenges

Gary Balas
Aerospace Engineering and Mechanics
Control Science and Dynamical Systems Center, Co-Director
University of Minnesota
balas@aem.umn.edu
http://www.aem.umn.edu/people/faculty/bio/balas.shtml

Systems and Control: Challenges in the 21st Century

Delft Center for Systems and Control
Technical University of Delft
Delft, The Netherlands
7-8 June 2004

UNIVERSITY OF MINNESOTA

On behalf of the faculties of the University of Minnesota and
colleagues in the Control Science and Dynamical Systems Center,
we congratulate the

Technical University of Delft

on the initiation of the Delft Center for Systems and Control.
May the spirit of collaboration continue between our two
universities, and may you enjoy great success in your new venture.

PRESENTED ON JUNE 8, 2004

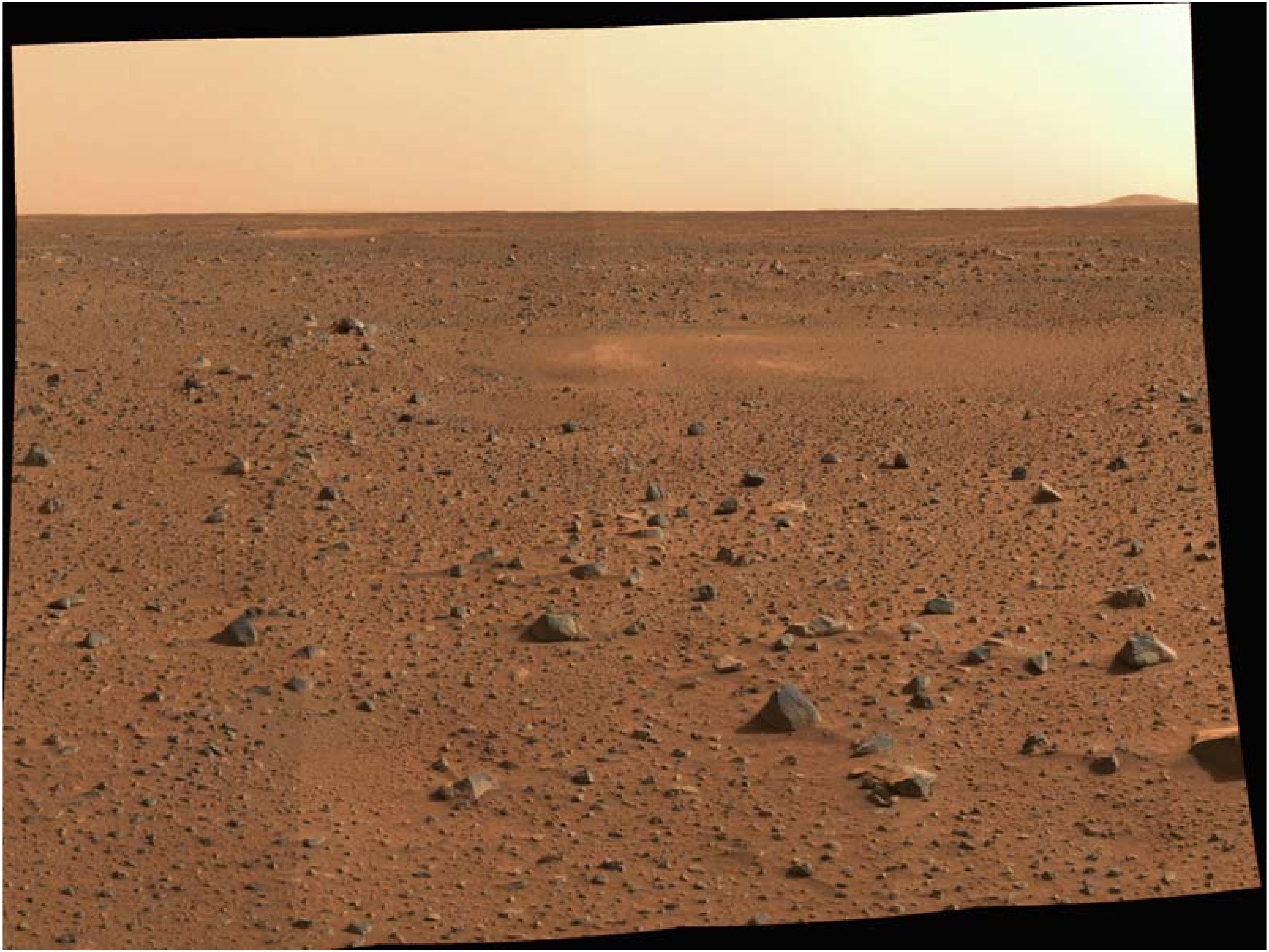
GARY BALAS, CONTROL SCIENCE AND DYNAMICAL SYSTEMS

WILLIAM GARRARD, HEAD, AEROSPACE ENGINEERING AND MECHANICS

TRYPHON GEORGIOU, CONTROL SCIENCE AND DYNAMICAL SYSTEMS

ROBERT BRUININKS, PRESIDENT


Wright Brothers: December 17, 1903



Is there a Future in Aerospace Control?

