



NASA LaRC Autonomy Incubator



B. Danette Allen
December 2014



Autonomy



The 'A' Word

Heavily quoted in <http://aviationweek.com/commercial-aviation/certifiable-trust-required-take-autonomous-systems-past-unmanned> from presentations in a Special Session on Autonomy at Aviation 2014.

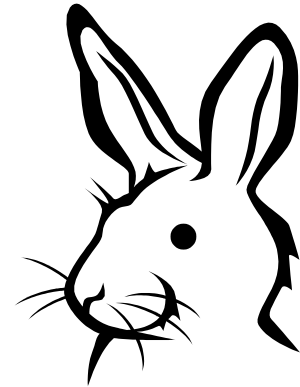
The 'A' Word





Down The Rabbit Hole: Definitions

- Etymology: from the Greek,
 - αὐτόματος (automatos) “self-moving, self-acting, spontaneous”),
 - αὐτονομία (autonomia), from αὐτός (autos, “self”)+νόμος (nomos, “law”).
- au·ton·o·mus
 - Definition: Acting on one's own or independently; acting without being governed by parental or guardian rules.
 - Synonyms: Self-governing, intelligent, sentient, self-aware, thinking, feeling, self-directed
 - Machine-based **decision-making**
- au·to·ma·tik or au·to·ma·shun
 - Definition: Done out of habit or without conscious thought
 - Synonyms: perfunctory, thoughtless, instinctive
 - Machine-based **execution**





Relegation → Delegation → Self-Awareness

- **Automation/automated process:** Replace manual process with software/hardware that follow a programmed sequence. Automation is a **relegation** of task(s).
- **Autonomy:** Allows participants to operate on their own, based on internal goals, with little or no external direction. Participants can be human or machines. Autonomy implies self-governance and self-direction. Autonomy is a **delegation** of responsibility to the system to meet goals.
- **Autonomicity¹:** Builds on autonomy technology to impart **self-awareness** to system/mission, which includes configuration, optimization, healing, protection. These are enabled by self-awareness, self-situation, self-monitoring, and self-adjustment

¹Truskowski, W., Hallock, L., Rouff, C., Rash, J., Hinchey, M.G., Sterritt, R. (2009) Autonomous and Autonomic Systems: With Applications to NASA Intelligent Spacecraft Operations and Exploration Systems



Another Rabbit Hole: Scales of Autonomy

Sheridan Scale

- Computer offers no assistance; human does it all
- Computer offers a complete set of action alternatives
- Computer narrows the selection down to a few choices
- Computer suggests a single action
- Computer executes that action if human approves
- Computer allows the human limited time to veto before automatic execution
- Computer executes automatically then necessarily informs the human

Credit: MITRE

Decide	Act
computer performs ranking tasks. The computer performs final ranking, but does not display results to human.	Computer executes automatically and does not allow any human interaction.
computer performs ranking tasks. The computer performs final ranking and displays a reduced set of options without displaying	Computer executes automatically and only informs the human if required by context. It allows for

to act to *make you better at*

Human

Supervisory
Control

Fully
Automatic

Chasm

Autonomy



- Algorithms respond to input data without human input or possibility of Override
- Take predetermined Action
- Control Theory - Feedback loops

- Non-deterministic
- Judgment
- Emergent behavior
- Perception & Reasoning

trade spaces, autonomy assist program managers, officers and developers in systems. It would also impact of a particular are discussed further in t

2	Human is the prime source for gathering and monitoring all data, with computer shadow for emergencies.	Human is the prime source of analysis and predictions, with computer shadow for contingencies. The human is responsible for interpretation of the data.	The human performs all ranking tasks, but the computer can be used as a tool for assistance.	Human is the prime source of execution, with computer shadow for contingencies.
1	Human is the only source for gathering and monitoring (defined as filtering, prioritizing and understanding) all data.	Human is responsible for analyzing all data, making predictions, and interpretation of the data.	The computer does not assist in or perform ranking tasks. Human must do it all.	Human alone can execute decision.



NASA's Missions and Humans

- Historic and current ATM and space exploration paradigms are human-centric. Humans are aided by automation to make intelligent decisions and intervene as needed, especially in off-nominal situations.



Five of the seven Apollo missions that attempted to land on the Moon required real-time communications with controllers to succeed.



NASA's Missions and Humans and Automation

- Historic and current ATM and space exploration paradigms are human-centric. Humans are aided by automation to make intelligent decisions and intervene as needed, especially in off-nominal situations.



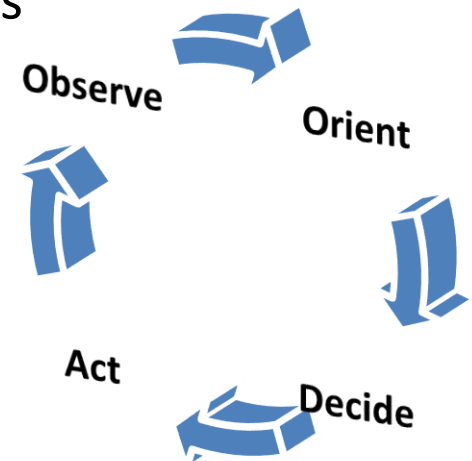
Things have changed but...
humans are still hovering around monitors waiting to intervene.



Bridging the Chasm:

