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Autonomy for On Orbit Service Assembly and Manufacture: A Smallsat Perspective

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Humuhumunukunukuapua`a Works

Special Projects Division (-2 ≤ TRL ≤ 2)

Outline

- Introductions.
- Background:
  - Qu'est-ce que c’est …
    - SmallSat?
    - Autonomy?
- Challenge – problem/pain point definition.
- Context:
  - Space vehicle proximity operation, rendezvous, docking/acquisition.
  - Spacecraft swarms/formations.
- Pain relief…
- Current work.
- Conclusions, i.e., a few thoughts.

Introductions

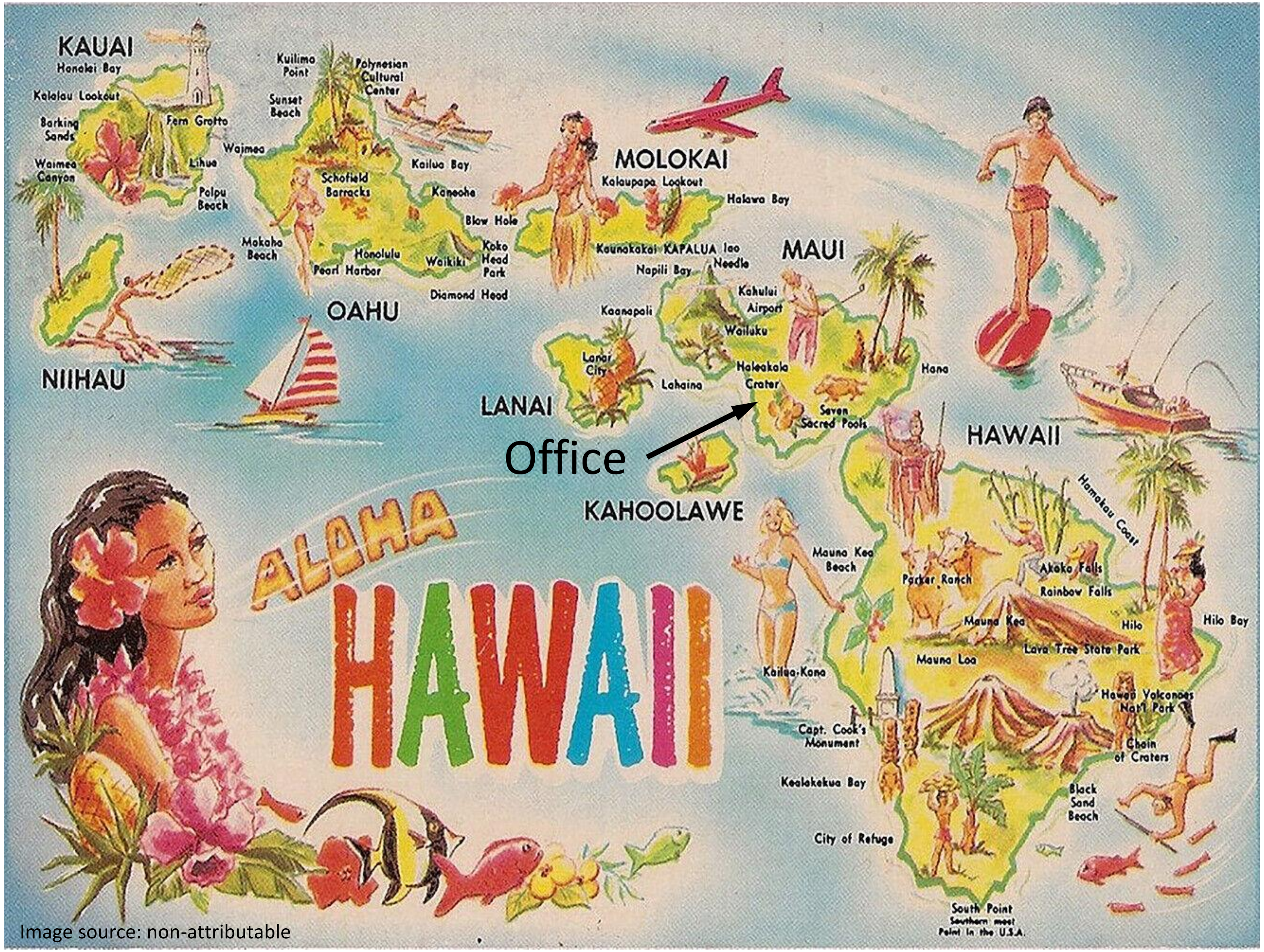

Image source: non-attributable

2014: Company founded in Florida to develop technologies for cooperating spacecraft.

2016: First SBIR Phase I contract.

2018: First STTR Phase I.

2019: Moved to Hawaii.

2020: First SBIR Phase II follow Phase I.

…

Background: What Is a SmallSat?

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- The four of five smallest classes of spacecraft by mass[1].
- Typically, single string architectures, matching NASA Class D risk posture definitions.

Bogdan's preference.

Bryce Tech[2]

Table 11 provides the spacecraft mass classes used by FAA AST.

Class Name	Kilograms (kg)	Pounds (lb)
Femto	0.01 - 0.1	0.02 - 0.2
Pico	0.09 - 1	0.19 - 2
Nano	1.1 - 10	3 - 22
Micro	11 - 200	23 - 441
Mini	201 - 600	442 - 1,323
Small	601 - 1,200	1,324 - 2,646
Medium	1,201 - 2,500	2,647 - 5,512
Intermediate	2,501 - 4,200	5,513 - 9,259
Large	4,201 - 5,400	9,260 - 11,905
Heavy	5,401 - 7,000	11,906 - 15,432
Extra Heavy	>7,001	>15,433

Table 11. Spacecraft mass classes.

[1]Table 11, p. 94 from The Annual Compendium of Commercial Space Transportation. Federal Aviation Administration Office of Commercial Space Transportation (FAA AST); 2018.
[2]Smallsats by the Numbers. Bryce Tech; 2022

Background: What Is Autonomy?

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Delegation of agency from a user, either human or a software agent, to software agent that utilizes a certain level of knowledge of the user's goals and desires[1].

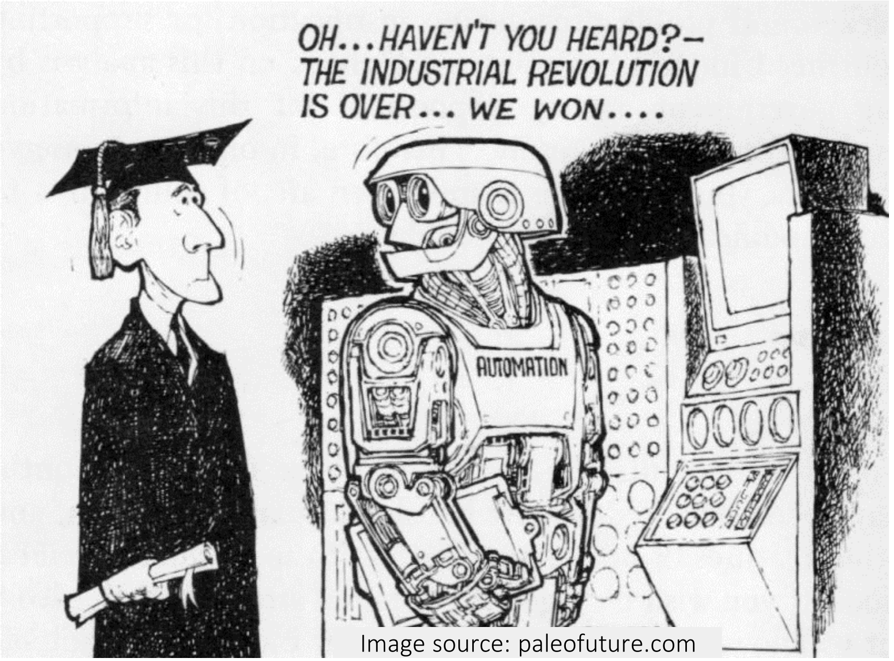

Image source: paleofuture.com

[1] Adapted from Zacharias, G. L. (2019). Autonomous Horizons The Way Forward Vol 2, Office of the US Air Force Chief Scientist

Challenge Problem/Pain Point Definition

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Problem

Labor and infrastructure intensive operations.

