Modern Review of the Autonomous Nano Technology Swarm (ANTS) Hardware and Controlling Software

Joshua Schertz
Center for Space Resources
Colorado School of Mines
1310 Maple St., Golden, CO 80401 USA
Email: jschertz@mymail.mines.edu

***Abstract*—The ANTS architecture represents a novel approach for efficiently surveying vasts sections of the solar system using a large swarm of autonomous picosatellites working together. This architecture was not technically possible when it was proposed in 2000, however, advances in commercial off the shelf electronics and neural networks are moving this architecture closer to reality. Multiple challenges still remain, including how to utilize a large solar sail, how to generating enough electricity for all spacecraft functions, and how to develop an autonomous system for operating each spacecraft within the swarm.**

***Index Terms*—artificial intelligence, biomimicry, neural networks, picosatellites, robotics, solar sails, space prospecting, swarms.**

I. Introduction

STEVE Jobs introduced the iPhone in 2007 by stating that every once in a while, a revolutionary product comes along that changes everything. The rapid development of smart phones accelerated the miniaturization of commercial electronic components, including both efficient computation architectures and high quality tiny sensors. In addition, the breakthrough research into neural networks between 2010 and 2012 has created a new industry focusing on designing production ready systems that capitalize on artificial intelligence. Utilizing the core technologies from these two fields, the ANTS architecture is closer to becoming a production ready system capable of autonomously surveying large swaths of the solar system.

The ANTS system has the potential to revolutionize how the solar system is surveyed, prospected and mined. Instead of sending one large, multi-purpose spacecraft to survey one object at a time, the ANTS system will use a large swarms of small, highly autonomous, and specialized spacecraft to survey dispersed structures simultaneously [1]. Due to the large round-trip communications delay the spacecraft will experience, and the unlikely presence of nearby manned missions, the spacecraft must be able to make in-situ decisions to ensure exploration opportunities, and resolve problems and undesirable situations [2]. The autonomous decision making requirement will need to occur both within the collective team and the individual spacecraft.

Some of the largest hurdles with the ANTS include designing a fully autonomous system for controlling all spacecraft systems, and assembling efficient and lightweight hardware for the system to be built on. This paper explores the ANTS architecture, and how recent advances in computing hardware, miniaturization of commercial electronics, and neural networks can enable a working system.

II. ANTS Architecture

The Autonomous Nano Technology Swarm (ANTS) was originally proposed as a system of a thousand picosatellites (less than 1 kg each) that would cooperatively work together to autonomously explore the asteroid belt, prospecting resources for future mining missions [1]. Each spacecraft, known as an ANT, would be responsible for a specific task, often having dedicated hardware to complete this task. Small teams of spacecraft would work together to survey individual asteroids, where workers survey the asteroid with their specific instruments, rulers direct the workers, and messengers communicate the team findings back to Earth. Figure 1 shows how the ANTS architecture would work.

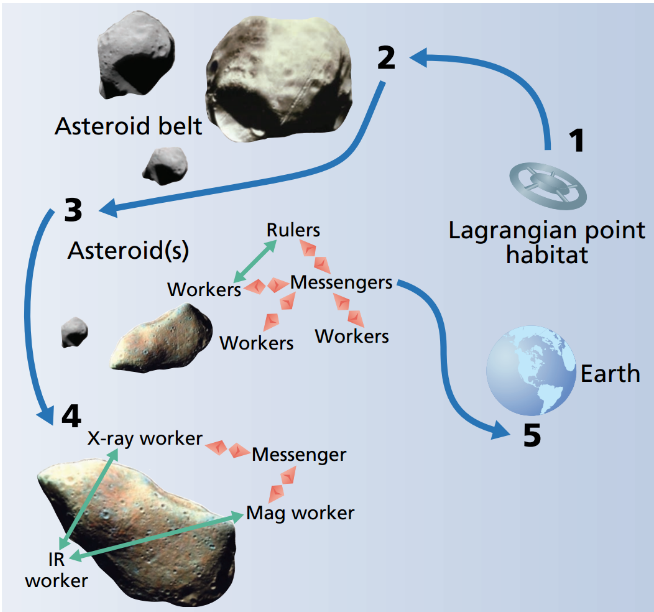

Figure 1. ANTS architecture overview: (1) A transport ship carrying either pre-built spacecraft, or a factory to build spacecraft arrives at a stable Lagrangian point where the rulers, messengers and workers are released into the asteroid belt. (2) Each spacecraft uses solar sails to travel throughout the asteroid belt. (3) Fly-bys of asteroids are used to provide basic data on whether an asteroid warrants further study. (4) Once an interesting asteroid is identified, a team comprised of a ruler, messenger and workers are formed to survey the asteroid. (5) Messengers are continually sending updates and data back to Earth. [3, Figure 1]