- Future Directions in Control, Dynamics & Systems (AFOSR, 2002)
- Commission on the Future of the US Aerospace Industry (Nov 2002)
- Future of Aerospace Power, Dr. Clark Murdock (former Deputy Director for Strategic Planning USAF)
- Air Force Office of Scientific Research (AFOSR)
- Unmanned Aerial Vehicles Roadmap 2002-2027, Office of the Secretary of Defense (2002)
- NASA FY2005 Budget Document
  - Autonomous Robust Avionics (AURA)
  - Aviation Safety Program
- Aerospace in 2020 - A European Vision, EU Commission (2002)
- European Space Agency

Future Directions in Control, Dynamics & Systems

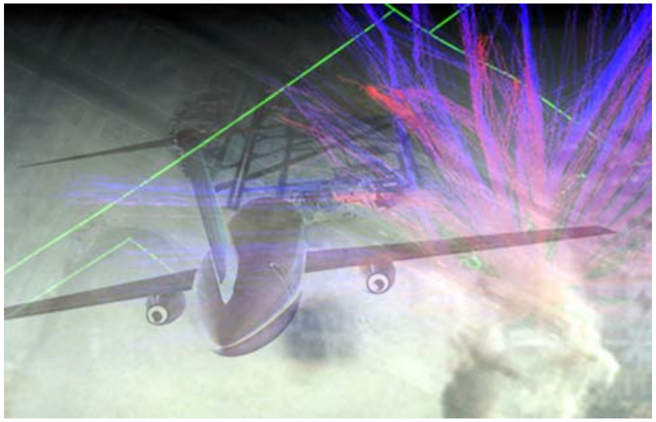
AFOSR sponsored panel to articulate challenges and opportunities for the field (R. Murray, Chair).

Aerospace Themes

- Autonomy
- Real-time, global, dynamic networks
- Ultra-reliable embedded systems
- Multi-disciplinary teams
- Modeling for control
    - more than just $\dot{x} = f(x, u, p, w)$
    - analyzable, accurate hybrid models

Aerospace Technology Areas

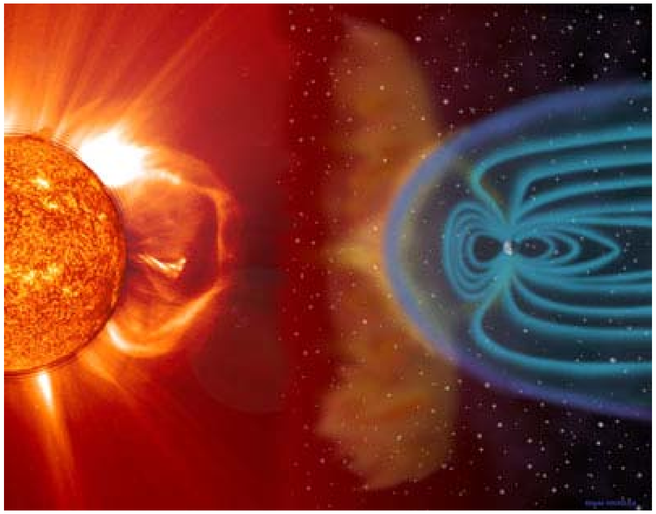
- Air traffic control, vehicle management
- Mission/multi-vehicle management
- Command & control, human-in-the-loop
- Ground traffic control (air & ground)
- Automotive vehicle & engine control
- Space vehicle clusters
- Autonomous control for deep space



Future Directions in Control, Dynamics & Systems

Panel recommendations associated with aerospace included:

- Substantially increase research aimed at integration of control, computer science, communication and networking
- Substantially increase research in control at higher levels of decision making, moving towards enterprise level systems
- Maintain support for theory and interaction with mathematics



DARPA Software Enabled Control

- ***Active State Models: Prediction & Assessment***
  - Dynamically exploit on-line system and environmental data to improve reference models
  - Prediction and rapid damage assessment
- ***On-Line Control Customization: Adaptation***
  - Control re-parameterization and reconfiguration during operation due to environmental disturbances, interference, and damage
  - Accommodate dynamic coordination requirements
- ***Coordinated Multi-Modal Control***
  - Achieve global stability, maximize system and mission performance
  - Provide joint fault detection, isolation, and recovery
  - Enable distributed control implementation for physically separated components
- ***Open Control Platform (OCP): Software***
  - Reusable control middleware and tool support
  - Parametric open systems framework necessary to support SEC active state model, hybrid/coordinated, and adaptive multi-modal control
- ***High Confidence Software Control Systems***
  - Assure safety and reliability under fault conditions
  - Design for verification, validation, and certifiability

http://www.darpa.mil

Commission on the Future of the U.S. Aerospace Industry Recommendations (2002)

- Increased public funding of long-term research and R&D infrastructure.
  - Information technology, Propulsion and power, Noise and emissions, Energy sources, Human factors and Nanotechnology.
  - Establish national technology demonstration goals for Space and Aviation.
- U.S. aerospace industry should take a leading role in applying research to product development.
- Deploy a new, highly automated air traffic management system.
- Revitalize U.S. space launch initiative and next generation communication, navigation, surveillance and reconnaissance capabilities.
- Prioritize and promote aerospace.
- Reverse the decline and promote the growth of aerospace education.