Missions that require rendezvous and proximity operations are unsustainable with current technologies.

Examples

- VisSidus (2014) active debris removal (ADR) mission design:
  - Single use servicer: $110K/kg removed[1].
  - Propellant refill servicer: $64K/kg removed.
- NASA ADR costs (2023): $60K/kg to $4K/kg removed[2].
- For the [Astroscale LEO] servicer to perform complex maneuvers that include capturing the client … the control system via ground stations must be in constant contact with the spacecraft for up to 20-30 minutes. . . . The 16 ground stations are spread across 12 countries in total …”[3]

[1]Udrea B, Nayak M,. A Cooperative Multi-Satellite Mission for Controlled Active Debris Removal from Low Earth Orbit. 2015 IEEE Aerospace Conference; 2015; Big Sky, MT 2015

[2]Colvin TJ, Karcz J, Wusk G. Cost and Benefit Analysis of Orbital Debris Remediation. In: NASA, editor. 300 E Street SW Washington, DC 20024: Office of Technology, Policy, and Strategy; 2023.

3 Rainbow, J. “Astroscale breaking new ground for on-orbit servicing demonstration,” SpaceNews 2021

Context – Active Debris Removal

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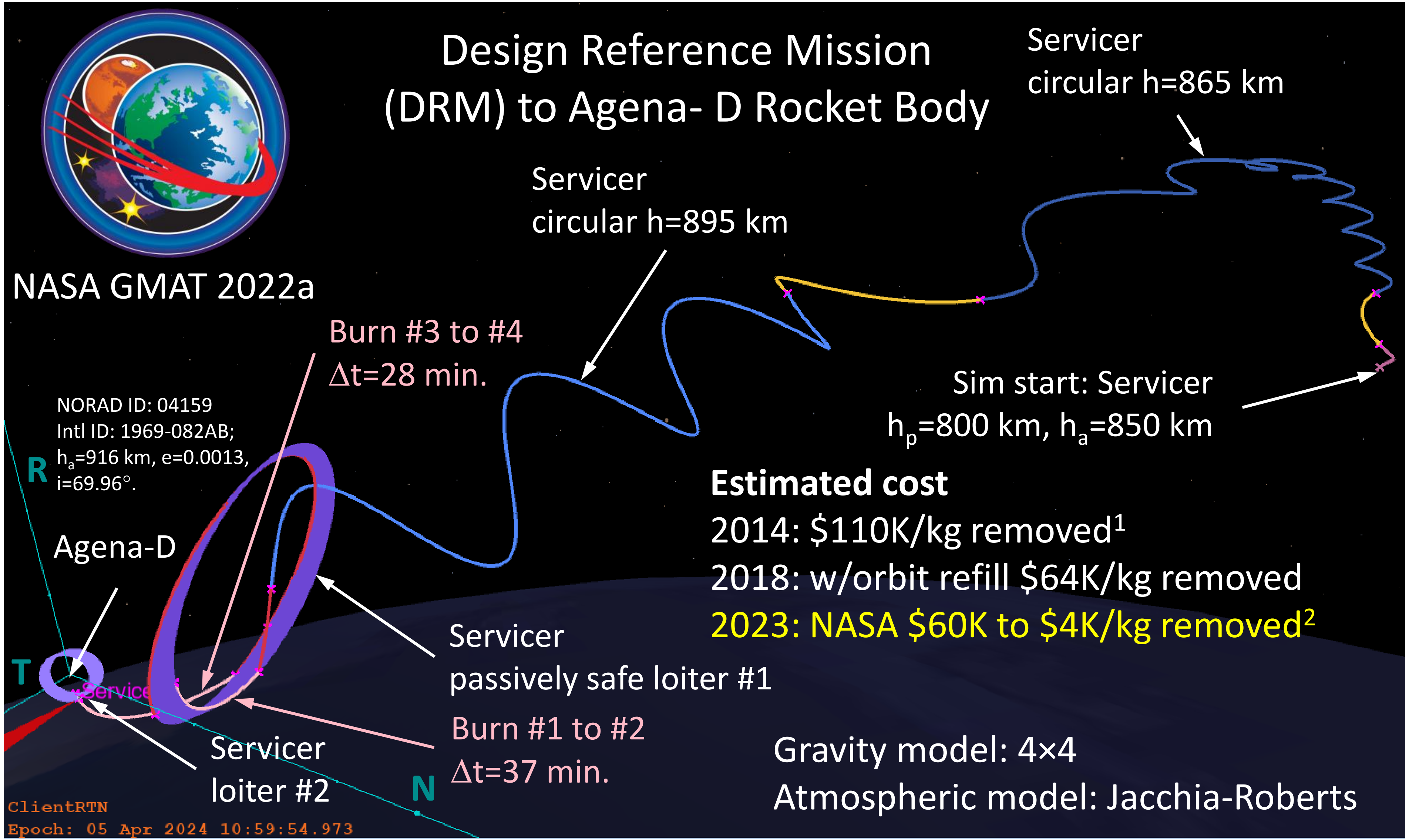
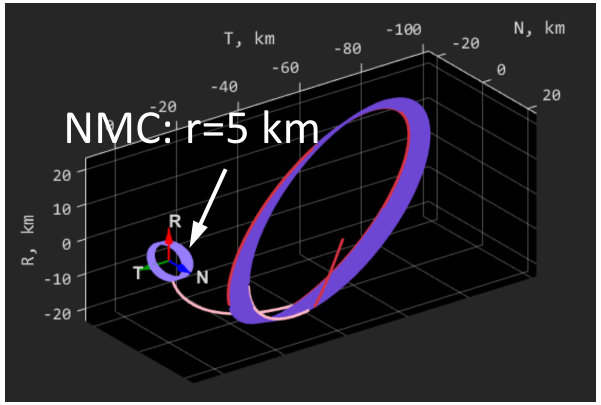
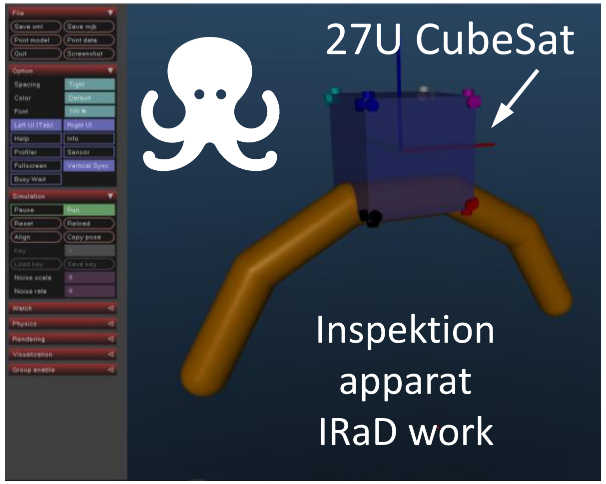