The ANTS architecture represents a major shift beyond today's missions architectures that use large spacecraft that have all sensors and logic embedded within them, where they are only able to visit one object at a time. ANTS will use a massive fleet of small, specialized spacecraft that are able to autonomously work together. By allowing the spacecraft to autonomously determine how to achieve their unique goals, mission planners will be able to ask much wider scientific and technical questions, while maintaining a cost efficient overhead.

The idea of using a swarm structure mimics nature and many complex social structures found in animals and insects. For instance, the alpha male wolf is accepted as the leader who communicates with the pack via body language, and marks the territory of the pack, excluding wolves that are not members [4]. ANTS uses a similar structure for organizing and controlling the individual spacecraft within the swarm and their immediate team. Ruler spacecraft guide the team of worker spacecraft they are responsible for, and the worker spacecraft do the work required to achieve their team's part of the overall mission objective.

III. ANTS Social Structure

The science and mission requirements impact the type of controlling social structure used. A few potential approaches for organizing the social structure of the swarm include cooperation among peers, coordination by an oligarchy, or competition in a market [1].

One approach for using cooperation among peers is to utilize self-organization for control and stigmergy for communications. Self-organization involves the macroscopic behavior that emerges solely from numerous interactions with lower level components of the system that use only local environmental information [5]. This means that each member of the swarm can learn how it should act to aid the goal of the swarm by only observing its local environment. No central controller directs the swarm, yet the individual members are able to self organize based on emergent behaviors from simple interactions [2]. A common way for self organized swarm communication is via stigmergy, which is the indirect communication determined through the environment [6]. By combining self-organization and stigmergy, individuals of a swarm know how to act to achieve the swarm's main goal without actually communicating with any other swarm member directly.

The combination of self-organization and stigmergy was used by the multirobot excavation for lunar application system [7], which simulated using multiple independent robots to build structures on the moon from lunar regolith. By using a novel neural network trained with genetic algorithms within the backpropogation system (Artificial Neural Tissue), all robots were able to independently determine how to act in order to accomplish the overall goal, while never communicating directly with each other [7]. This biomimicry approach imitates how ants are able to build sophisticated nests by following their instincts, and reacting to changes in the environment for determining what to do next [8].

Social structures using coordination by an oligarchy rely on one or more rulers to guide the workers in what they should be doing so that the group as a whole accomplishes its main goal. This approach is more centralized than cooperation among peers which is fully decentralized. However, a more centralized approach allows for specialization that has greater efficiency at accomplishing a task using less time or resources.

ANTS uses a three tier structure that is similar to an oligarchy, with a ruler class, a messenger class, and a worker class [1]. The entire swarm is composed of multiple teams of ANT spacecraft. Each team has at least one ruler, one messenger, and multiple workers. Normally there would be enough workers to handle each instrument required for the particular goal the team is responsible for.

A. ANT Ruler

The ruler coordinates the data gathering through the use of rules about what asteroid types and data are of interest [3]. Rulers assemble their teams based on the instruments that nearby workers are carrying. Each team's ruler is responsible for coordinating with other team rulers to ensure the swarm's end goal is proceeding, and that no team is duplicating work of prior teams. Rulers would have dedicated hardware for greater computation and task optimization processing.

B. ANT Messenger

Messengers coordinate communications between workers and rulers, and ground control on Earth [3]. In addition to working with the messenger's immediate team, they also network with other team's messengers. This cross swarm communication is important for ensuring that the swarm as a whole continues to work towards the overall objective. Messengers can either have the same hardware as controllers, or have dedicated communications hardware that would allow them to communicate at higher bandwidths than other classes can handle.