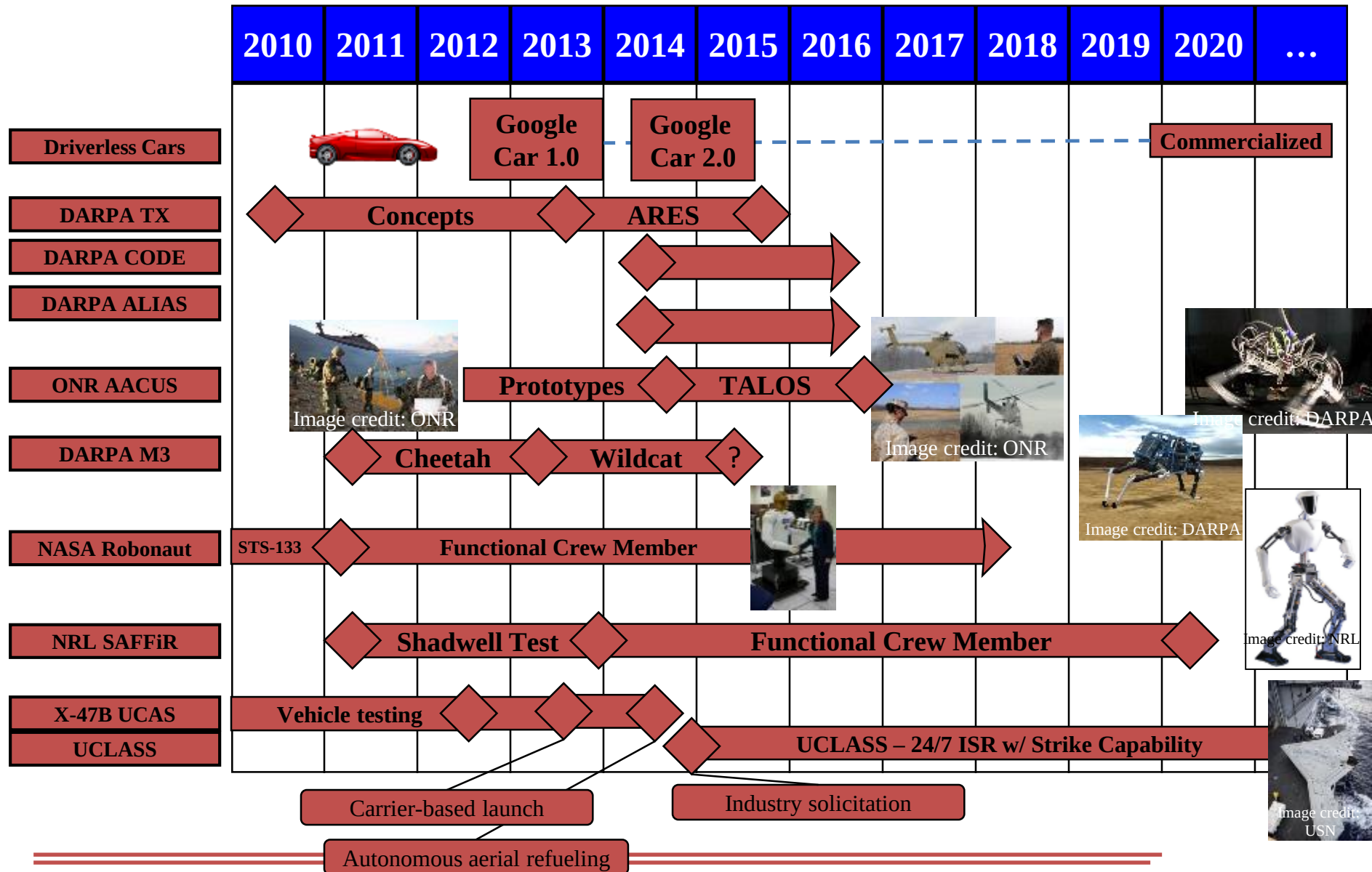
NASA's Missions and Autonomy

- As we move towards On-Demand Mobility (ODM) in aeronautics and beyond LEO and L2 in space exploration, **human intelligence** applied to supervision, control, and intervention of operations will **no longer** be **viable** due to system/mission complexity, short reaction/decision time, comm delays, distance, hostile environments, and close proximity.
- This requires that we design, build, and test systems capable of responding to expected and unexpected situations with **machine intelligence** similar to that of humans. This means
 - trusted and certified-safe systems capable of
 - sensing and perception
 - situation assessment/awareness
 - decision-making
 - taking action
 - and knowledge acquisition (learning)





The Autonomy Frontier



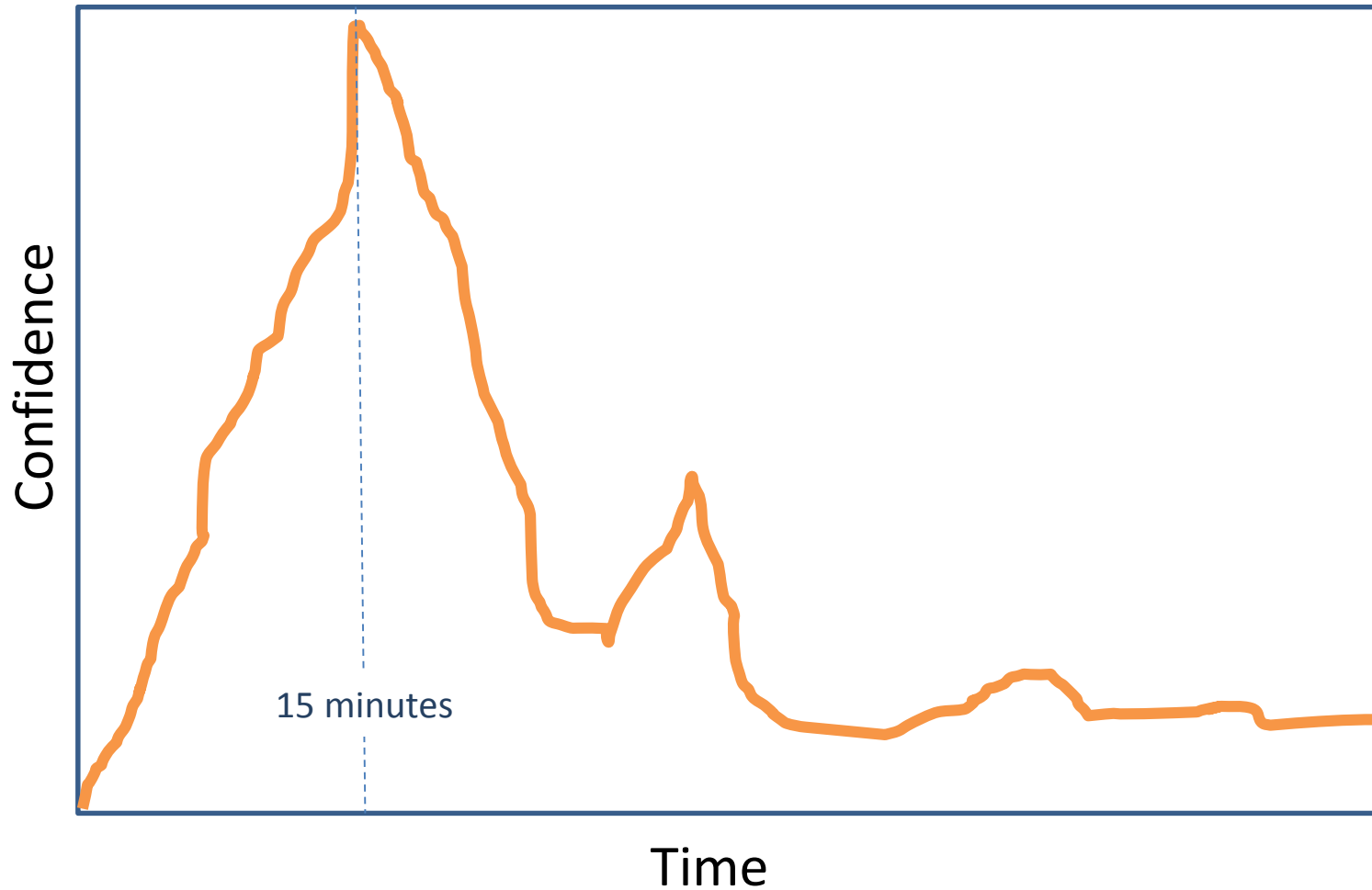


Why Autonomy Seems Easy...

- It's a simple problem to relate to
- It has a little bit of everything
 - Mechanics
 - Electronics
 - Programming
 - Psychology
 - Signal Processing
 - Math
 - ...



The 15-Minute Effect



BD Allen, G Bishop, G Welch, "Tracking: Beyond 15 Minutes of Thought"
Proceedings of the 28th Annual SIGGRAPH Conference, 2001.



Why Don't You Just...

- Negotiate mission?
- Swarm?
- Self-separate?
- Fuse multiple sources of information?
- Leave the human in the loop?
- Put the human on the loop?
- Pull the human out of the loop?
- Detect a target
- Find the bird...



Finding the Bird

Credit: <http://xkcd.com/1425/>



IN CS, IT CAN BE HARD TO EXPLAIN
THE DIFFERENCE BETWEEN THE EASY
AND THE VIRTUALLY IMPOSSIBLE.

In the 60s, Marvin Minsky assigned a couple of undergrads to spend the summer programming a computer to **use a camera to identify objects** in a scene. He figured they'd have the problem solved by the end of the summer. Half a century later, we're still working on it.