Recommendations

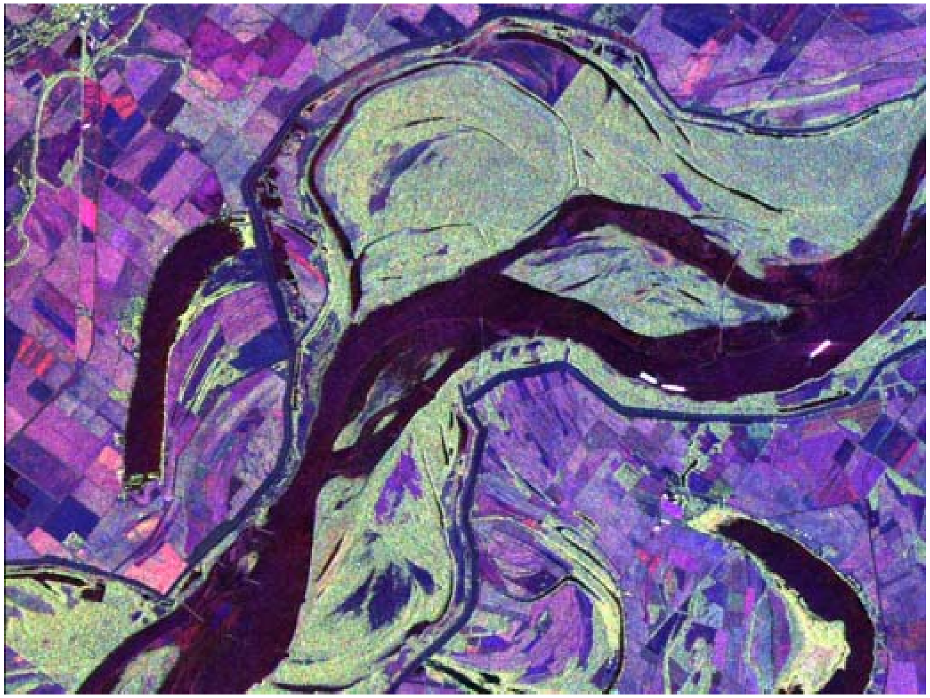
Information technology

- Modeling and simulation, high confidence systems
- High bandwidth communication, large scale networks
- Reliable, robust and fault-tolerant software

Propulsion and power

- Subsonic,supersonic and hypersonic flight
- Access to space
- Noise and emissions
- Breakthrough energy sources

Recommendations



Human factors

- Human centered design
- Automation

Nanotechnology.

- Customized materials
- Revolutionize aerospace vehicle structure design
- Morphing airframes
- Small satellites

Transformation of USAF: 2000-2020

2000 Capabilities

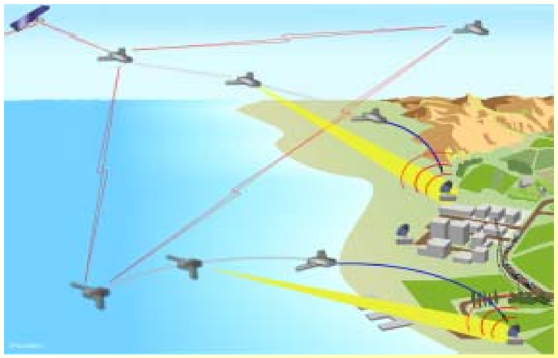
- Stealth, Standoff All-Weather, Precision Guided Weapons, Small Smart Bombs, JSTARS, Real-time Info to cockpit, LOCASS (UAV)

2020 Capabilities

- UAVs, Hyper-velocity weapons, Numerous low cost sensors, Real-time adaptive systems, Information and space operations, Nanotechnology, Micro-Satellites, Space maneuvering vehicles.