C. ANT Worker

Each worker focuses on a particular mission goal by only gathering its assigned data type, which is determined by what instrument it carries [3]. Each worker spacecraft has its own instrument in order to be more efficient. Typically, each instrument has a different optimal range, thus a spacecraft with multiple instruments would either have to wait for each instrument to take measurements in their optimal range, or have multiple instruments concurrently take measurements at non-optimal ranges, impacting data quality [1]. Using specialized ANT workers with a single instrument prevents them from having to travel to multiple ranges or take sub-optimal measurements. Ultimately, this means that each worker spacecraft is a specialist for the type of instrument they carry and the type of measurements they make. Some example remote sensors include imagers, spectrometers, and radiation and particle detectors using active and passive techniques.

The proposed ANTS architecture assumes that each worker would only have one instrument, however, a compromise could be made where a worker could house multiple sensors with similar operating characteristics. This change would require fewer spacecraft for surveying asteroids, reducing the overall mission costs and overhead.

A unique characteristic of the ANTS architecture is the ascension possibility from a worker to a ruler (or messenger). This would be required if multiple rulers failed and the swarm needed to compensate for the attrition. Also, some mission structures even require the worker who first discovers important mission objectives to become the ruler, assembling the team of workers they need in order to survey the identified asteroid. The flexibility in dictating which spacecraft is a ruler and worker gives the swarm much more resiliency, both in terms of gracefully handling attrition, and in adapting to mission changes over time.

IV. ANTS Spacecraft Design

All ANT spacecraft have the same general functions that facilitate basic survival, including [1]:

- Distributed intelligence and resource management
- Communications capabilities within and outside the swarm
- Navigation ability
- Collision avoidance
- System housekeeping and conflict resolution

These base functions allow each spacecraft to operate independently, ensuring they can interact with the rest of the swarm, they don't damage themselves, and they have error handling capabilities. In the worst case situation, each spacecraft must be able to survive when it looses contact with all other swarm members.

In order to fulfill each of these base functions, all spacecraft have the following subsystems [1]:

- AI heuristic controller and data processing
- Attitude determination and control
- Communications
- Guidance and navigation
- Power generation and energy storage
- Propulsion (solar sail)
- Structures and mounting mechanisms
- Thermal regulation

The requirement to make all of these subsystems fit within a picosatellite is a monumental challenge. A fully functioning spacecraft weighting no more than 1kg must be able to traverse large distances of space while making autonomous decisions and processing observed data.

Recent advances from the semiconductor industry have been made towards the miniaturization of commercial electronics, which might have a place on future spacecraft. Research is being performed on ensuring these commercial electronics can handle the extreme radiation of space, and how they should be selected and validated [9]. For instance, it is prudent to verify the critical components of a system are able to sustain a minimum level of radiation, and are built within a fault tolerant design.

The original ANTS proposal only mentioned general technological concepts needed for the system, however, recent work in femtosatellites (mass less than 100 grams) [10] and Spacecraft on a Chip projects [11][12] have demonstrated designs and prototypes of fully functioning extremely lightweight spacecraft.

A. Spacecraft on a Chip

The spacecraft on a chip design is based on including all of the functionality of a spacecraft on a single integrated circuit, often with all discrete components attached concurrently in a single process [10]. The idea of having a spacecraft on a chip is similar to a System on a Chip (SoC) architecture in that all components of a computer are integrated onto a single piece of silicon [13]. Not only does this decrease the manufacture cost for a SoC, but it allows the end product to be much smaller.

One potential downside of SoCs is that they are essentially throwaway parts because it is difficult to fix or upgrade their hardware due to the hardware being preprogrammed and soldered in place. However, there are some variations of SoCs, such as field-programmable gate arrays (FPGAs), that allow controller chips to be reprogramming. This approach may be ideal for long duration missions where the exact requirements to complete a mission are not know ahead of time.

The KickSat mission demonstrated an architecture for using general purpose commercial electronics assembled on a 3.5 by 3.5 centimeter circuit board with a mass of 5 grams (a Sprite) that is able to transmit sensor data from low Earth orbit [11]. The KickSat mission was comprised of 128 Sprites and a 3U CubeSat that would deploy the Sprites after launch. Figure 2 shows a Sprite that was launched in 2014.