Mid- to close-range proximity operations analysis



Multiple Joints with Contact (MuJoCo) simulation



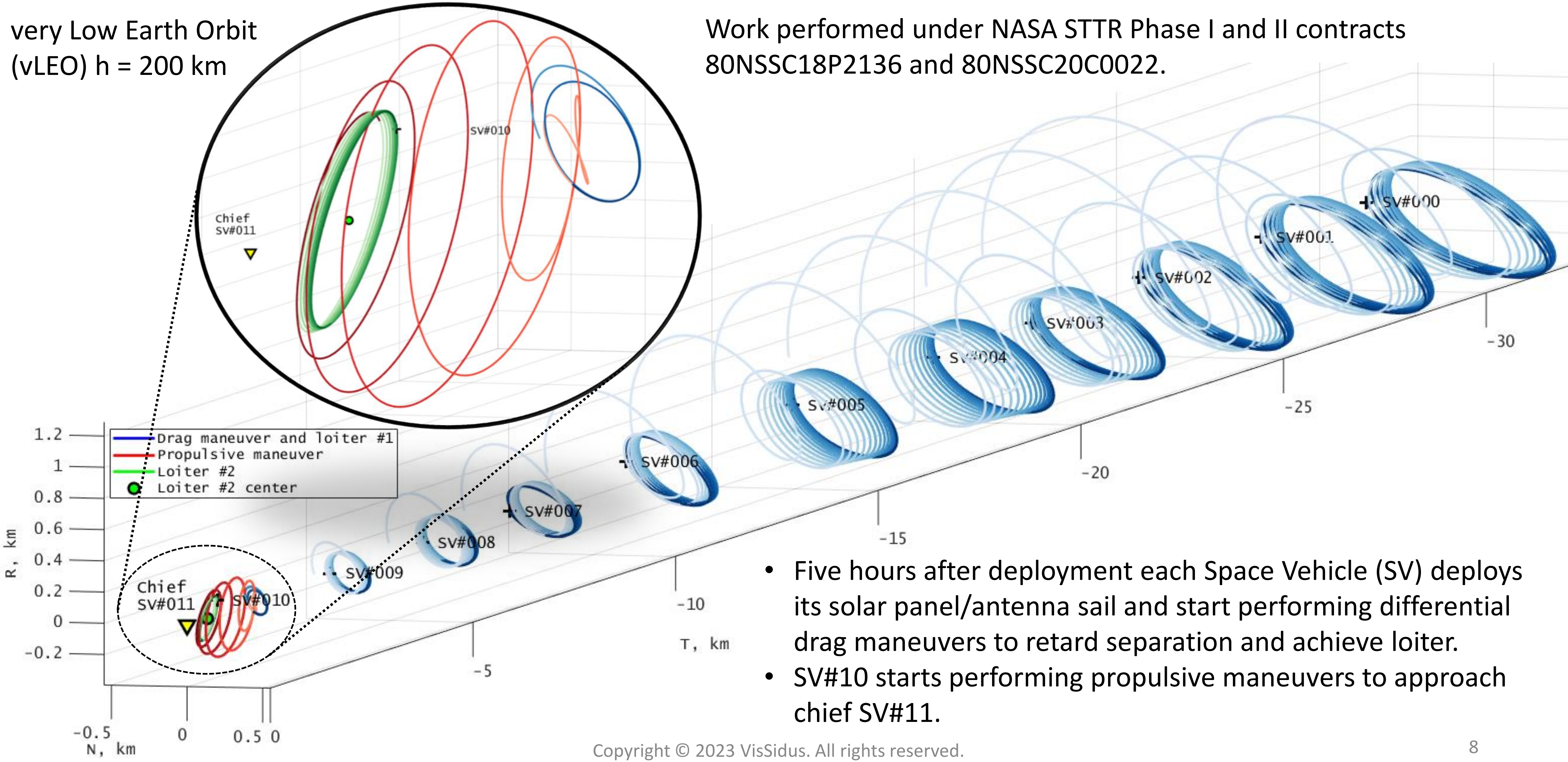
[1] Udrea B, Nayak M,. A Cooperative Multi-Satellite Mission for Controlled Active Debris Removal from Low Earth Orbit. 2015 IEEE Aerospace Conference; 2015; Big Sky, MT 2015

[2] Colvin TJ, Karcz J, Wusk G. Cost and Benefit Analysis of Orbital Debris Remediation. In: NASA, editor. 300 E Street SW Washington, DC 20024: Office of Technology, Policy, and Strategy; 2023.

Context – Spacecraft Swarm of 12 L-Band SAR

very Low Earth Orbit (vLEO) h = 200 km

Work performed under NASA STTR Phase I and II contracts 80NSSC18P2136 and 80NSSC20C0022.



- Five hours after deployment each Space Vehicle (SV) deploys its solar panel/antenna sail and start performing differential drag maneuvers to retard separation and achieve loiter.
- SV#10 starts performing propulsive maneuvers to approach chief SV#11.

Solution/Pain Relief

On-board software and on-board computers/data handling hardware that:

1. Significantly increase on-board **automation** from commissioning to calibration to operations.
2. Support gradual deployment of **autonomy:**
   - Awareness of self and environment.
   - On-board decision making.

Bogdan's Favorite: Neuromorphic for Autonomy

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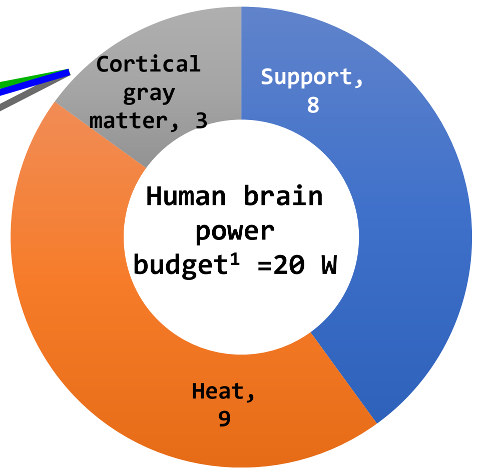
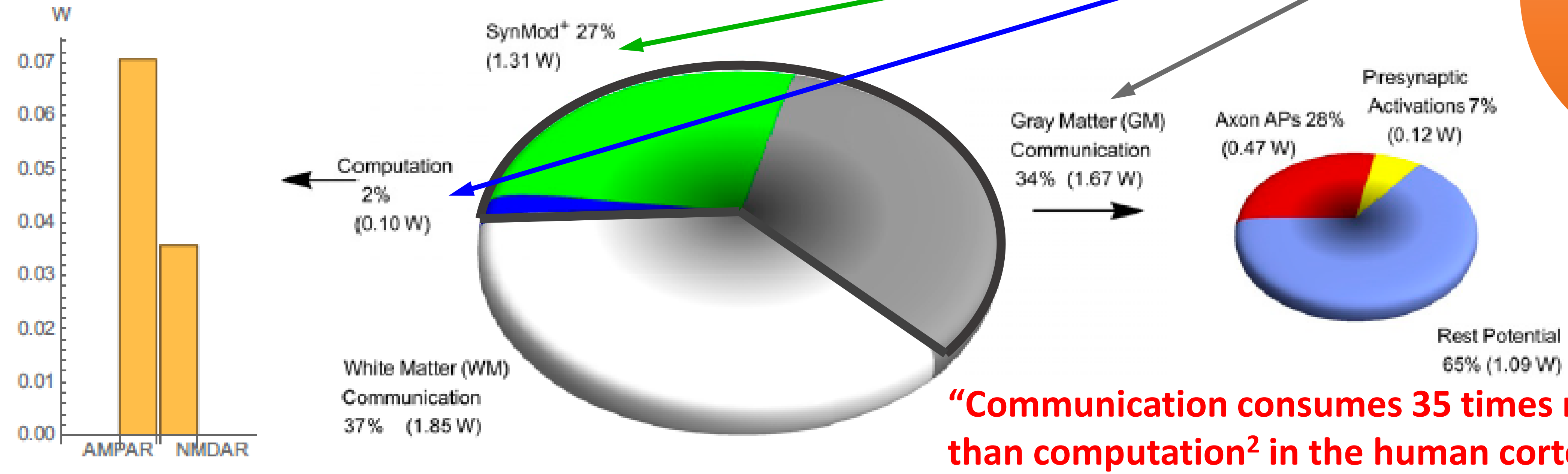
Attempt to reach the "compute efficiency" of biological brains.





