ON NEUROMORPHIC ARCHITECTURES FOR EFFICIENT, ROBUST, AND ADAPTABLE AUTONOMY IN LIFE DETECTION AND OTHER DEEP SPACE MISSIONS.

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Introduction: Recent discoveries on Mars, at icy moons (Europa, Enceladus), and at dwarf planets have reshaped our notions of the solar system to encompass a wider array of active processes, and in some cases, perhaps life itself. Despite intense interest in these worlds and those yet unexplored, deep space missions are currently limited in scope and cadence due to their significant cost. All deep space missions share stringent limits on mass, power, volume, and many require tolerance to extreme temperatures or radiation, long lifespans, and, perhaps most critically, autonomy to carry out mission activities despite time delays or limited or absent communications opportunities. How can costs be lowered while improving science value?

Background: On Earth, autonomy is poised to create and dramatically reshape entire industries, from drones to autonomous cars. Future planetary science missions should leverage these massive investments in autonomy (perception, planning and control) and develop implementations offering the efficiency and robustness required for deep space missions.

The 2011 Planetary Science Decadal Survey [1] specifically describes these technology needs, including "increased spacecraft autonomy," "new and improved sensors," and highlights prospects for life beyond Earth. Here we focus on this search, recognizing that neuromorphic architectures are a cross-cutting technology with applicability to all deep space missions.

Neuromorphic Architectures (NAs): NAs use a distributed representation, in which independent units cooperate to perform a computation, and communications are encoded via *events* (inspired by spikes) transmitted among units [2]. In neuromorphic architectures computation and memory are co-localized and distributed through massive parallelism, while these functions are separated through dedicated hardware in typical (von Neumann) computational architectures. Moreover, neuromorphic systems are asynchronous and event-driven, as opposed to the periodically sampled/updated traditional architectures, which allow for treatment of salient data exclusively, easing the extraction of useful information from the measured data.

While neuromorphic computing has been pursued since the '70s, concrete implementations of neuromorphic sensors (e.g., Dynamic Vision Sensor, DVS) or processors (e.g., IBM's *TrueNorth*) are recent [3]. For example, *TrueNorth* has 1 million digital neurons, each with 256 connections to other neurons, and achieves 4 billion calculations/s. IBM reports an energy cost of 30 pJ per operation, up to 10^5-fold more efficient than traditional computers [4, 5], and DVSs achieves an equivalent of thousands of frames/s at 23 mW.

Neuromorphic algorithms, such as the neural networks that power so-called deep learning, can be implemented using traditional computers but perform best when paired with distributed computation and memory hardware, hence the current trends, by Google, Intel, NVIDIA, IBM, and others, towards distributed systems.

Challenges for Life Detection: Major mission challenges include access to habitable zones, sample acquisition, *in situ* data processing, and, when the data are too extensive to transmit back to Earth, selection of data or analyses to return to Earth.

On *Mars*, access to so-called *special regions* is inhibited by both inaccessibility and the expense of rating vehicles for Planetary Protection (PP) IVc operations; we envision breaking the current paradigm through a division of labor between multiple vehicles with different PP classifications, e.g. IVc-rated drone or climbing/burrowing bots surveying and sampling, then caching samples to be retrieved and processed by a rover or astronaut. Interesting sampling sites include cave systems and other subsurface environments, or recurring slope lineae [6], locations sheltered from space radiation and where liquid water brines may exist, respectively, that are typically unreachable with a rover.

A plume sampling mission to *Enceladus* [7] would require fine orbit and attitude control to compensate for the instability of the polar orbit, if low relative velocities are required in order to preserve biomarkers of interest. Of note, plumes may host high molecular weight organic materials [8].

The extreme radiation environment of *Europa*, in addition to limited bandwidth to Earth, pose non trivial challenges. Payload operations will have to push the balance between performance, power efficiency, and robustness, e.g., to radiation induced memory errors [9]. Future missions may extend into Europa's icy shell or explore its ocean, requiring extreme autonomy to permit operation without Earth contact for extended periods.

Life Detection: Adaptation to the unexpected is critical for navigating these worlds as well as for life detection. For example, biomarkers such as informational polymers (IPs) could include deoxyribonucleic acid (DNA) or involve non-standard bases or polymers, requiring *adaptability* of the processing algorithms.