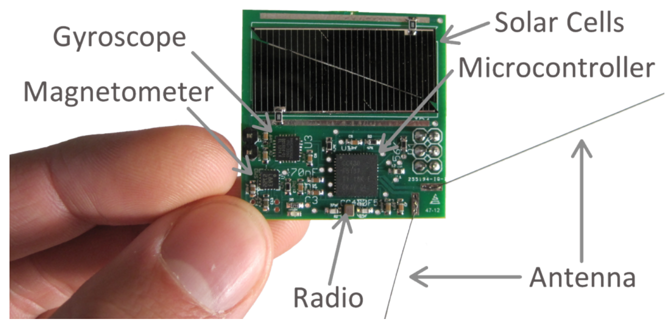

Figure 2. KickSat Sprite launched in 2014, which is a 3.5 by 3.5 centimeter, 5 gram satellite on a chip [11, Figure 3]

Even though the Sprite lacks a propulsion system, it is a proof of concept illustrating the current limits of spacecraft design. The Breakthrough Starshot mission proposes using a spacecraft on a chip design that will be used in a flyby mission to Alpha Centauri [12]. This mission would use spacecraft no larger than a few centimeters across, where a lightsail would allow Earth based lasers to propel the spacecraft up to 20% the speed of light, enabling them to reach Alpha Centauri in just over 20 years from launch. Many of the challenges explored in this mission are applicable to the ANTS mission, especially the solar sail propulsion and radiation hardness of the electronics.

B. Propulsion

Solar sails are the primary propulsion system considered for the ANTS because the limited mass and size of the spacecraft motivate a propellantless actuation, with a side benefit of using the solar sail to concentrate light onto solar cells for power generation [1]. The original ANTS proposal suggested a solar sail 100 m^2 in size, which would allow acceptable acceleration within the asteroid belt at around 2.8 AU [1]. Figure 3 illustrates a schematic of an ANT with the solar sail fully extended, and an estimated transfer time from Earth to the asteroid belt (2.8 AU) of 3.5 years when moving a 1 kg spacecraft.

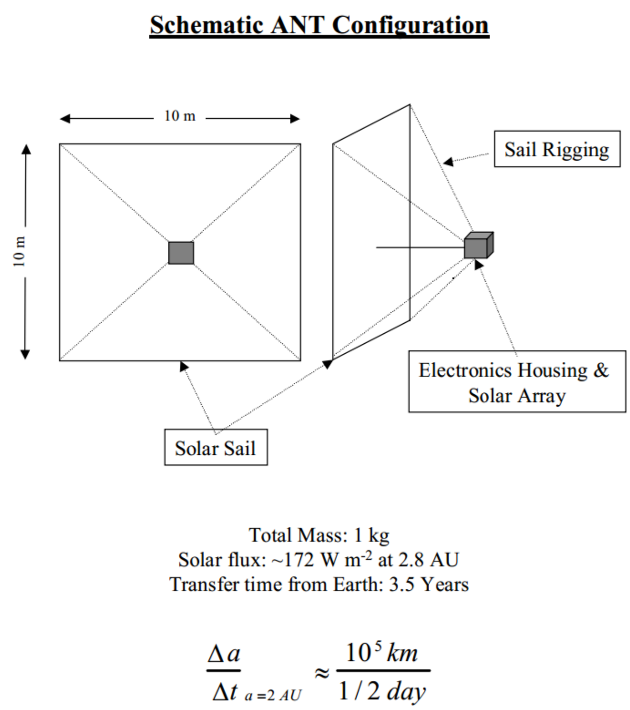

Figure 3. ANT solar sail schematic where a 100 m^2 sail is required for adequate propulsion at 2.8 AU [1, Figure 1]

However, launching and controlling a 10 m by 10 m solar sail is currently an untested feat. The main challenges with large solar sails include unfurling them after launch, and holding them taut to prevent unpredictable wrinkling in the sail surface, which can impact the forces being applied to the spacecraft [14]. The added complexity of managing the sail makes sudden attitude adjustments challenging because there are risks of tangling the sail, and overwhelming the sail and its anchoring system.

Multiple novel propulsion methods and techniques have been proposed for use on femtosatellites. For example, environmental perturbations due to gravity, particle collisions, radiation and magnetic fields can be capitalized for propulsion, including the use of the Lorentz force for navigating through magnetic fields [10]. Many of these solutions make sense for missions near large orbital bodies, but they are not applicable for missions within heliocentric orbit. Therefore, solar sails may still be the optimal solution for femtosatellite and picosatellite propulsion when moving around the solar system.