"Communication consumes 35 times more energy than computation[2] in the human cortex…"

Fig. 1. Computation costs little compared to communication. Communication alone accounts for more than two-thirds of the available 4.94 ATP-W (Table 1), with slightly more consumption due to WM than to GM (big pie chart). Computation, the smallest consumer, is subpartitioned by the two ionotropic glutamate receptors (bar graph). *SynMod*+ includes astrocytic costs, process extension, process growth, axo- and dendro-plasmic transport of the membrane building blocks, and time-independent housekeeping costs (although this last contributor is a very small fraction). The small pie chart subpartitions GM communication. See *Results* and *Materials and Methods* for details. WM communication includes its maintenance and myelination costs in addition to resting and action potentials.

[1] Balasubramanian V. Brain power - Comment. Proc Natl Acad Sci USA. 2021;118.

[2] Levy WB, Calvert VG. Communication consumes 35 times more energy than computation in the human cortex, but both costs are needed to predict synapse number. Proceedings of the National Academy of Sciences. 2021;118(18).

Current Work: Dynamic Vision Sensors for RPO

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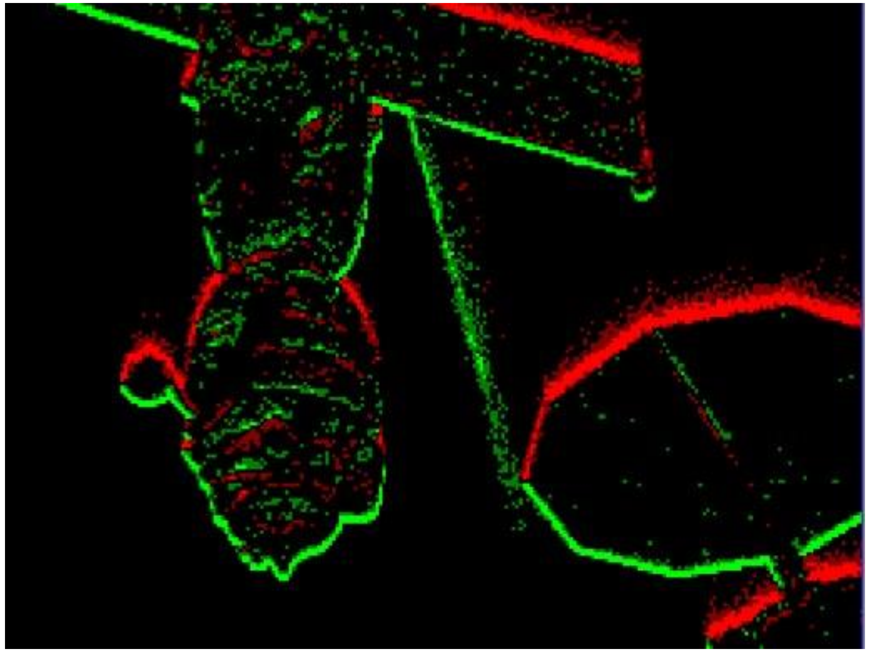
- Bio-inspired semiconductor devices also known as:
  - Silicon retinas.
  - Dynamic vision sensors.
  - Event-based cameras.
- Use photodiodes to realize phototransduction.
- Measure brightness changes at each photodiode (pixel):
  - Brightness = log(V_p)
  - Brightness reaches:
    - **above** ON threshold → **ON event.**
    - **below** OFF threshold → **OFF event.**
- Output:
  - Asynchronous event streams.
  - Address-Event Representations (AER) snapshots

Snapshot of AERs during Soyuz docking with the International Space Station



Original footage credit: NASA
Processed with v2e and jaer by the VisSidus STEMWorks summer 2022 interns.