At 15 Minutes

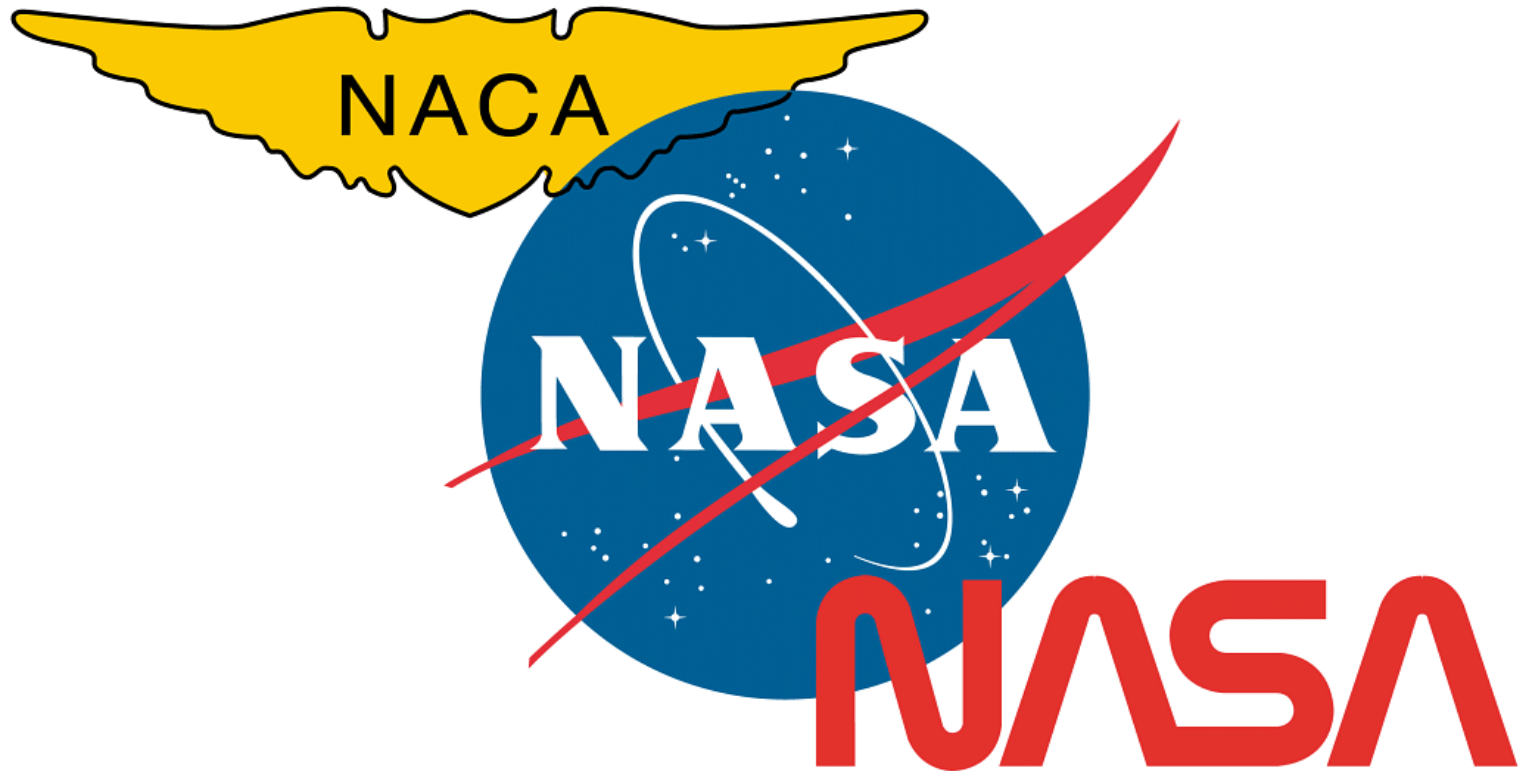
Autonomy

“Math is Hard”

A large blue arrow with a black outline, pointing diagonally upwards from the phrase “Math is Hard” towards the word “Autonomy”.



Beyond 15 Minutes





Why Autonomy?

- **Effectiveness**
- Efficiency
- Assistance
- Companionship
- The “ilities”
 - Adaptability
 - **Affordability**
 - Accessibility
 - Agility
 - Flexibility
 - Mobility
 - Scalability
 - Reliability
- **Safety**

MISSING DRONE



Answers to ‘Heidi’...
(or not)



Technology and Humans and Safety



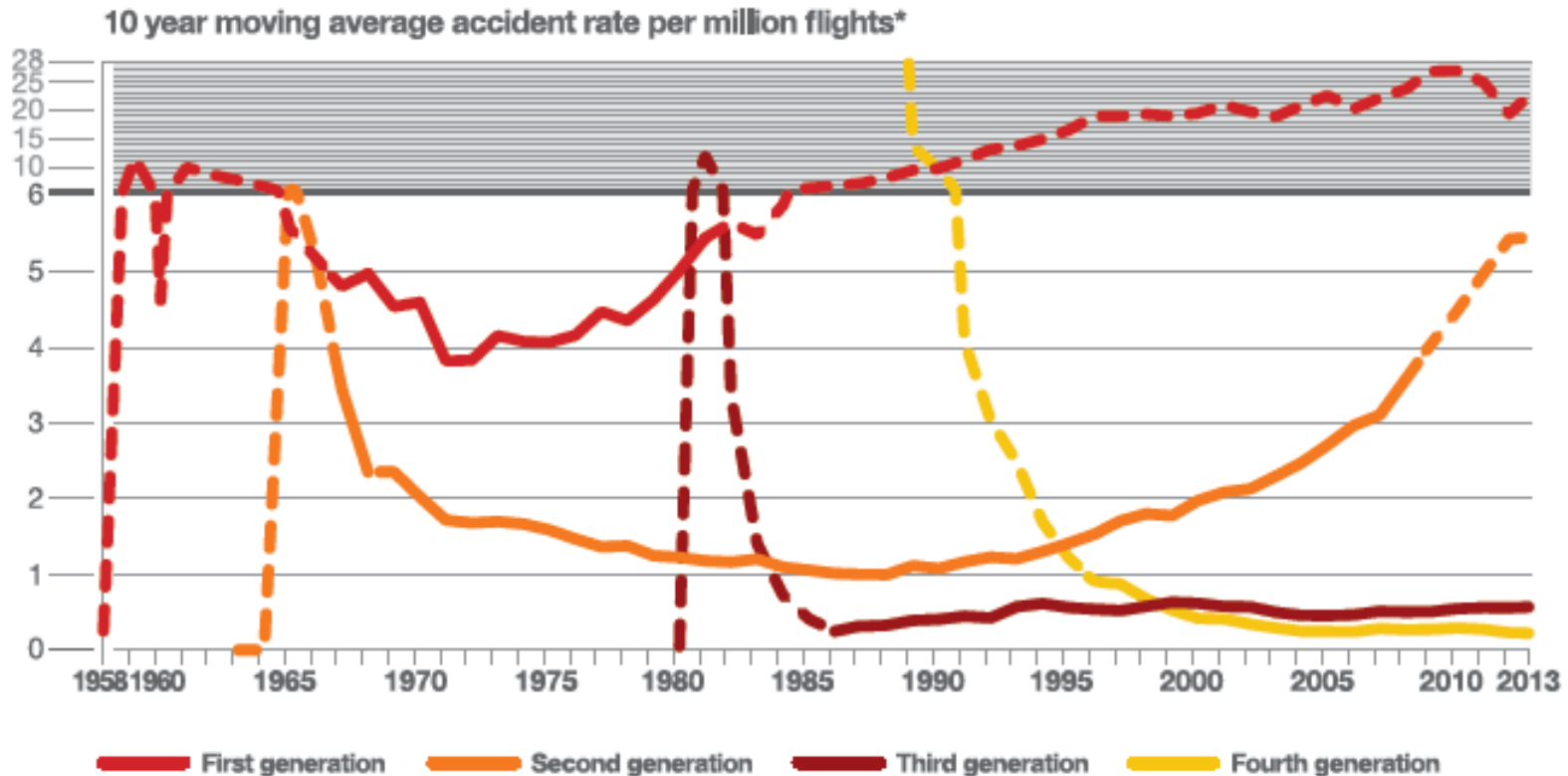
Image credit: NASA



New Technologies and Safety

Historically, new technologies increase accident rates...

Commercial Aviation Accidents 1958 – 2013 A Statistical Analysis; (Airbus study)



*Below 10 years of operation, the moving average is based on the number of years of operation.