One proposed solution for simplifying solar sails of femtosatellites is to use rigid solar sails, which benefit from both the high surface area to mass ratio, and the structural rigidity of the spacecraft [14]. The rigid solar sails would be built directly into the spacecraft itself, drastically reducing launch and operational complexities. Additionally, this approach enables the spacecraft to handle much greater adjustments and accelerations without having to worry about deforming the sail. The challenge with rigid sails is finding materials that allow a range of performance characteristics for modifying the attitude of the spacecraft [14]. Further flight testing will need to be done, but rigid solar sails could be a near term solution to propelling the ANTS.

C. Attitude Control

The ANTS would require dedicated attitude control hardware if solar sails are used for propulsion. At a minimum, a three-axis pointing system is needed [1], where the solar sail could be used for one axis of control. More research should be done to determine if a monopropellant based attitude system is required, or if a propellantless system could be utilized for further minimizing weight.

D. Navigation

Once outside of Earth orbit, the ANTS will need to perform stellar navigation. However, instead of installing a star camera on each spacecraft at additional cost and weight, only a few spacecraft could have cameras to perform celestial positioning, broadcasting that data to the swarm, essentially creating a swarm based GPS network [1]. This would limit the distance some spacecraft could get away from those with star cameras installed, but may be an efficient approach for reducing redundant hardware. At a minimum, each spacecraft would have to a star camera, however, the camera might be able to pull double duty as an optical viewing camera for surveying and imaging asteroids.

E. Controller

The spacecraft controller represents the actual computer managing the spacecraft, including the processor, memory and storage. It is one of the most critical components of the spacecraft because it manages all operational activities, including communication, power management, navigation, data processing and system sustainability. Not only does the controller need to have enough computational power to handle all these tasks concurrently, it should be highly configurable so that it can handle the specific tasks required for each ANT class [1].

Recent studies have explored the use of commercial off the shelf (COTS) electronics in spacecraft [9], and many components can be successfully used after following proper verification, taking certain precautions, and adding some system redundancies. Despite these results, the constant radiation exposure over years leads to the accumulation of positively charged effects in the chip's silicon dioxide layer, causing an increase in the current that leaks through a transistor when it's supposed to be turned off [15].

Radiation is a large risk to all electronics in the spacecraft, but the technical complexity of the controller makes it highly susceptible to damage. Historically, spacecraft have either used radiation hardened electronics or shielding to minimize the chance of radiation damage, however, hardened components are often much more expensive and less powerful, and shielding adds extra weight, nullifying the miniaturization of picosatellites. One potential solution would be to use self-healing chips that can heal themselves after they suffer sufficient radiation damage. A recent study [15] using experimental gate-all-around nanowire transistors (as opposed to existing fin-shaped channels) has shown that radiation induced damage can be repaired by applying heat to the transistors, even after thousands of repair sessions. Nanowire transistors can be used in processors, memory and storage, ensuring that all controller hardware can survive during long duration space flights.

The specific computing hardware used on the spacecraft should be determined as close to their launch as possible in order to capitalize on Moore's Law [16], the more than doubling of transistors on circuits about every two years, which allows for designs with more powerful and efficient computing hardware. The challenging aspect of this approach is ensuring that enough testing and validation can be performed on the hardware to ensure it can handle the rigors of space, thus this is a difficult trade off when determining hardware.

If neural networks are a core technology used in the controlling system, it will be worthwhile to use hardware that is specifically built for processing neural networks. For example, Google [17] and Nvidia [18] recently released hardware that includes tensor processing units (TPUs), which are processors specially built for processing matrix multiplication commands, a central part of neural network training. Due to the massively parallelized matrix multiplication possible with a TPU, TPUs are able to process hundreds of thousands of operations per cycle, compared to tens and tens of thousands of operations per cycle of current generation CPUs and GPUs, respectively [17]. Combined with the lower power usage of TPUs, this means that TPUs have orders of magnitude better performance per watt than alternative hardware. Ultimately, the benefit of including a TPU in an ANT is that neural network models could be continually retrained in-situ while the mission is ongoing, allowing the swarm to adapt and learn as its mission advances.

F. Power Generation

Solar cells are proposed for power generation for the ANTS, however, the limited solar intensity in the asteroid belt will be challenging to work with, even when using the solar sails to concentrate the solar light [1]. Low power generation is a key driver for an energy efficient controller and sensor hardware. The power limitation could very well be one of the largest restrictions imposed on the ANTS design. In addition, limited thermal production will need to be considered for all hardware.