Apollo 14 Lunar Orbit Rendezvous – DVS Simulation

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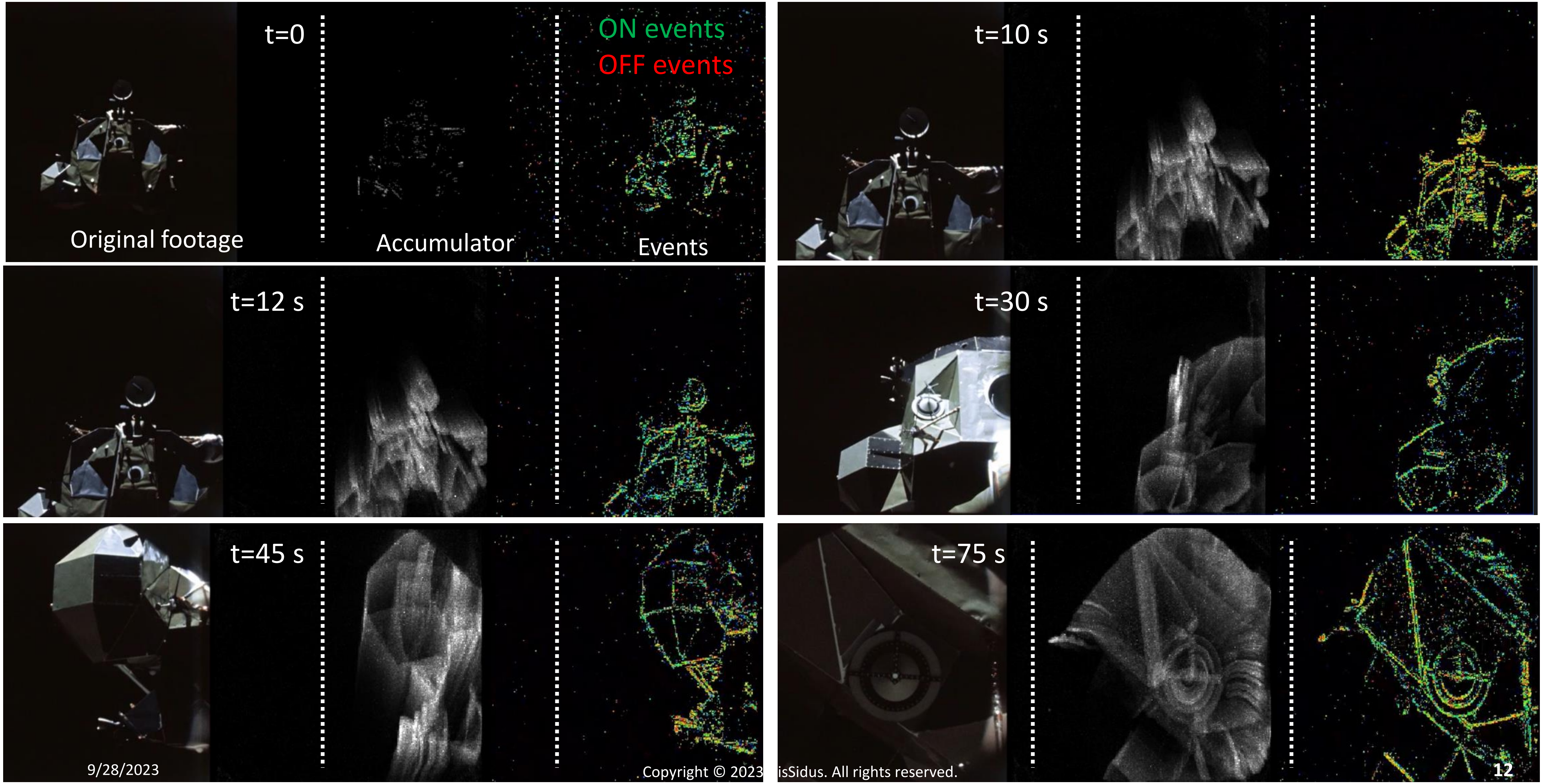
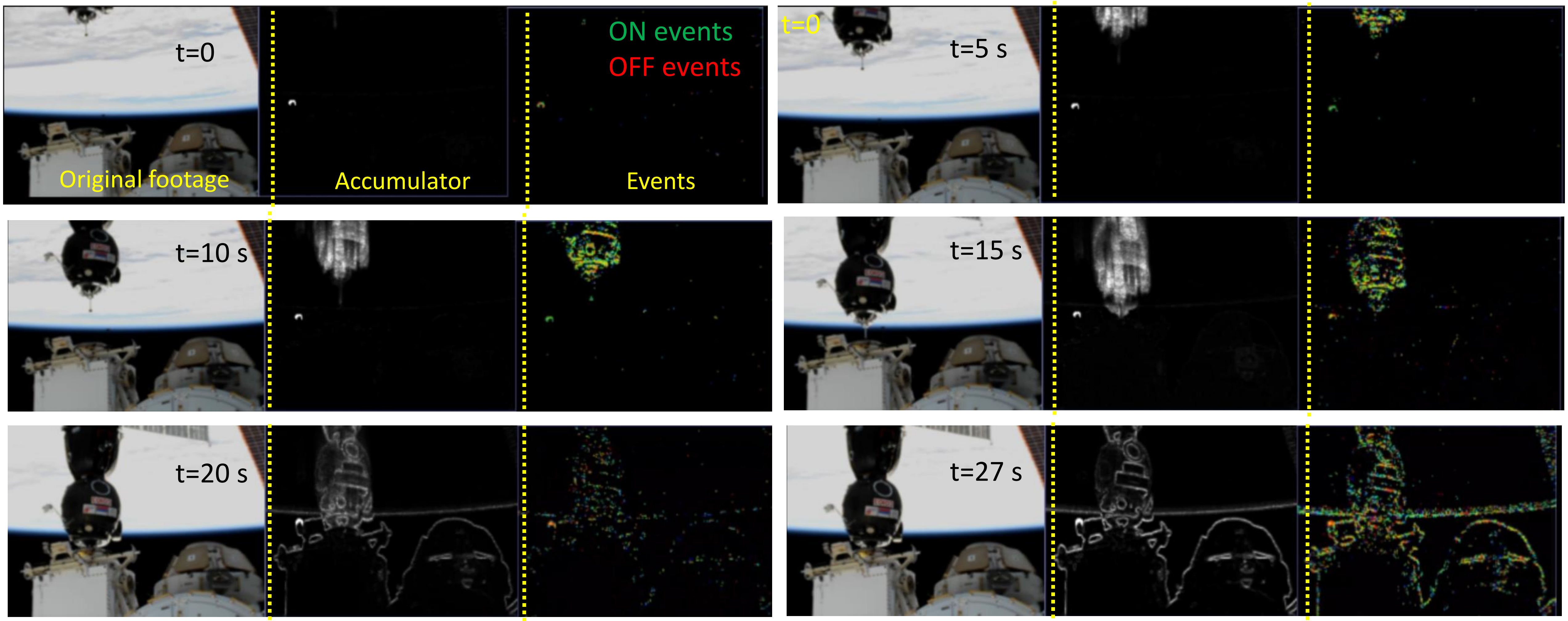
Original footage credit: NASA

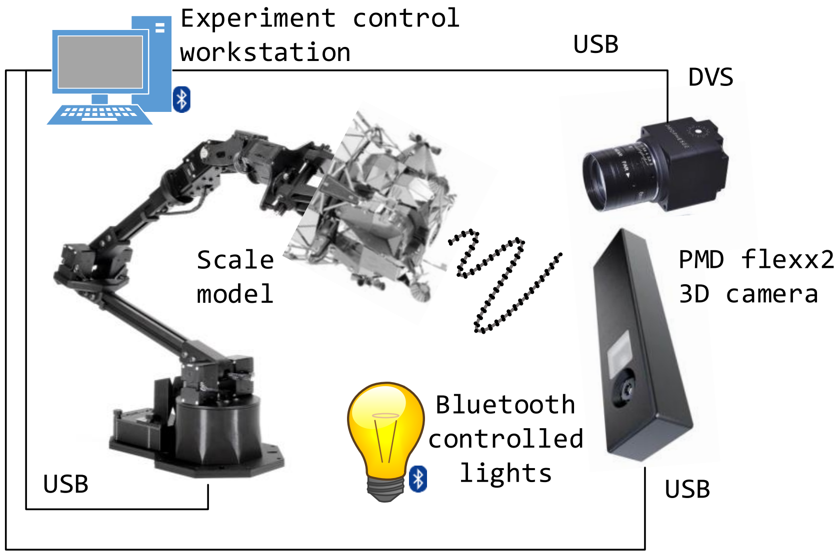


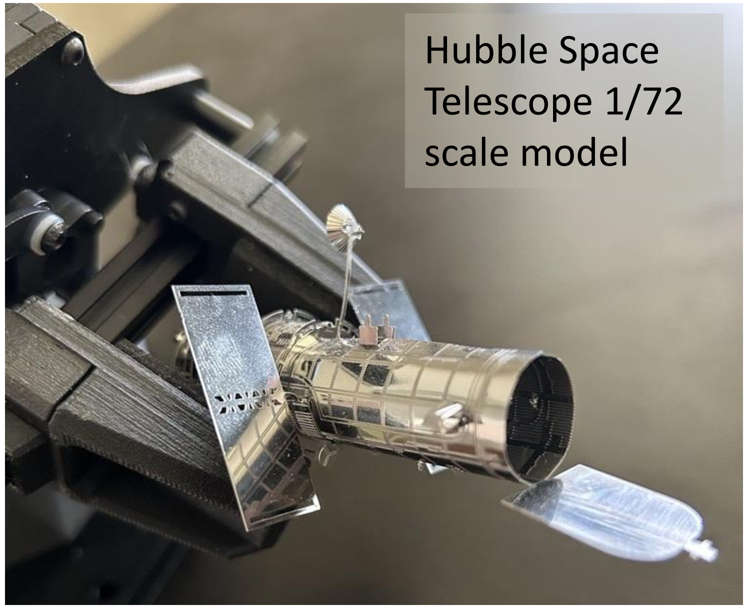
Soyuz Rendezvous with ISS – DVS Simulation