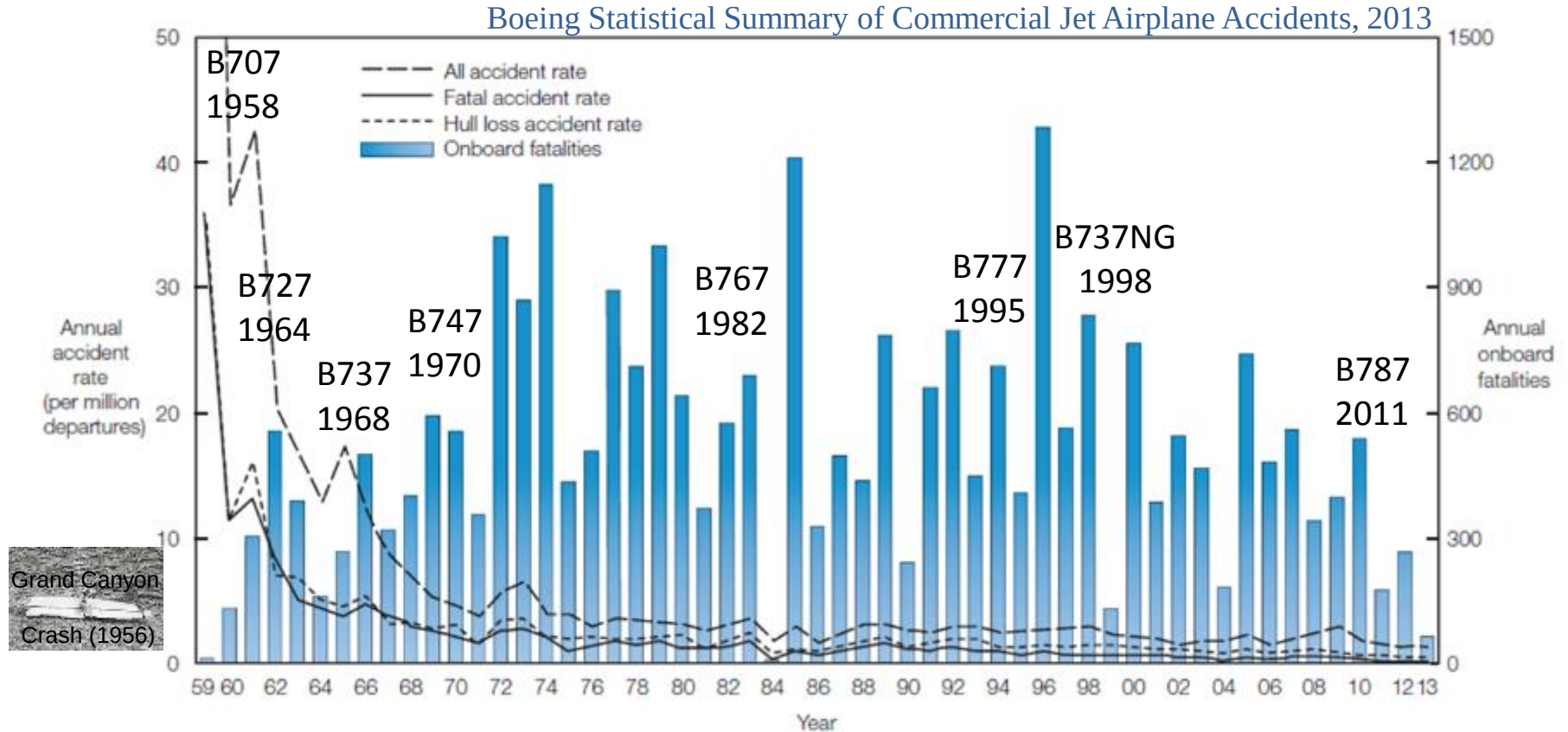
Hull loss

...but with experience and continuous improvement it gets better.



New Technologies and Safety

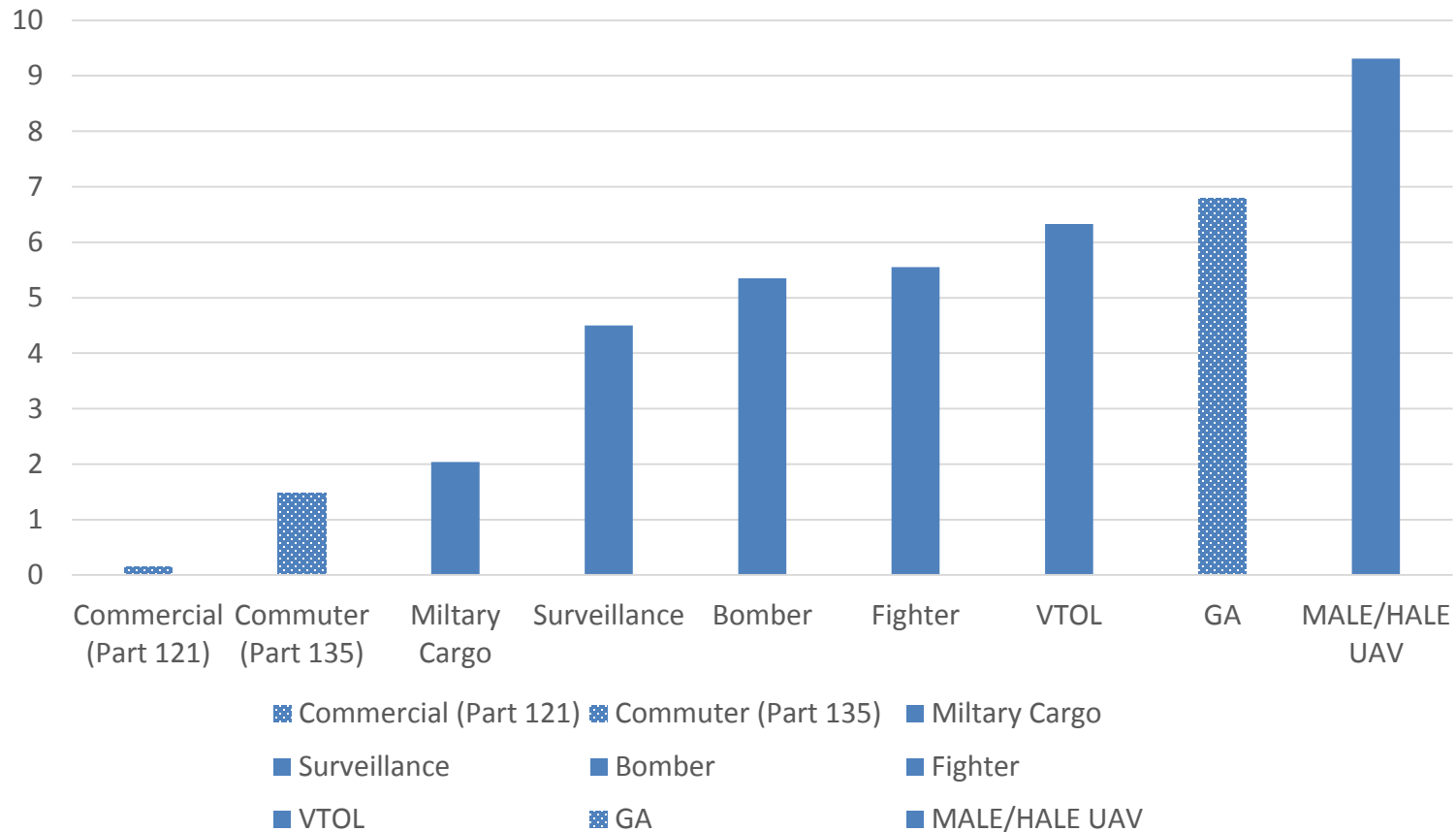
Historically, new technologies increase accident rates...



...but with experience and continuous improvement it gets better.

Autonomous Systems Are No Exception

Historically, new technologies increase accident rates...
Accidents per 100,000 Flight Hours



...Unmanned/Manned Ratio: 2.13 after 5 years, 1.26 after 15 years.

<http://www.bloomberg.com/news/2012-06-18/drones-most-accident-prone-u-s-air-force-craft-bgov-barometer.html>

NTSB Annual Safety Report (2013)



Autonomy...

enabled by a diverse portfolio of
new technologies...

that will enable new missions by...

increasing affordability

Increasing efficiency

increasing safety



Autonomy...

enabled by a diverse portfolio of
new technologies...

that will enable new missions by...

increasing affordability
Increasing efficiency
increasing safety



June 2014 NRC Report

Autonomy Research for Civil Aviation: Toward a New Era of Flight

PREPUBLICATION DRAFT – Subject to Further Editorial Correction

Autonomy Research for Civil Aviation

Toward a New Era of Flight

Key Challenge

How can we assure that advanced **Increasingly Autonomous (IA) systems** – especially those that rely on adaptive / nondeterministic software – will **enhance rather than diminish the safety and reliability** of the NAS?