Approaches for *in situ* detection and sequencing of IPs include our Search for Extra-Terrestrial Genomes (SETG) instrument, which currently utilizes strand sequencing using protein nanopores [10] coupled to recurrent neural network (RNN) basecalling [11] deployed on a traditional (von Neumann) architecture. Strand sequencing detects translocations of bases through an array of nanopores. The assignment of sequence data (e.g., A,C,G,T bases for DNA) is achieved by monitoring the ionic current blockage produced by bases within a critical pore region. The simplicity and versatility of pore sequencing is not limited to DNA and can be used to detect RNA, modified or non-standard bases, and, potentially, other IPs.

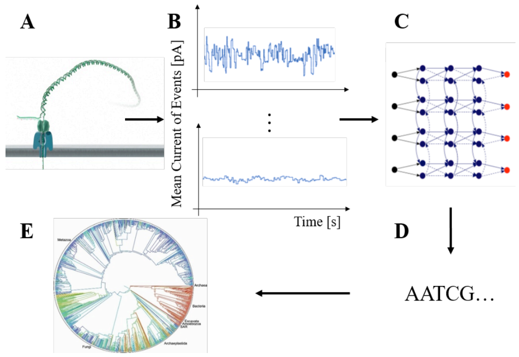

Figure 1: Typical pipeline for single molecule nanopore-based sequencing. Translocation of IPs through a nanopore array (A) generates a large quantity of ionic current measurements (B), that are processed through a RNN to detect the polymer type and (C) to generate an estimated base sequence (D), which, for DNA or RNA, is mapped to the known tree of life (E) to detect ancestral relationships or identify contaminants.

A future NA approach would integrate *event-based sensing*, to reduce the rate of uninformative ionic current measurements, and a distributed hardware *implementation* of the RNN, to improve data processing efficiency, fault tolerance, robustness, and adaptability.

Event-based sensing allows for efficient data processing. DVSs convert the luminance of a signal to a series of events. No events are generated if the signal does not change, therefore no computation is wasted on redundant data, achieving efficient data processing. Similarly, ionic-current signatures of specific bases are detected through impulsive variations of the measured current. *Event-based neuromorphic sequencing and analysis:* detected events would then be processed through a neuromorphic implementation of an ionic-current to taxonomic classification RNN, allowing the sequencing technology to adapt to interpret *in situ* findings. In addition, just as a brain can heal, a neuromorphic architecture can likely be made resilient to radiation noise. In a conventional processor, a bit flip can provoke catastrophic failure while in distributed neural coding, an error or permanent fault of one unit does not propagate catastrophically. Instead, it is expected that a bounded interference will produce bounded degeneration of the output, i.e., a *graceful degradation* of performances. Moreover, *redundancy* in the neural architecture (number of neurons and layers) adds *regenerative* capabilities, where spare units replace damaged ones.

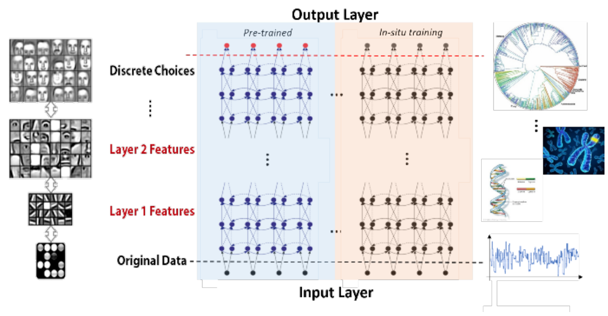

Figure 2: Neuromorphic algorithms in computer vision and speech recognition learn hierarchies of relevant features within noisy data for pattern recognition applications. A similar process applies to *in situ* detection of IPs. Augmenting pre-trained networks with *in situ* training supports adaptation.

Conclusions: NAs, paired with new radiation resistant forms of memory, offer solutions for extreme autonomy. To leverage the inherent advantages of neuromorphic computation over traditional computing and enable a host of deep space missions, in particular for life detection, it is desirable to have a (a) neuromorphic hardware implementation qualified for space flight, in addition to (b) specifically designed neuromorphic algorithms. Event based sensors for strand sequencing and end-to-end learning networks represent examples of promising avenues of research. NASA's interest in considering secondary payloads on essentially all future planetary science missions offers opportunities to demonstrate neuromorphic solutions for deep space, with the vision of developing brain-like systems that can go where no human brain has gone before.

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