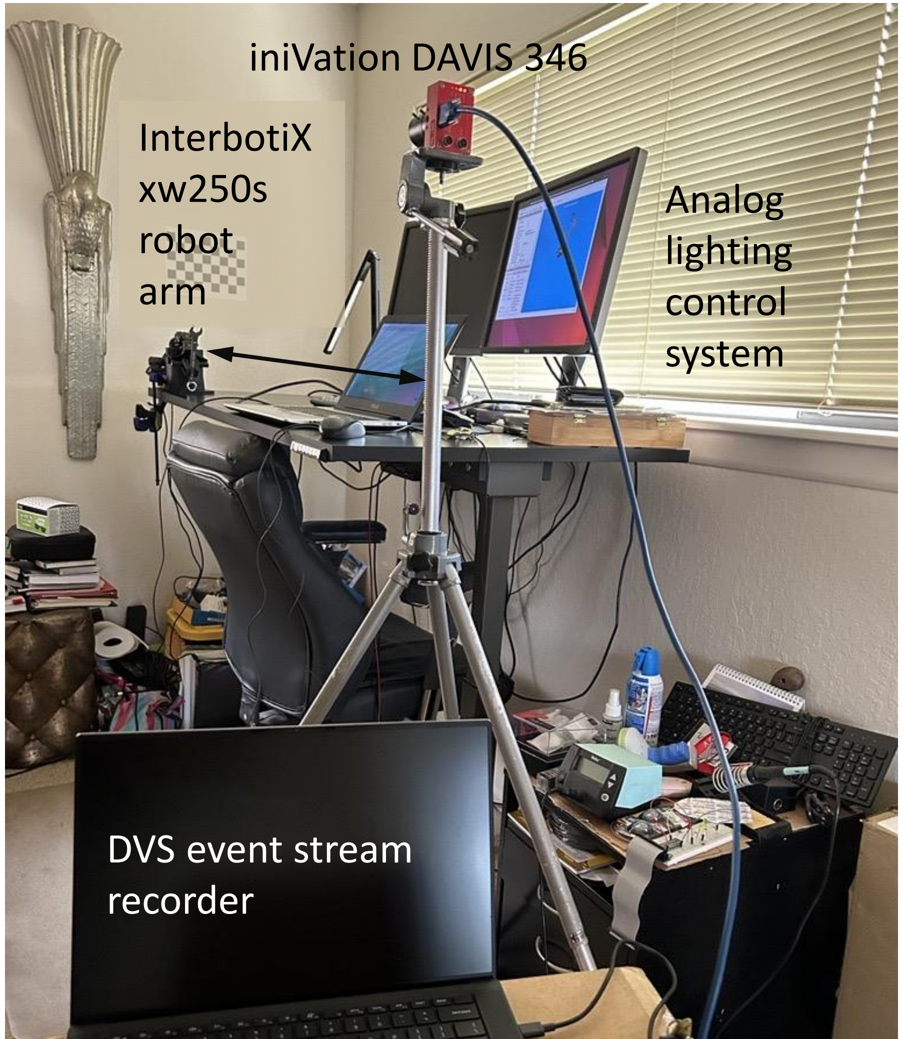
Original footage credit: NASA



DVS Set Up and Lab Data Flow Test

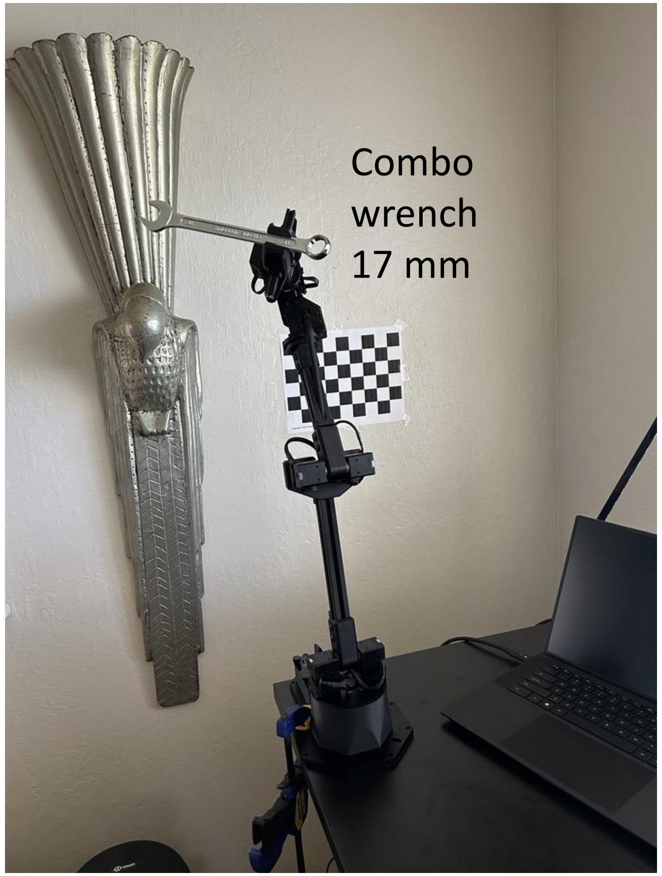






Work performed under ongoing NASA SBIR Phase I contract 80NSSC23PB623.

- Start with a simple object: 17 mm combo wrench.
- Employ two DAVIS 346 stereo + sync for key feature tracking.



Conclusions – Personal Opinions

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1. We are **very far** from on-board autonomy for spacecraft.
2. Steps to improve the situation:
   a. Use the extensive telemetry data sets available to train fault detection isolation (**self-aware**) and recovery (**decision making**) algorithms.
   b. Run the algorithms on-board – do you need a few Nvidia Jetsons?
   c. Prove that Steps a. to b. reduce the labor and infrastructure costs for single and multi-spacecraft missions.
   d. Determine what HW+SW combinations can support Steps a. to c. for SmallSats at reasonable cost down.
   e. Apply the same approach to complex parts of the operations phase: commissioning/calibration, science, and RPO.
3. Exit by selling to ??? and retire to Cap d'Antibes.

Support Slides

- Biological brains and neuromorphic computing.
- Additional details on dynamic vision sensors.

[1]A **stateful system** remembers previous interactions with the system and stores information about them. (https://www.baeldung.com/cs/stateful-stateless-system)

Background: Biological Brains

See Sandamirskaya Y, Kaboli M, Conradt J, Celikel T. Neuromorphic computing hardware and neural architectures for robotics. Sci Robot. 2022;7(67) and their citations.

1. Processing and memory "units" are indistinguishable:
   - Neurons and synapses store information **and** process it.
2. Information storage is performed on networked "units:"
   - Projection from a low dimensional to a high dimensional vector space (see semantic pointers.)
3. Computation is innately time-dependent, stateful[1], and occurs at multiple time scales:
   - Does not require synchronization via a central oscillator.