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

PREPUBLICATION COPY—SUBJECT TO FURTHER EDITORIAL CORRECTION

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- Key Challenge
How can we assure that advanced **Increasingly Autonomous (IA) systems** – especially those that rely on adaptive / nondeterministic software – will **enhance rather than diminish the safety and reliability** of the NAS?
- National Research Agenda

deterministic

ous human

Certification

gies and

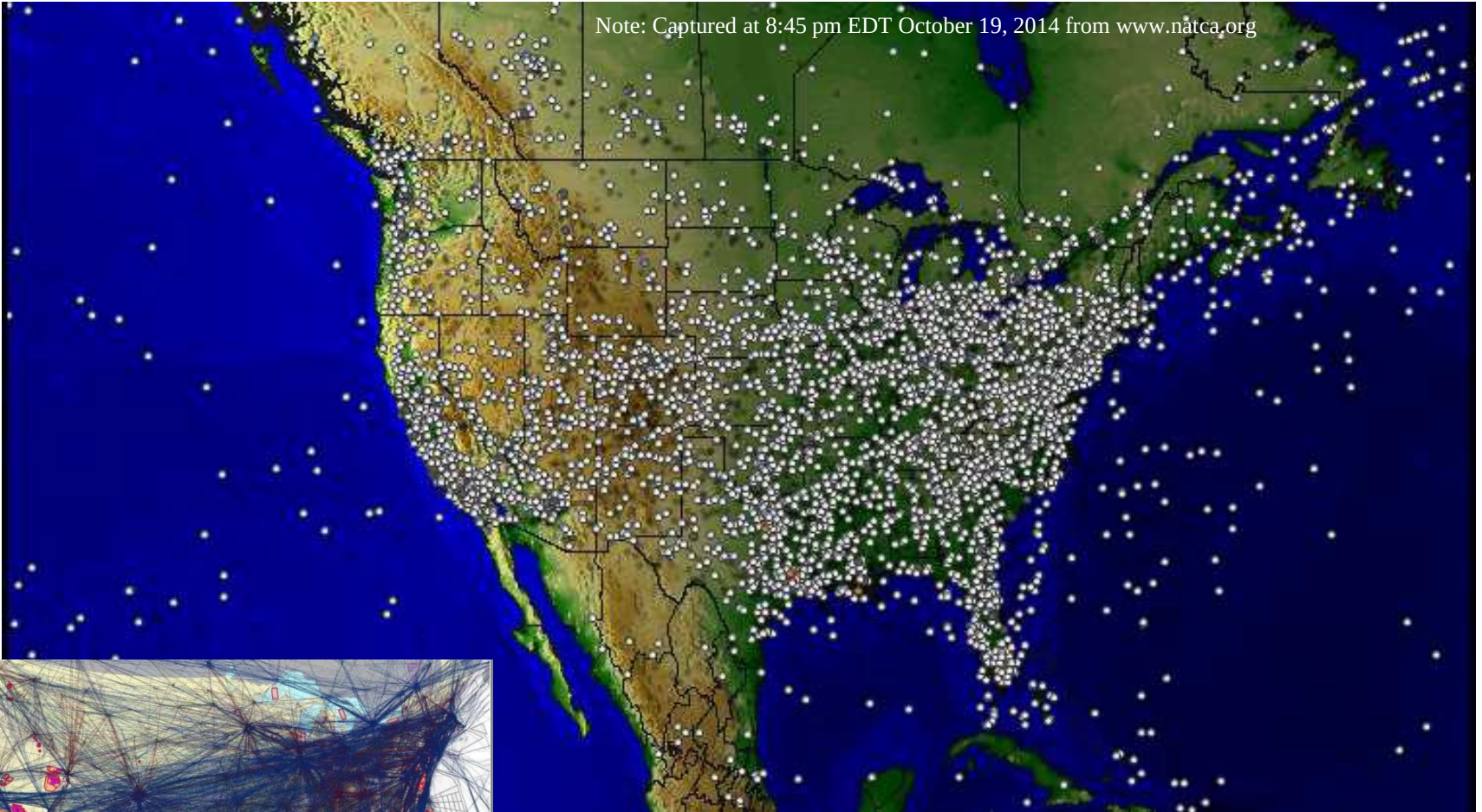
- Safety and Efficiency
- Stakeholder Trust

http://sites.nationalacademies.org/DEPS/ASEB/DEPS_046747



How Much Safer Can We Be?

Note: Captured at 8:45 pm EDT October 19, 2014 from www.natca.org



~7000 aircraft in the NAS at any given time
~250M cars on the road today $\rightarrow 10^5$

A Day In The NAS (Image Credit: FAA)



Increased accessibility

Average annual fatalities in the United States, 2000-2009

	Private Transportation			Commercial Transportation		
	Crashes solely involving private users	Crashes with commercial highway carriers	Crashes with commercial non-highway carriers	Passengers	Employees	Bystanders
Highway Modes						
Cars and light trucks	26,678	3,766	245 ^a	7 ^b	9 ^b	n.a
Pedestrians & bicycles	4,930	545	592 ^c	n.a	n.a	n.a
Motorcycles	3,989	156	2 ^a	n.a	n.a	n.a
Large Trucks	n.a	n.a	n.a	n.a	724	n.a
Buses	n.a	n.a	n.a	30	9	n.a
Non-Highway Modes						
Maritime	704	0	1	42	85	1
Aviation ^d	548	0	1	74	21	2
Railroads	n.a	n.a	n.a	7	27	4
Rail Transit	n.a	n.a	n.a	22	3	0
Pipeline	n.a	n.a	n.a	n.a	5	12
Totals						
Total	36,849	4,467	839	182	883	19
U.S. Total	43,239					

<http://journalistsresource.org/studies/environment/transportation/comparing-fatality-risks-united-states-transportation-across-modes-time#>



Personal Autonomy

Safety is a tradespace.



Image credit: NASA



Image credit: NASA



Machine Autonomy

Safety is a tradespace?



Machine Autonomy

Safety is a tradespace?

"Viewer discretion advised."



Machine Autonomy

Safety is a tradespace?

- Technology brings risk (at least initially)
- Affordability reduces the cost of entry
- Accessibility opens up the user base
- Safety is already high –
the safest airspace in the world



How do we mitigate risk?

Multiple Disciplines

- Mechanics
- Electronics
- Programming
- Psychology
- Signal Processing
- Math
- ...

Rise to the Autonomy challenges

- Size, Weight And Power (SWAP) – for sUAS
 - Monocular CV
- Sensor Fusion
- Adaptive Control
- Geo-containment
- Sense/Detect and Avoid
- Object Detection and Classification
- Separation Management
- Precision trajectories
- Landing site selection
- Human-Machine Interaction/Teaming
- Adaptation and Learning
- Performance Standards
- Verification and Validation (V&V)
- Certification
- Trust
- Communication, C2
- Data-rich and Data-deprived environments
- Test and Evaluation (T&E)



NASA LaRC

@AutonomyIncub8r



- 14 permanent team members
- 2 PhD GAs (NCA&T, CU)
- Up to ~12 student interns (MS, BS)
- Working with universities
 - Boston University
 - MIT
 - Old Dominion University
 - Virginia Tech
- Working with other NASA Projects
 - SASO
 - UAS in the NAS
 - RW VLHA