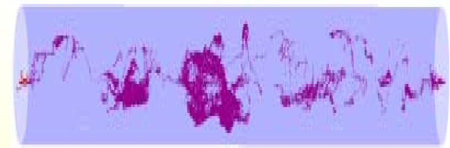
AFOSR Dynamics & Control Research Areas

Enterprise Level Systems

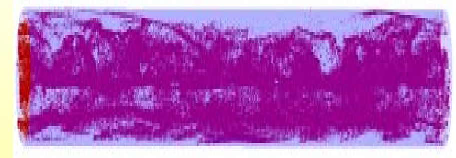


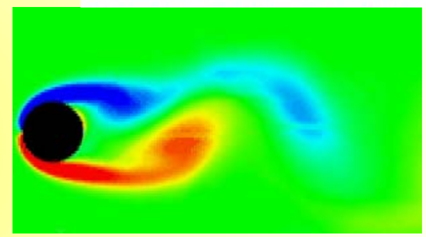
Intelligent Autonomy

Uncertainty Management



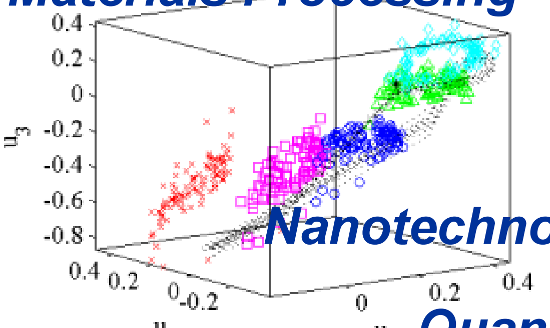
Aeroengines





Aerodynamic Flow

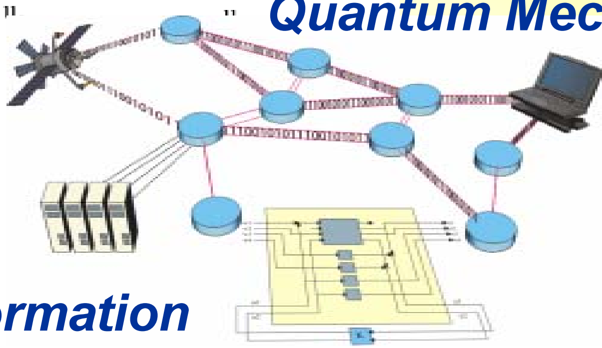
Materials Processing

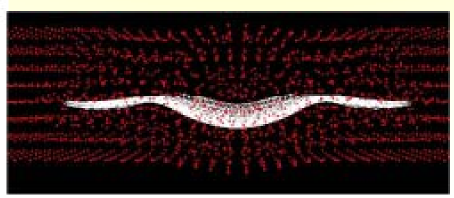


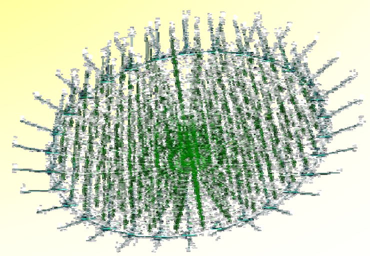
Nanotechnology

Growth areas: Control for high risk, long range multidisciplinary applications

Quantum Mechanics







V&V

Optics

Electromagnetics

Imaging & Vision

Information & Networks

Bio-inspired Systems

Multi-scale Systems

Approved for public release; distribution is unlimited

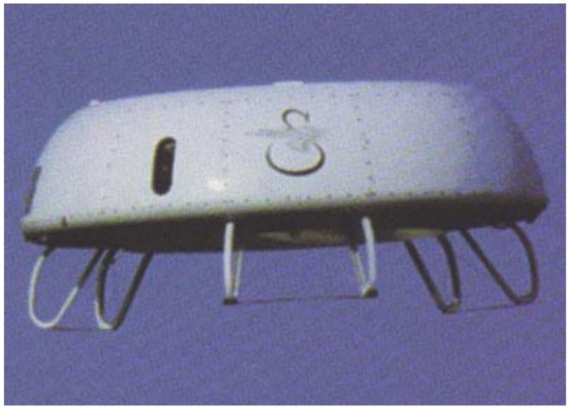
AFOSR Research Community Impact

Future Air Force and DoD needs can not be met without the innovative ideas of the Guidance & Control research community!

- **Uncertainty and constraint management for complex systems**
- **Smart, reconfigurable control system design**
- **Novel control for aerodynamic systems**
- **Cooperative control in dynamic, uncertain, adversarial environments**
- **Integrated control, computing and communications for robust networked systems**
- **Multi-resolution modeling, design and analysis**
- **Bio-inspired guidance, imaging and control**
- **Innovative control for unconventional applications**

Lt Col Sharon Heise, USAF, PhD, AFOSR, sharon.heise@afosr.af.mil

Uninhabited Aerial Vehicles (UAVs)

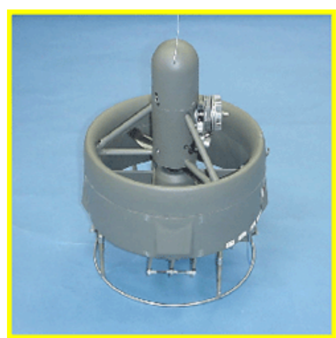


Neptune

UCAV

Global hawk

Organic Air Vehicle



Predator

Uninhabited Aerial Vehicles (UAVs)

- US Department of Defense (DoD) has 20 UAVs in service or under conceptual development:
- DoD will have invested over $10 Billion in UAVs by 2007*.
- DoD UAV systems will grow to 300 by the year 2010*.
- 32 Nations are developing more than 250 models of UAVs*.
- Over 60 small and Micro UAV programs are under way through out the world.

* DoD Unmanned Aerial Vehicle Roadmap: 2002-2027

UAV Technical Issues

Micro (0.5-2’ wingspan, .05-5#)

- Power
  - Batteries
  - Communication
- Platform
  - Low Reynolds #
  - Flapping
  - Sensors
  - Configuration
- Capability
  - Endurance
  - Payload
  - Control

Micro & Small (2-10’ wingspan, 1-200#)

Brains

- Situational awareness
- Intelligent autonomy
- Teaming
- Cooperation

Systems

- Navigation
- Sensor grids
- Noise
- Cost

Operation

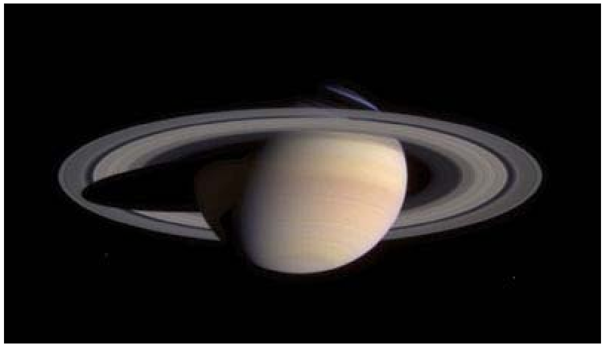
- Operator
- Drop & forget
- Expendable
- Con-Ops

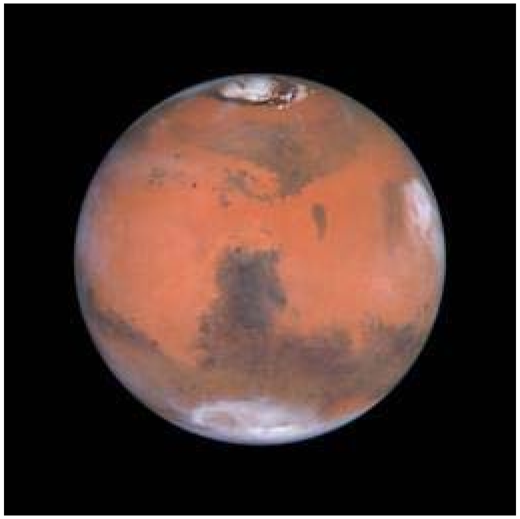
UAV Challenges and Opportunities

- High performance, robust, inner-loop control
  - Constraints, expense
  - Underactuated control systems
  - Rapid prototyping, automated design and analysis
  - Unmodeled aerodynamic effects
- Adaptive, robust trajectory tracking
  - Varying accuracy and length of preview information
  - Constraints, limitations
  - Mission level performance criteria
  - Robust to environment, damage, etc.
- Autonomous operation
- Reliability, fault tolerance, reconfiguration
- Flight certification, verification and validation