G. Communication

The original ANTS proposal mentioned that each ANT would have at least a low and a high bandwidth (LBW, HBW) communications functionality, where the LBW link will be used for collective operations, and the HBW link will be used for close range ANT to ANT transfers [1]. Assuming an omnidirectional antennae is used, the LBW link might have a transfer rate of tens of bits per second with a max range of $2 * 10^5 km$, while the HBW link might transfer megabits per second with a max range of a few hundred kilometers [1].

The proposal did not mention if the messenger class would have dedicated communications hardware, but it might be worthwhile to have a dedicated communications dish for establishing a high bandwidth connection with Earth. Additionally, it might be possible to use the solar sail as a communications dish, although the spacecraft would have to balance the solar thrust with the need to transmit data. This approach would require additional research.

H. Instruments

The core concept of the ANTS is that each worker has its own instrument for surveying different aspects of an asteroid, allowing each ANT to specialize in the type of measurements it makes, all while capturing measurements concurrently. Potential measurements include the following characteristics [1]:

- Chemical (outgassing, interior and surface compositions)
- Physical (albedo, density, interior and surface structure, mass, magnetism)
- Orbital (rotation, eccentricity)

These measurements can often be made with multiple instruments, which allows both flexibility in hardware selection and in-situ team composition. Each sensor usually has it's own operational and performance criteria, meaning that some instruments should not be paired together, and some instruments may require more stringent measurement criteria to be meet before optimal measurements can be made. Each of the instrument types mentioned below already has a sensor developed with the required sensitivity and operational capabilities at masses that are less than 500 grams [1].

1) Camera: A high speed, monochromatic camera can be used for multiple measurements, including asteroid rotation, albedo, and surface structure. Camera measurements enable a model of the asteroid to be built that can be used for the close flybys required for certain measurements. Small, durable, and high quality cameras have greatly benefited from the smart phone revolution. It is possible to find camera sensors that have high pixel density, excellent low light capabilities, and high frame rate video recording. All of these advances will enable future spacecraft to capture much higher resolution images of asteroid surface details.

2) Radio: Radiosounders have been used on prior Mars missions [19] to measure structures several kilometers under the surface. Radiosounders would work well for allowing a spacecraft to measure how an asteroid is composed, making inferences on the concentration of subsurface resources.

Radio ranging is a good technique for indirectly measuring the mass and density distribution of asteroids by measuring small shifts in the frequency of radio transmissions from one spacecraft to another as one spacecraft orbits the asteroid [1]. Different subsurface mass concentrations force the orbiting spacecraft's trajectory to change slightly, resulting in the radio signals modulating, which the other spacecraft can detect. This measurement only requires to two spacecraft to be communicating with each other, meaning that all the orbiting ANT spacecraft could be contributing to this measurement.

3) Spectrometers: Spectrometers are the main instruments used for measuring the chemical composition of the asteroid. Different wavelengths are used for measuring chemicals at varying depths in the asteroid. For instance, visible, near-infrared, UV and x-ray fluorescence spectrometers all provide chemical measurements for materials on the surface of asteroids, whereas gamma-ray spectrometers can return chemical compositions several meters under the surface of asteroids [1]. UV and visible spectrometers are also used for detecting the presence of volatiles on asteroids. Thermal-IR spectrometers can find localized radioactive heat sources or cold-sinks, the later of which can be indicative of large masses of ice near the surface [1].

Each spectrometer can have very different optimal viewing angles and distances. This means that depending on the measurement type and objective, many of the spectrometers should be placed on individual spacecraft.

V. Neural Networks

The original ANTS proposal was vague in how the swarm and spacecraft would be controlled. The controlling network will be the most complicated part of the entire ANTS architecture because it is responsible for autonomously managing all spacecraft operations, and implementing how the spacecraft will accomplish their individual objectives. A multilayer heuristic topology was mentioned, where it might be comprised of either neural networks, fuzzy logic, genetic algorithms or distributed AI [1]. In practicality, however, a much more detailed plan is required before the system can be prototyped.

Even though developing the required network is a monumental task, substantial research has been done on neural network since the 1990s [20][21][22][23][24], allowing neural networks to become the dominant technique for autonomous, self learning systems. Additionally, extensive improvements in computing hardware, especially GPUs, has allowed very large and deep neural networks to be built, enabling models to efficiently automate a wide range of tasks never possible before [25].