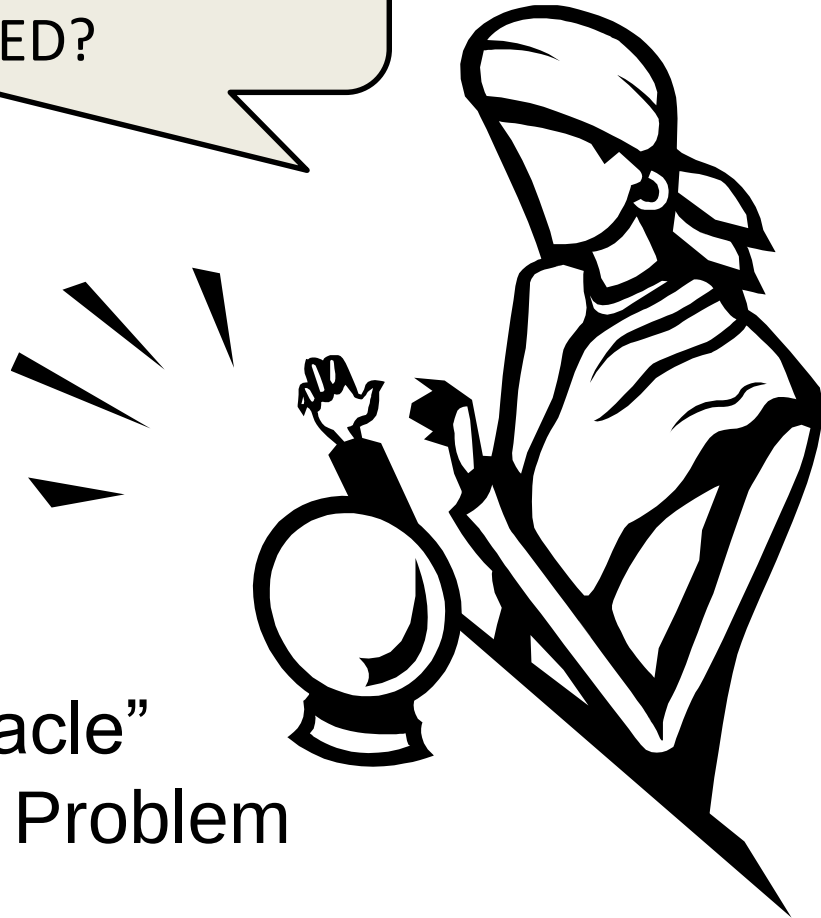


November 2014



A Sensor Fusion Design Tool

HOW MANY (AND DIFFERENT!)
SOURCES AND SENSORS DO I
REALLY NEED?

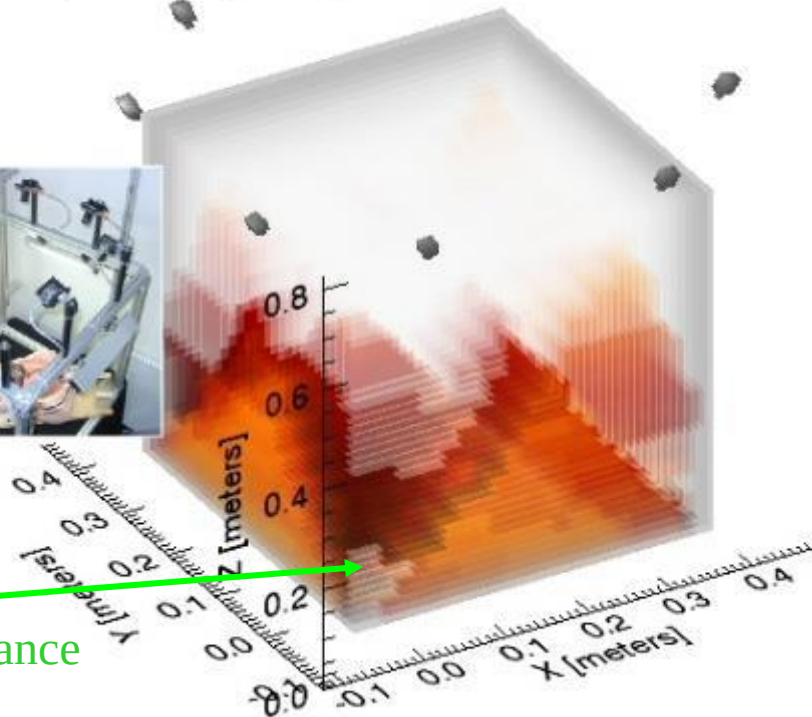
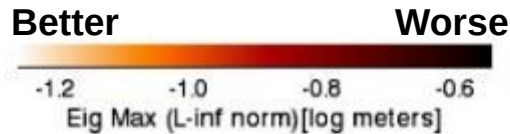


The “Oracle”
An NP-Hard Problem

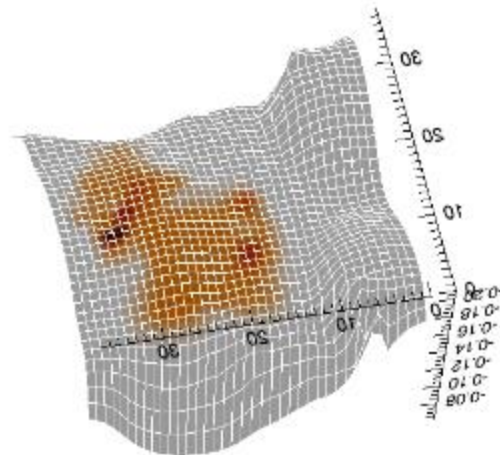
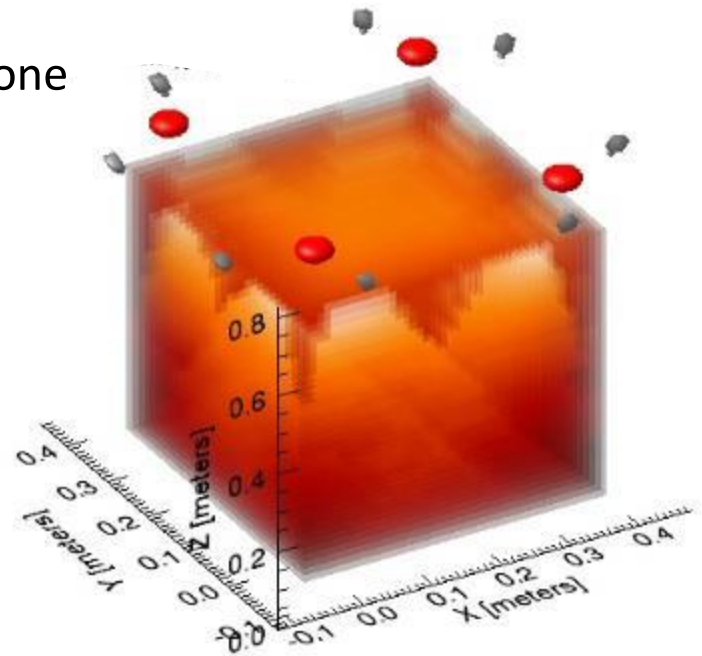


How well will my system perform?

- Recognizable view frusta of the individual cameras
- Best performance at $z=0.24$ [m].
- Unobservable above 0.6 meters w/cameras alone



peak
performance
height





Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project

- **Objective:** Develop and mature to TRL6 an autonomous landing GN&C and sensing system for crewed, cargo, and robotic descent vehicles.
 - Global precision: Land within 30 meters of designated location
 - Hazard Detection: Detecting rocks > 30 cm in height, and slopes > 5 deg. over 10 m
 - Local precision: Land within about a meter of safe site identified in real-time
 - Landing anywhere and under any lighting conditions
 - Autonomous landing
 - Crew interface