NASA Future Plans (2005, $16.2B)

Space Science ($4.1B)
- Solar system exploration
- Mars and lunar exploration
- Structure of the universe





Earth Science ($1.5B)

Biological and Physical Research ($1B)

Aeronautics ($0.9B)
- Aviation safety and security
- Air transportation system, emissions and efficiency
- Flight system demonstrations, rotorcraft research

Education ($0.2B)

Exploration Systems ($1.8B)
- Human and robotics, space transportation

Space Flight ($6.7B)
- International Space Station, Space Shuttle,

S112E05823

NASA Aviation Safety Program

Christine M. Belcastro, Ph.D., NASA Langley, christine.m.belcastro@larc.nasa.gov

VHM & CUPR Integration

Control Upset Prevention & Recovery

Upset / Failure Detection & Accommodation

Upset Recovery

Enhanced Dynamics Models

VHM & CUPR Management

Vehicle Health Management

Propulsion System

Flight Systems

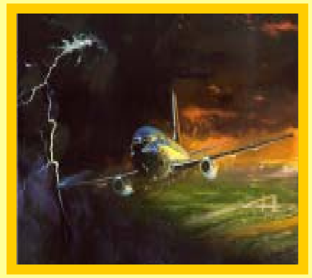
Airframe Structure

Integrated Technologies for Adverse & Upset Conditions

Integrated Technologies Validation

Off-line Crew Training, & Maintenance & Data Trending

On-line Systems to Improve Situational Awareness & Control



Adverse Conditions:

- *Faults / Failures / Damage*
- *Atmospheric Disturbances*
- *Crew Input Errors*

Upset Conditions:

- *Flight Beyond Normal Envelope*
- *Unstable Modes of Motion*
- *Out-of-Control Motion*

Integrated Crew Interfaces

On-line Crew Notification & Cueing

Existing Warning Systems

Integration of Notification, Warning,& Cueing Strategies

Vehicle Health Management

Control Upset Prevention & Recovery

FCS Software/Hardware Integration

Reliable, Retrofittable Implementations

Integrated VHM & CUPR

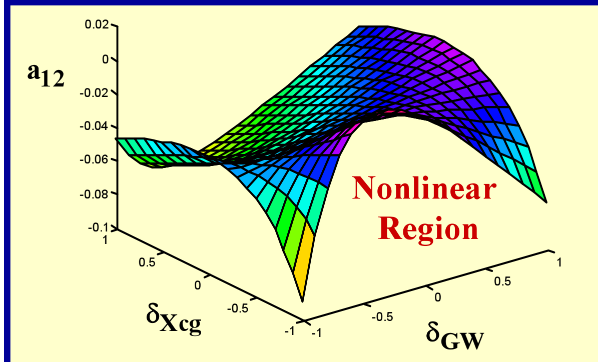
Hardware / Software Implementation

Vehicle Integration

Flight Certification, Verification & Validation

Analysis

Robustness



Uncertainty Scenario i

Reliability

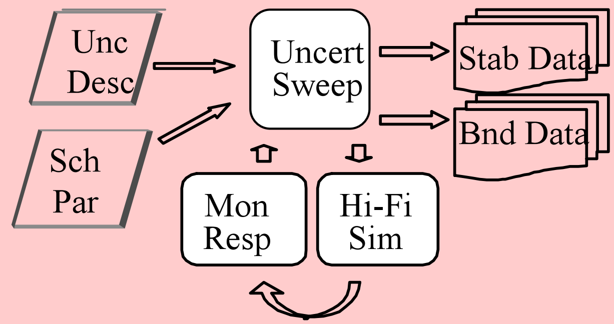
System Failure Rate & Coverage

Decision & Interface Algorithms

- Detect & Ident Algms
- Estim & Predict Algms
- Guid & Cont Algms

Simulation

Guided Monte Carlo



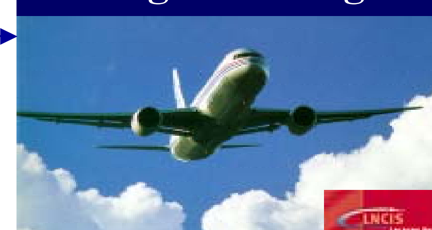
Real-Time Piloted

Experiments

SAFETI Lab

- Aircraft Simulation
- Flight Hardware
- Failures & Errors
- Environment Simulation

Flight Testing



GARTEUR FM(AG11, 1999-2002)

"New analysis techniques for clearance of flight control laws,"

NASA AURA PROJECT

Autonomous Robust Avionics (AURA)

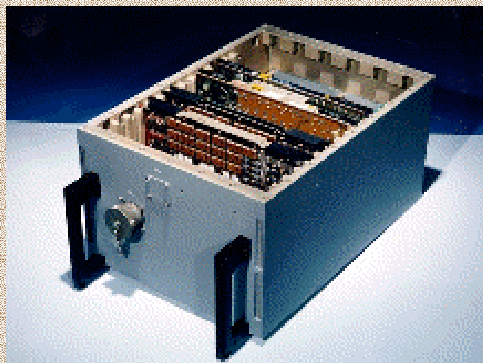
Smart Aircraft and Autonomous Control

- Enable aircraft to fly with reduced or no human intervention, to optimize flight over multiple regimes, and to provide maintenance on demand towards the goal of a feeling, seeing, sensing, sentient air vehicle