Machine learning systems have been used in multiple space based missions over the past few years [26], thus using modern machine learning techniques with the ANTS is a valid option. Due to the complexity of the model required to control the swarm automation, a machine learning process with self learning should produce the best results. For instance, a model using reinforcement learning or deep neuroevolution [27] would enable to model to develop novel intuition for solving problems on its own. However, these models often require simulations for training, requiring extensive knowledge of the environment to ensure the model will be effective in the field. This will require additional research to find potential solutions around this requirement.

One potential machine learning architecture that could be used with the ANTS is the Artificial Neural Tissue architecture, which uses standard neural networks with a coarse-coding mechanism, allowing the network topology to change during training, facilitating self-organized task decomposition and task allocation [7]. Essentially, the Artificial Neural Tissue is a neural network that uses evolutionary selection processes to breed controllers over multiple generations. By defining only the global objective, the Artificial Neural Tissue model is able to autonomously learn how to control and coordinate multiple agents so they can complete the specified goal. The largest restriction with this system is that the training must happen within a simulation because the model requires running multiple generations in order to develop intuition for how to act. Due to this restriction, in-situ training for the ANTS would require a modification for how training is normally performed.

VI. Conclusion

The ANTS architecture represents a novel approach to making use of artificial intelligence for exploring the solar system using picosatellites. Technological advancements made since the original ANTS proposal in 2000 have provided guidance on how such a system could be feasibly built today. The developments made in the miniaturization of commercial off the shelf electronics has created many electronics that can be used in prototype ANT spacecraft, including the computing hardware and instruments. Recent neural network research has defined some approaches for how an ANTS based system would be automated, including the use of reinforcement learning or deep neuroevolution. Additionally, extensive work in driverless cars and machine learning applications have establishing the groundwork for generic autonomous systems, allowing engineers to learn their limitations. Current neural network systems are no golden pill for a completely autonomous system like the ANTS, but they increase the understanding of how to build systems with expanded functionalities.

Even with the additional research done over the past two decades, the ANTS architecture is still not fully feasible. Additional research is required for propulsion, power generation, hardened electronics and machine learning control systems. Dedicated development into these areas could enable the ANTS architecture to become feasible within a few decades.

Acknowledgment

The author would like to thank Dr. Chris Dreyer for the advice he provided while writing this paper, and to Dr. Steve Curtis and Dr. Michael Rilee for providing a copy of their ANTS paper [1].

References

[1] S. A. Curtis, J. Mica, J. Nuth, G. Marr, M. Rilee, and M. Bhat, “Ants (autonomous nano technology swarm) - an artificial intelligence approach to asteroid belt resource exploration,” in *IAF, International Astronautical Congress, 51st, Rio de Janeiro, Brazil; INTERNATIONAL ORGANIZATION; 2-6 Oct. 2000*. Rio de Janeiro, Brazil: International Astronautical Federation, October 2000.

[2] C. Rouff, “Intelligence in future nasa swarm-based missions.”

[3] W. Truszkowski, M. Hinchey, J. Rash, and C. Rouff, “Nasa’s swarm missions: The challenge of building autonomous software,” *IT professional*, vol. 6, no. 5, pp. 47–52, 2004.

[4] M. G. Hinchey, J. L. Rash, W. F. Truszkowski, C. A. Rouff, and R. Sterritt, "Autonomous and autonomic swarms," January 2005.

[5] E. Bonabeau, G. Theraulaz, J.-L. Deneubourg, S. Aron, and S. Camazine, "Self-organization in social insects," *Trends in Ecology & Evolution*, vol. 12, no. 5, pp. 188–193, 1997.

[6] P.-P. Grassé, "La reconstruction du nid et les coordinations interindividuelles chezbellicositermes natalensis etcubitermes sp. la théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs," *Insectes sociaux*, vol. 6, no. 1, pp. 41–80, 1959.

[7] J. Thangavelautham, K. Law, T. Fu, N. A. El Samid, A. D. Smith, and G. M. D'Eleuterio, "Autonomous multirobot excavation for lunar applications," *Robotica*, vol. 35, no. 12, pp. 2330–2362, 2017.

[8] E. Bonabeau, M. Dorigo, and G. Theraulaz, *Swarm intelligence: from natural to artificial systems*. Oxford university press, 1999, no. 1.