SENSORS

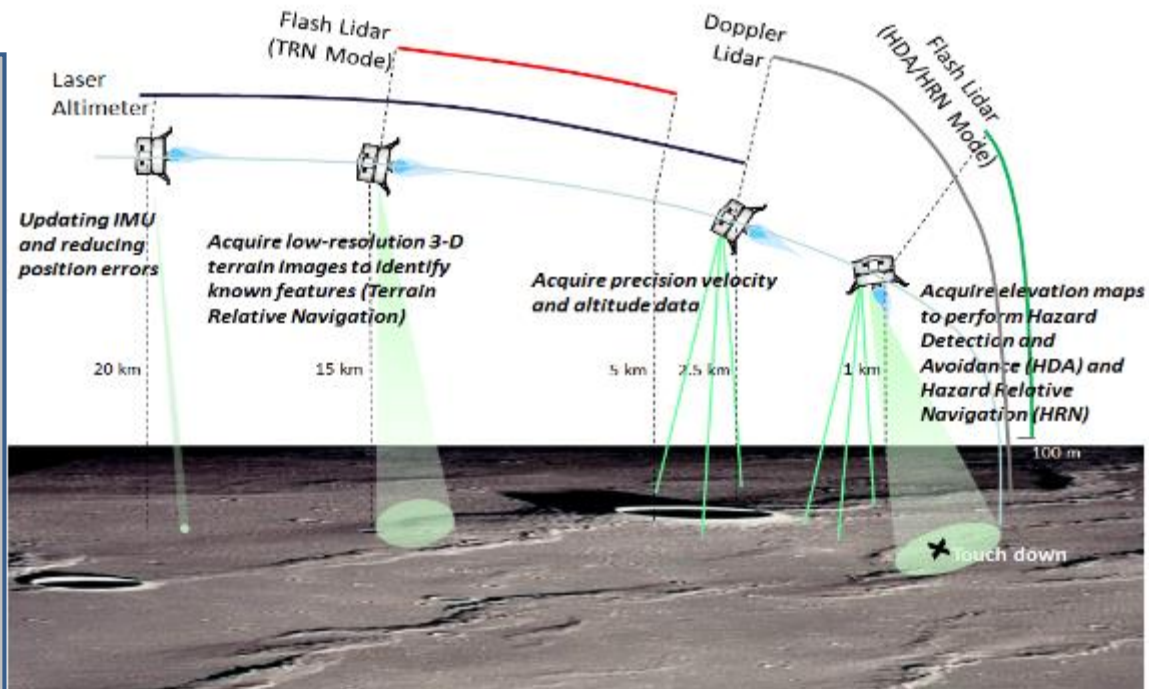
➤ **3-D Imaging Flash Lidar:**

- Hazard Detection and Avoidance and Hazard Relative Navigation (1 km to 100 m, 128x128 pixels)
- Terrain Relative Navigation (15 km to 10 km, 12x12 pixels)

➤ **Laser Altimeter:** Altitude measurements (50 km to 50 m)

➤ **Doppler Lidar:** Velocity and Altitude (2200 m to 5 m)

Lunar Landing Operational Scenario





ALHAT Free Flight on Morpheus at KSC



Image credit: NASA

<https://www.youtube.com/watch?v=tmkPJUHYdRA>



SWAP



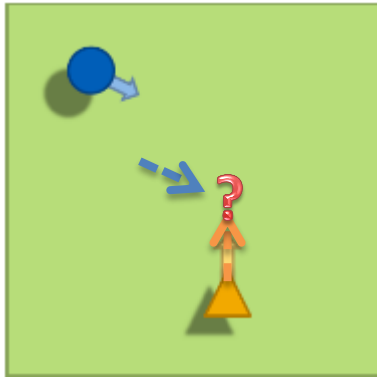
Image credits: NASA



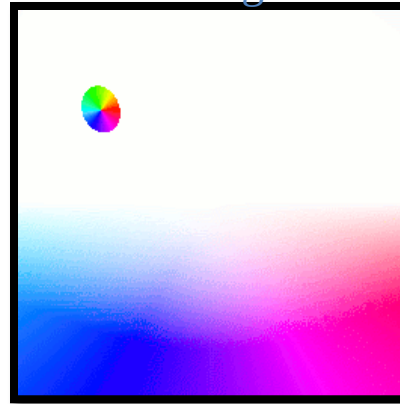


Neuromorphic Computing and Monocular Flow-Based Navigation for Collision Avoidance

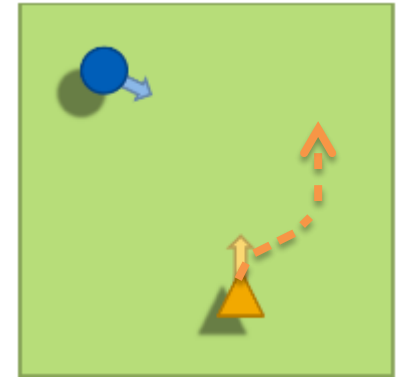
Moving UAS on Collision Course with Aircraft



Resulting Optic Flow Signal



Navigate to Avoid Collision



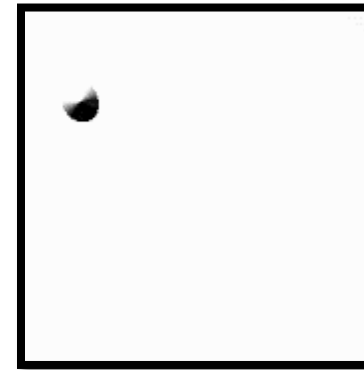
Decompose

Ego Motion



Q Learning

Object Motion



A large-scale **neuromorphic algorithm** separates ego- and object-motion and evaluates each for collision detection. **Reinforcement learning** is used to train for collision avoidance.



Neuromorphic Computing and Monocular Flow-Based Navigation for Collision Avoidance



<http://www.bizjournals.com/boston/blog/startups/2014/03/cambridgesneurala-using-flight-simulator-to-train.html>

<http://neurala.com/blog/uav-collision-avoidance>



RDT&E in Relevant Environment

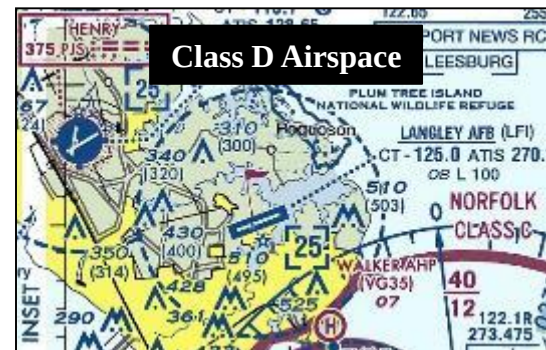
CERTAIN (City Environment for Range Testing of Autonomous Integrated Navigation) Allows RDT&E under Relevant Conditions ... Onsite at NASA LaRC

**Obstacle Avoidance – Small-scale Features
– Transient Targets**

**Airspace Avoidance –
Autonomous Geo-fencing**

**Collision Avoidance –
Multiple Autonomous UAS**

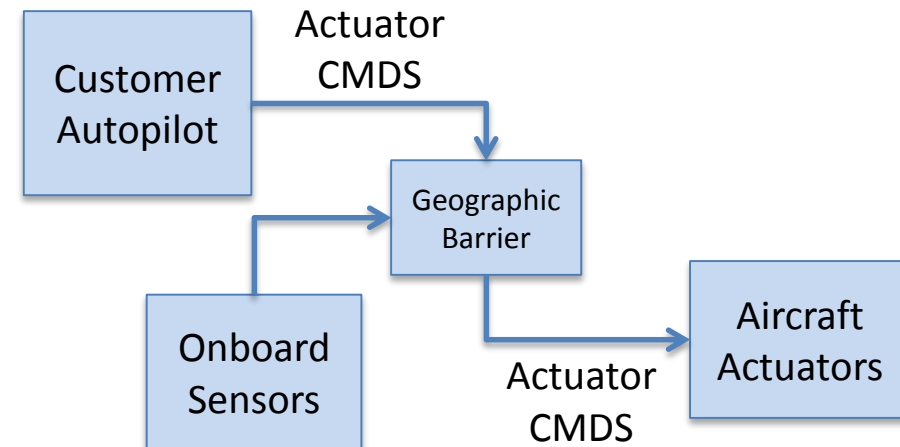
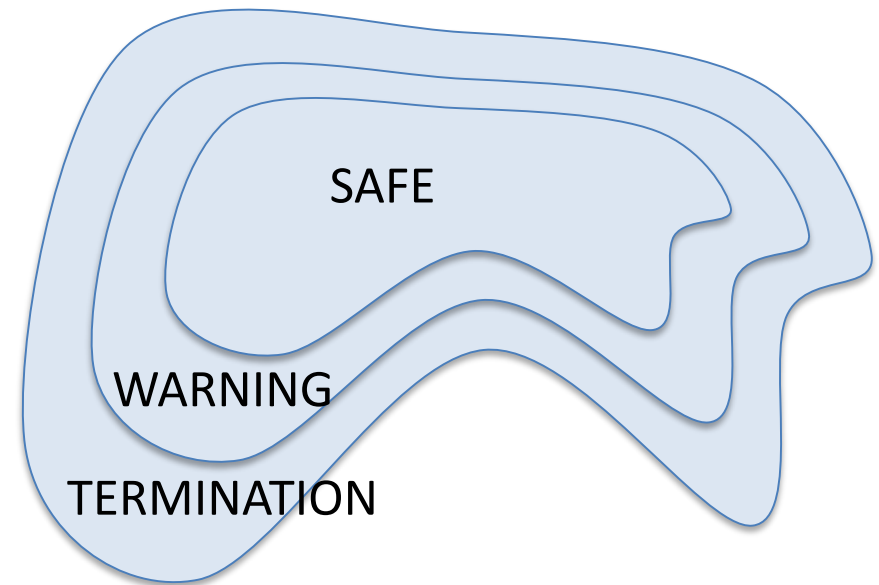
**Ground Movement
Target Characterizing
– Challenging Complex Environment**