Jim Burley, Project Manager James.R.Burley@nasa.gov, ph. 757-864-2008

AuRA 5-year Project Scope

Integrated Vehicle Systems Management



Adaptive Optimal Flight Control

Intelligent Mission Management

UAV Sector

Autonomous Vehicle Operations

PAV Sector

Rotorcraft Flight Controls

RC Sector

Sentient Air Vehicles

Sector independent

AuRA Deliverables *UAV Sector*

- Robust, fault tolerant avionics architecture…both hardware & software
- Autonomous on-board detection, diagnostic & prognostics system for vehicle health mgmt
- Reliable flight control system capable of autonomous reconfiguration in the presence of multiple system failures
- Intelligent mission management system capable of dynamic re-tasking and executing multiple missions using the same architecture
- Coordinated/interoperable intelligent mission management system capable of being implemented on multiple different UAV's

European Aeronautics: "A Vision for 2020"

Two great prizes to win:

- A world-class European air transport system that meets society's needs
- Global leadership for the European aeronautical industry

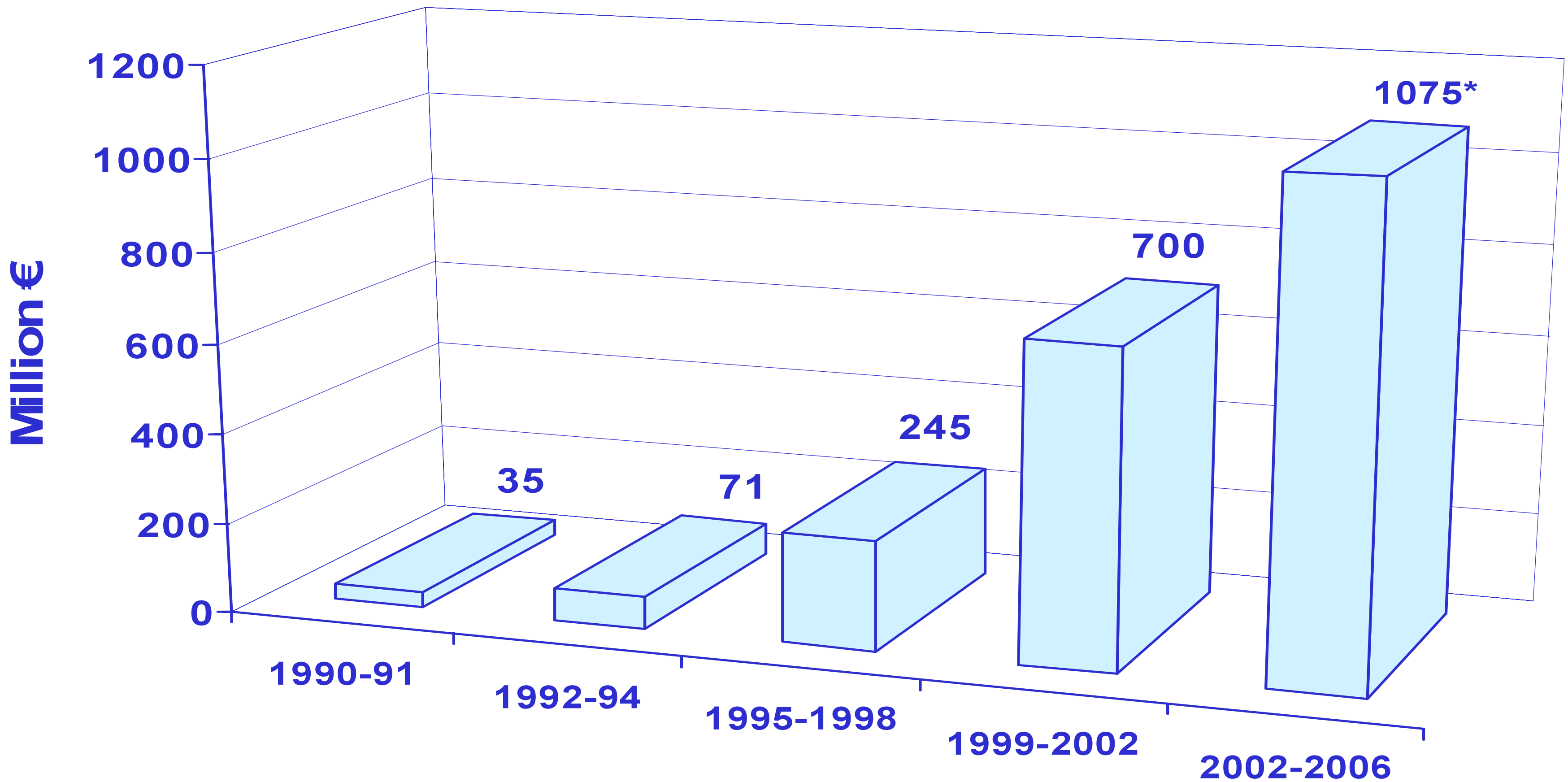
Doc. Available: http://europa.eu.int/comm/research/growth/aeronautics2020/en/index.html