[9] K. A. LaBel and S. M. Guertin, "Nasa past, present, and future: The use of commercial off the shelf (cots) electronics in space," 2017.

[10] T. R. Perez and K. Subbarao, "A survey of current femtosatellite designs, technologies, and mission concepts," *Journal of Small Satellites*, vol. 5, no. 3, pp. 467–482, 2016.

[11] Z. Manchester, M. Peck, and A. Filo, "Kicksat: A crowd-funded mission to demonstrate the world's smallest spacecraft," 2013.

[12] Breakthrough-Initiatives, "Breakthrough starshot," 2018, [Online; accessed 22-February-2018]. [Online]. Available: https://breakthroughinitiatives.org/initiative/3

[13] W. contributors, "System on a chip — wikipedia, the free encyclopedia," 2018, [Online; accessed 22-February-2018]. [Online]. Available: https://en.wikipedia.org/w/index.php?title=System_on_a_chip&oldid=823414650

[14] L. Weis and M. Peck, "Active solar sail designs for chip-scale spacecraft," 2014.

[15] I. Spectrum, "Self-healing transistors for chip-scale starships," 2017, [Online; accessed 22-February-2018]. [Online]. Available: https://spectrum.ieee.org/semiconductors/devices/selfhealing-transistors-for-chipscale-starships

[16] G. E. Moore, "Cramming more components onto integrated circuits," *Proceedings of the IEEE*, vol. 86, no. 1, pp. 82–85, 1998.

[17] K. Sato, C. Young, and D. Patterson, "An in-depth look at google's first tensor processing unit (tpu)," 2017, [Online; accessed 25-February-2018]. [Online]. Available: https://cloud.google.com/blog/big-data/2017/05/an-in-depth-look-at-googles-first-tensor-processing-unit-tpu

[18] J. Appleyard and S. Yokim, "Programming tensor cores in cuda 9," 2017, [Online, accessed 25-February-2018]. [Online]. Available: https://devblogs.nvidia.com/programming-tensor-cores-cuda-9/

[19] R. Jordan, G. Picardi, J. Plaut, K. Wheeler, D. Kirchner, A. Safaeinili, W. Johnson, R. Seu, D. Calabrese, E. Zampolini *et al.*, "The mars express marsis sounder instrument," *Planetary and Space Science*, vol. 57, no. 14-15, pp. 1975–1986, 2009.

[20] L. Bottou, C. Cortes, J. S. Denker, H. Drucker, I. Guyon, L. D. Jackel, Y. LeCun, U. A. Muller, E. Sackinger, P. Simard *et al.*, "Comparison of classifier methods: a case study in handwritten digit recognition," in *Pattern Recognition, 1994. Vol. 2-Conference B: Computer Vision & Image Processing., Proceedings of the 12th IAPR International. Conference on*, vol. 2. IEEE, 1994, pp. 77–82.

[21] S. Hochreiter and J. Schmidhuber, "Long short-term memory," *Neural computation*, vol. 9, no. 8, pp. 1735–1780, 1997.

[22] C. Cortes and V. Vapnik, "Support-vector networks," *Machine learning*, vol. 20, no. 3, pp. 273–297, 1995.

[23] D. C. Ciresan, U. Meier, J. Masci, L. Maria Gambardella, and J. Schmidhuber, "Flexible, high performance convolutional neural networks for image classification," in *IJCAI Proceedings-International Joint Conference on Artificial Intelligence*, vol. 22, no. 1. Barcelona, Spain, 2011, p. 1237.

[24] A. Krizhevsky, I. Sutskever, and G. E. Hinton, "Imagenet classification with deep convolutional neural networks," in *Advances in neural information processing systems*, 2012, pp. 1097–1105.

[25] T. Dettmers, "Deep learning in a nutshell: History and training," 2015, [Online, accessed 26-February-2018]. [Online]. Available: https://devblogs.nvidia.com/deep-learning-nutshell-history-training/

[26] A. McGovern and K. L. Wagstaff, "Machine learning in space: extending our reach," 2011.

[27] F. P. Such, V. Madhavan, E. Conti, J. Lehman, K. O. Stanley, and J. Clune, "Deep neuroevolution: Genetic algorithms are a competitive alternative for training deep neural networks for reinforcement learning," *arXiv preprint arXiv:1712.06567*, 2017.