Geo-Containment

- A virtual fence
- A bolt-on solution for a range of vehicles
 - Remain vehicle type configuration free
 - and applicable to any autopilot
- Enforce Range Control to maintain safe and law/policy compliant ops
 - Aircraft autopilot has complete freedom in Safe zone
 - Command aircraft back to Safe zone upon entering Warning zone
 - Flight termination in Termination zone
- Employ customer autopilot actuator command pass-through mode during nominal ops
- Do no harm - Verifiably safe





Yes, this is an invisible fence...





-
- The screenshot shows the Maple 12 software interface. On the left, a worksheet contains several lines of mathematical expressions, including a definition of a function $f(x, y, z)$ and a series of calculations involving partial derivatives and the chain rule. The expressions are:

$$f(x, y, z) = x^2 + y^2 + z^2$$

$$\frac{\partial f}{\partial x} = 2x$$

$$\frac{\partial f}{\partial y} = 2y$$

$$\frac{\partial f}{\partial z} = 2z$$

$$\frac{d}{dt} f(x(t), y(t), z(t)) = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt} + \frac{\partial f}{\partial z} \frac{dz}{dt}$$

$$= 2x \frac{dx}{dt} + 2y \frac{dy}{dt} + 2z \frac{dz}{dt}$$

$$= 2(x \frac{dx}{dt} + y \frac{dy}{dt} + z \frac{dz}{dt})$$

$$= 2 \frac{d}{dt} (x^2 + y^2 + z^2)$$

$$= 2 \frac{d}{dt} f(x, y, z)$$
 On the right, a 3D plot of a sphere is displayed, with a green circle overlaid on its surface. The plot is titled "3D Plot of f(x, y, z) = x^2 + y^2 + z^2". The axes are labeled x, y, and z. The sphere is centered at the origin (0, 0, 0) and has a radius of 1. The green circle is located on the surface of the sphere, centered at (0, 0, 1).

Execute



Bot cannot complete its mission but can return to START or FINAL location.



Trust: Humans and (Ghost In the) Machines

- Trust: “Developing methods for establishing ‘certifiable trust in autonomous systems’ is the single greatest technical barrier that must be overcome to obtain the capability advantages that are achievable by increasing use of autonomous systems.”

U.S. Air Force “Technology Horizons” 2010-2030, http://www.au.af.mil/au/awc/awcgate/af/tech_horizons_vol-1_may2010.pdf

- Trust is objective and subjective, technical and interpersonal
- Trust accommodates uncertainty – is probabilistic
- Trust is gained over time
- Interpersonal Trust is acquired
 - Information
 - Integrity
 - Intelligence
 - Interaction
 - Intent
 - Intuition



NASA Autonomy Validation Workshop, August 2012
Sponsored by NASA Office of Chief Technologist



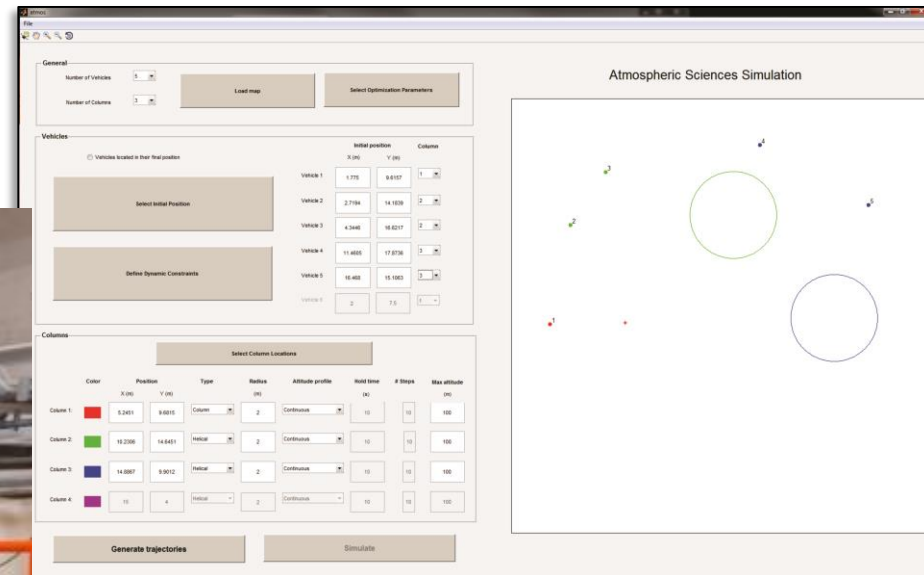
Where's all this headed?

Enabling New Missions



Package Delivery

- Sensor placement for science missions
- In-situ pollution measurements in urban areas





Search & Rescue

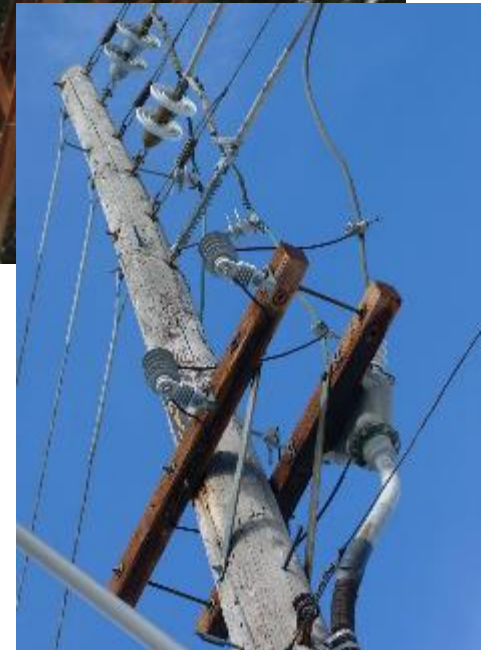
- Multi-vehicle
- Under the canopy
- Data-denied





Infrastructure Inspection

- Bridges
- Pipelines
- Power lines





Autonomous ATM

- CERTAIN
- UTM





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Backup Charts



New Technologies and Safety

Aircraft Generations

In 2013 Detail of Aircraft Generations

First Generation

Early commercial jets



10,000 flights
50 aircraft

Second Generation

More integrated Auto Flight System



1 million flights
1,000 aircraft

Third Generation

Glass cockpit and FMS



16 million flights
12,000 aircraft

Fourth Generation

Fly-By-Wire with flight envelope protection



11 million flights
8,000 aircraft

1st year of entry into service:

1952

Caravelle, Comet, BAC 111, Trident, VC-10, B707, B720, Convair 440/440X, DC-8

1964

Concorde, A300 (except A300-600), BAE 146, Mercure, B727, B737-100/200, B747-100/SP/200/300, F-28, L-1011, DC-9, DC-10, VFW 614

1980

A300-600, A310, Avro RJ series, B717, B737-300/400/500, B737 NG -600/700/800/ 900, B757, B767, B747-400, B747-8, Bombardier CRJ Series, Embraer ERJ Series, 328JET, F-70, F-100, MD-11, MD-80, MD-90

1988

A318/A319/A320/A321, A330, A340-200/300/500/ 600, A380, B777, B787, Embraer E Series

Commercial Aviation Accidents 1958 – 2013 A Statistical Analysis; (Airbus study)