EU Keys to Success

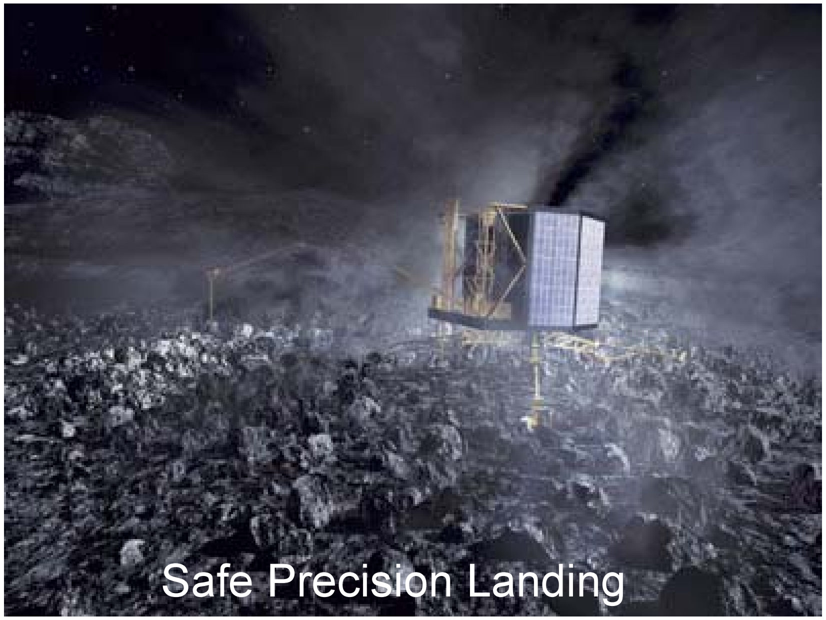
- Maintaining consensus among aeronautics stakeholders (industry, airlines, airports, air traffic service providers, governments, research institutes and academia).
- Better co-ordination between EU, national and regional research programmes.
- Optimising research facilities to sustain public and private networks of excellence.
- Fostering synergies between defense and civil sectors.
- Education policy to ensure first-class, well-trained and suitable qualified people.

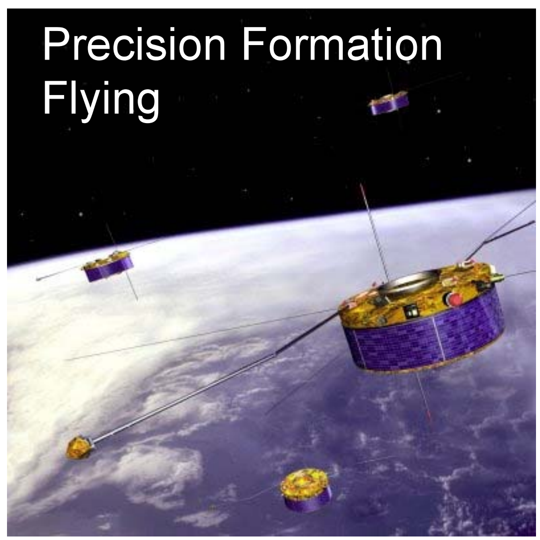
R&TD Funding for Specific Aeronautics Research on EU Level

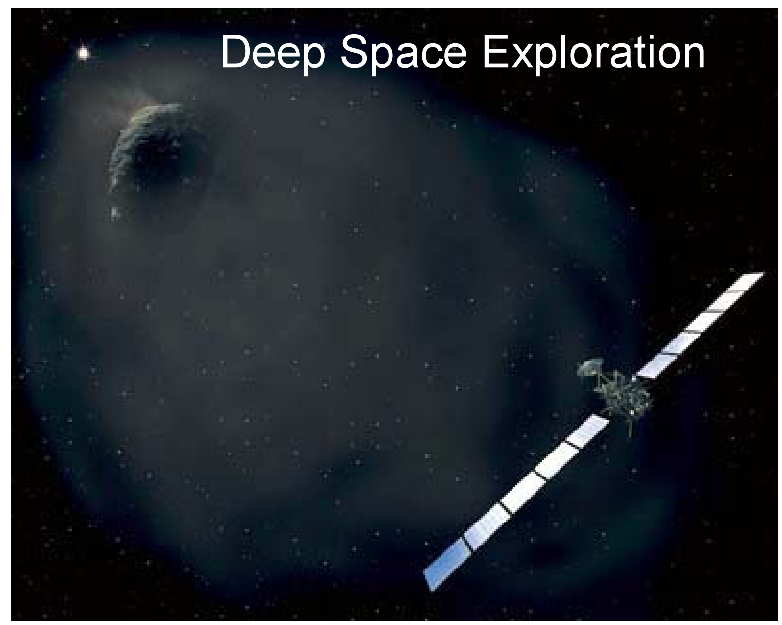
**Budget 2002 - 2006 for Aeronautics, Air Transport &Space*



European Space Agency: New Missions







ESA: Novel Control Techniques

Requirements

- Safety, Reliability, Autonomy
- Multi-mission
- Short turn around time
- Operational costs

Features

- Time-varying, uncertain, precision
- Distributed
- Constrained maneuvers
- Terminal point guidance