[1]A **stateful system** remembers previous interactions with the system and stores information about them. (https://www.baeldung.com/cs/stateful-stateless-system)

Background: Biological vs Neuromorphic

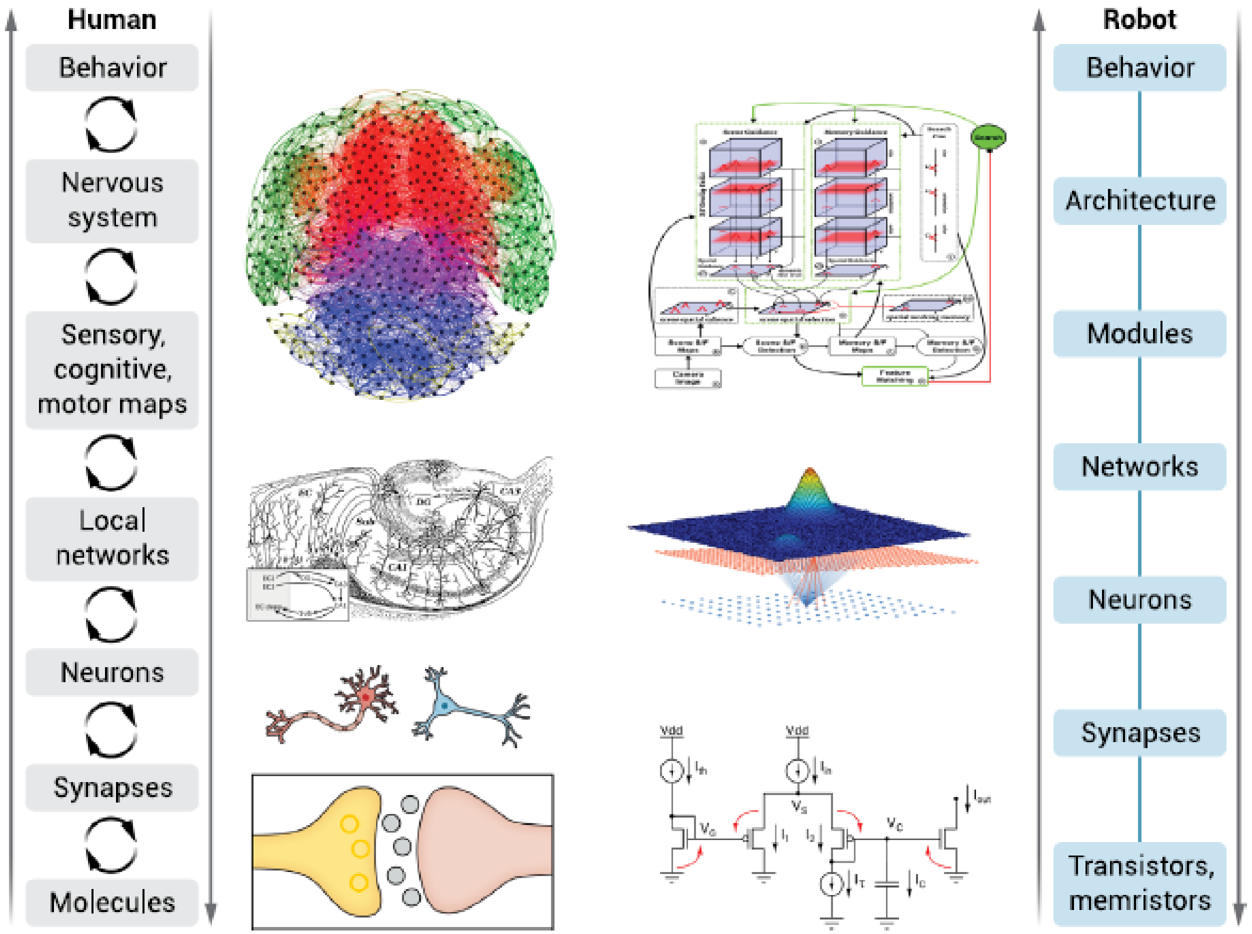


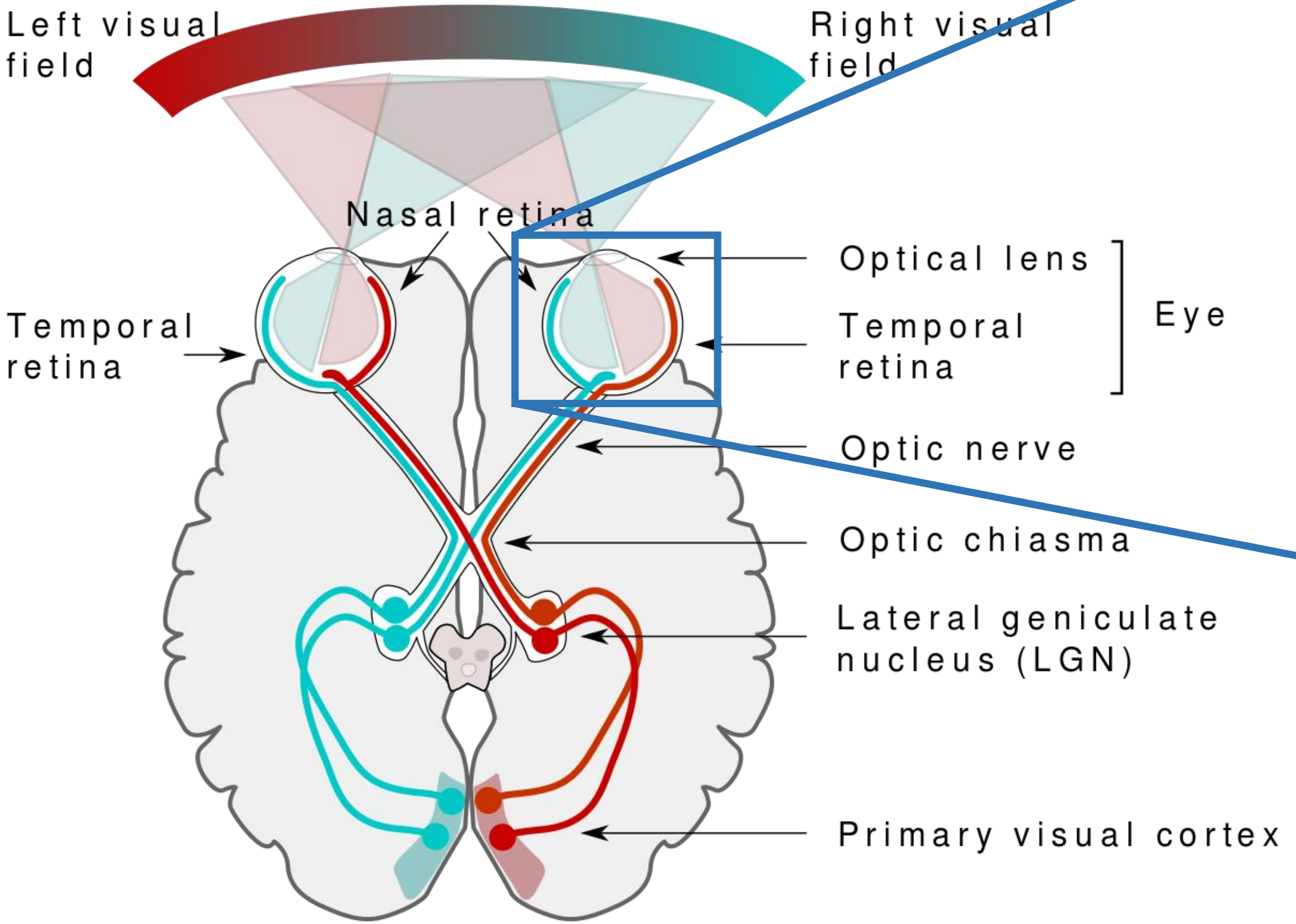
Fig. 2. Principles of information processing in biological networks and in neuromorphic circuits. The signal flow in biological and neuromorphic circuits unfolds on different spatial and temporal scales. A hierarchy of closed-loop control flows can be built both for biological neural systems and neuromorphic systems. In biology, these loops start with molecular dynamics of neurotransmitters, followed by dynamics of neurons and synapses, then local network circuits (e.g., the hippocampal circuits shown here), different sensory-motor cortical maps, ultimately leading to behavior. In a similar fashion, starting with dynamics of individual transistors and simple circuits, dynamics of neurons and synapses can be built, followed by networks, network modules, and whole architectures that can control autonomous behavior of a robot. We need to build theory, computing framework, and algorithmic understanding on these different levels of abstraction.