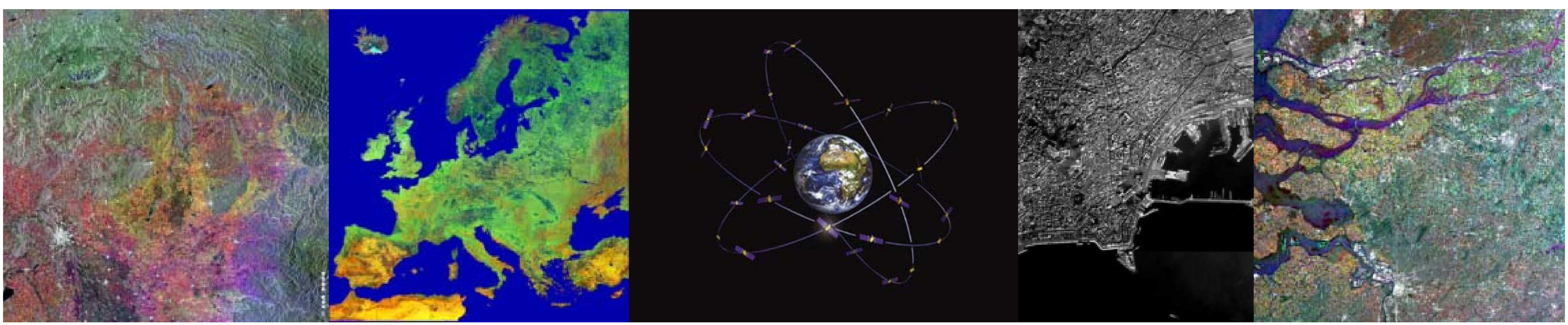
Control Techniques

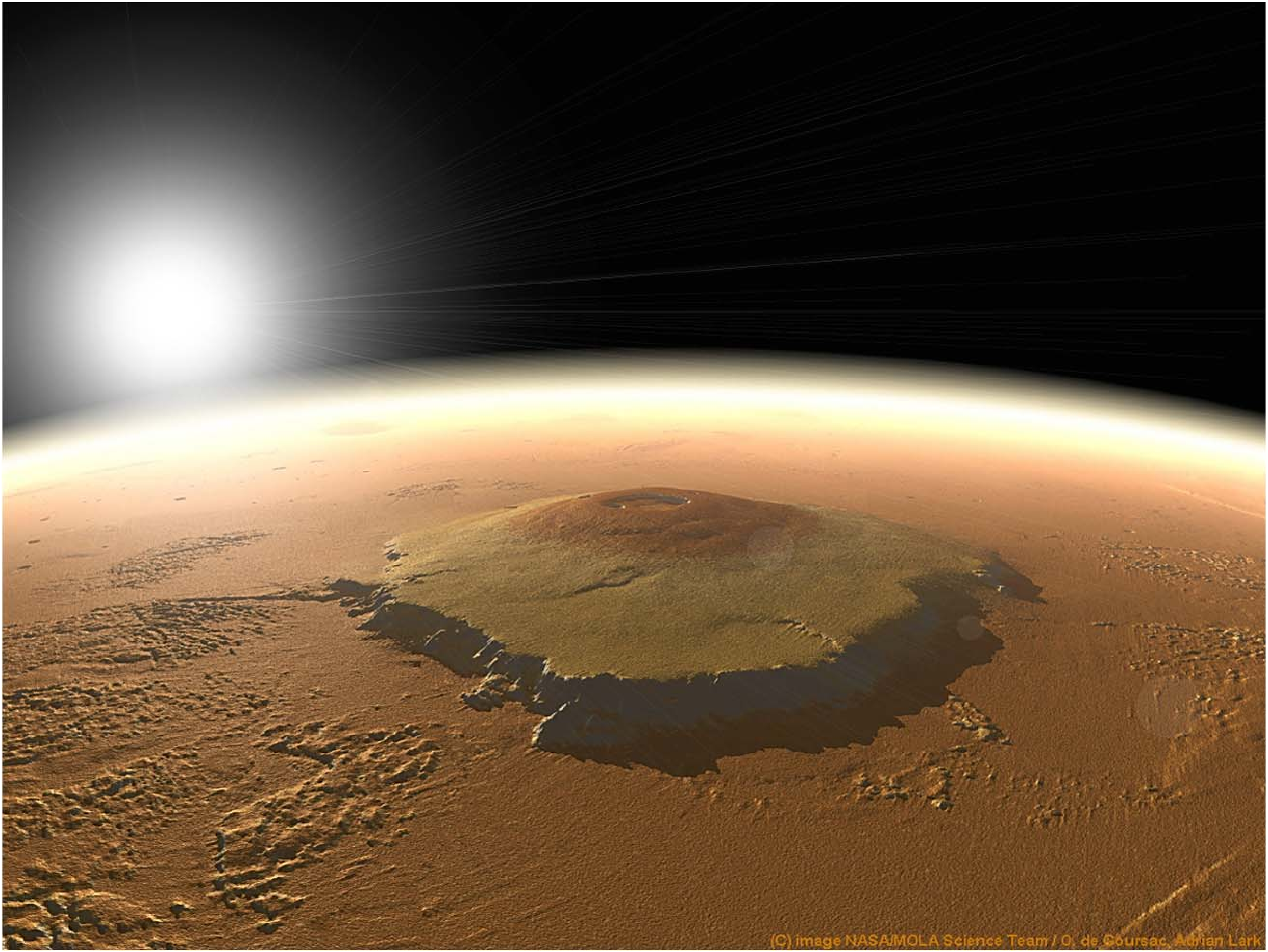
- Robust Control
- Linear Parameter Varying (LPV)
- Model Predictive Control
- Robust Estimation
- Analytical redundancy
- System identification
- Clearance techniques

The Future of Aerospace Control

Aerospace Systems and Control (TU Deflt) is poised for tremendous growth over the coming decades:

- Autonomy
- Real-time, embedded adaptive control systems and software services infrastructure
- Distributed sensing and actuation systems
- Systems level design and analysis
- Software certification, tools, guidelines, & practices




(C) image NASA/MOLA Science Team / O. de Goursac, Adrian Lark