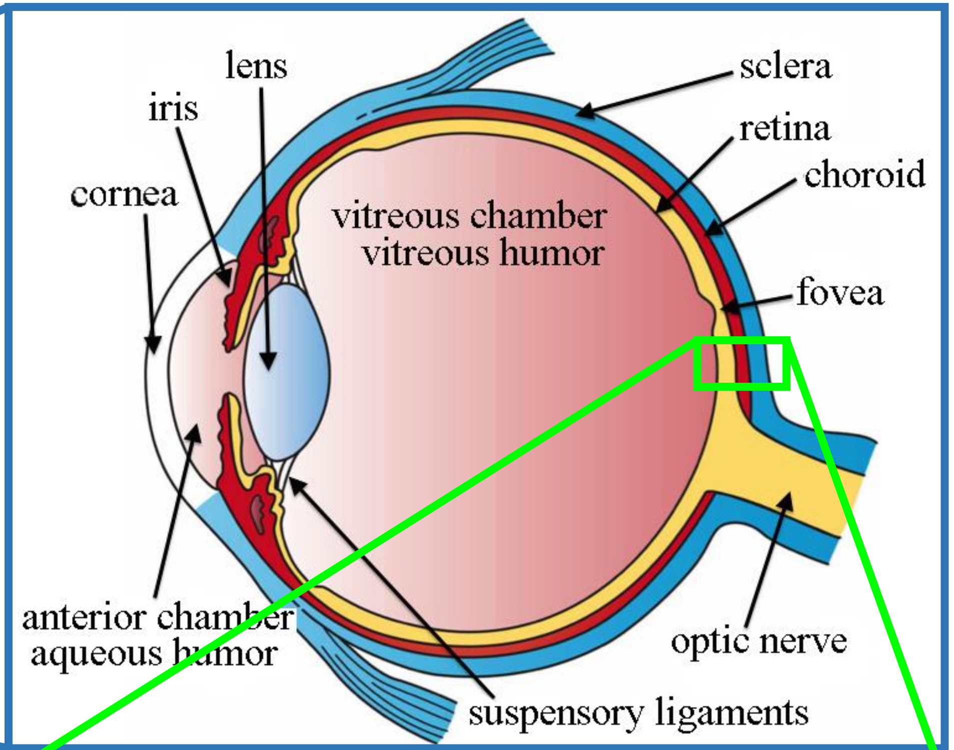
From Sandamirskaya Y, Kaboli M, Conradt J, Celikel T. Neuromorphic computing hardware and neural architectures for robotics. Sci Robot. 2022;7(67)

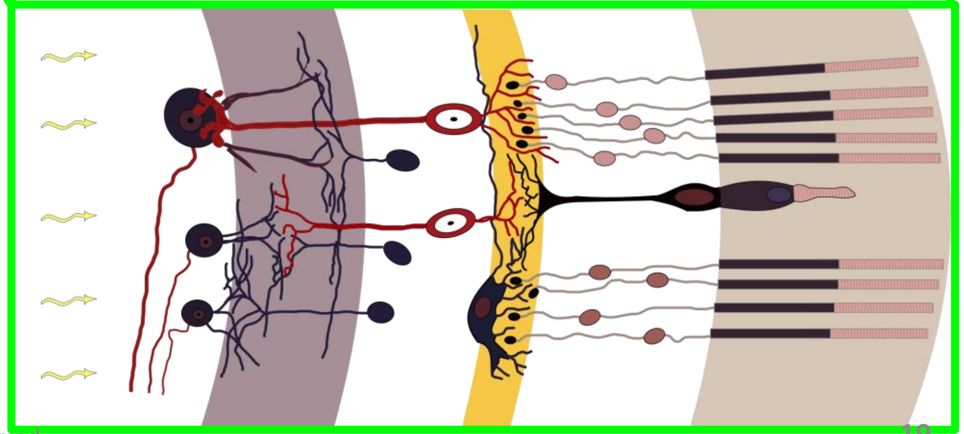
Background: Vertebrate Vision

Vision in humans (and most vertebrates)

"Phototransduction via molecular cascades*"



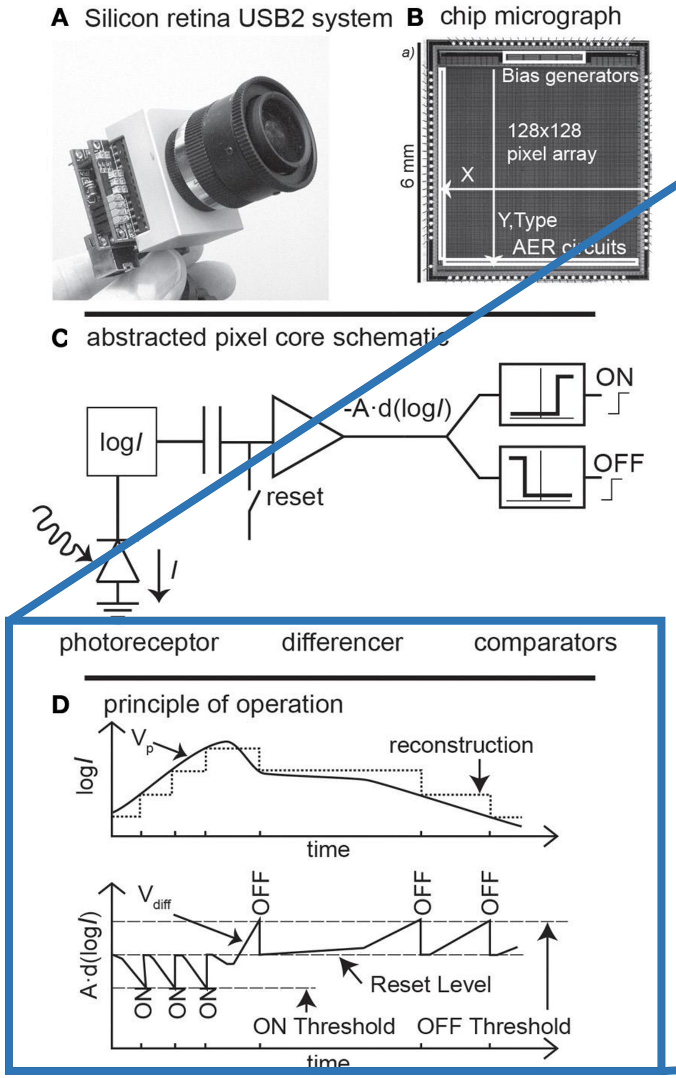




Images from Wikipedia; Images are the copyright of their authors * https://openwetware.org/wiki/BIO254:Phototransduction

Background: Dynamic Vision Sensors

Figure 2 from Delbruck, T., and Lang, M. "Robotic goalie with 3 ms reaction time at 4% CPU load using event-based dynamic vision sensor," Frontiers in Neuroscience Vol. 7, 2013



What constitutes an event?