**Research Campaign: Automation and Artificial Intelligence for Materials Research in Low Earth Orbit**

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The space orbital environment is characterized by several factors that affect scientific experiments and the operation of instruments and equipment, including robots and computers. The main factors are microgravity, high-energy radiations, very low atmospheric pressure, and dramatic differences in temperature.

Low Earth Orbit refers to trajectories about the Earth that are at altitudes typically less than 1000 km. Although there has been a continued quest by NASA for its collaborating institutions and companies to provide Low Earth Orbit (LEO) commercial and international platforms, the International Space Station (ISS) so far provides the most widely used and best understood LEO platforms. The ISS orbits the Earth at an altitude of ~ 400 km.

The state of microgravity, typically 10-5 *g*, is achievable in LEO. Gravity effects hide other effects pertaining to materials or fluids under study, and that depends often on the intrinsic properties or the state of matter [[1](#microg)]. Microgravity research thus allows to study the gravity effects on phenomena that are normally masked by gravity on Earth. Ref. [[1](#microg)] provides a description of the main modifications in the study of the behavior of matter in physical and chemical processes that involve at least one fluid phase, e.g. crystal growth, alloy solidification, separation of biological substances, in a microgravity environment.

Radiation in space can be classified into trapped and transient types – see description in [[2](#ESA)]. The trapped particles are the subatomic particles, mainly protons and electrons, trapped by Earth's magnetic field, which create the so-called van Allen radiation belts around our planet. The transient radiation is mainly composed of protons and cosmic rays that constantly stream through space and are enhanced during the magnetic storms on the Sun called solar flares. The innermost van Allen belt is at a closest distance that is ~ 600 km from the Earth’s surface, and as far as above 1000 km from the Earth’s surface. LEO platforms at altitudes lower than 600 km such as the ISS are thus protected from most of the transient radiation. Despite this shielding by the van Allen belts, protective measures from high-energy single particle radiation events that can cause damage or disrupt the operation of spacecraft instruments and similar hardware in LEO have remained in consideration.

The space thermal environment experienced by a platform in LEO is defined by three effects [[3](#Astrome)]: the solar flux, the albedo (a measure of the diffuse reflection of solar radiation out of the total solar radiation) and Earth’s infrared radiation. The latter two effects are a function of altitude of the orbit, while the first one is a function of distance from the Sun. During the sun–lit phase of the orbit, the platform heats up from all of the three mentioned thermal effects. When in the eclipse phase, the solar flux and albedo effects are not encountered, and the platform can be exposed to temperatures as low as the Earth’s average infrared temperature of -18˚C. The temperature in sunlight in LEO can be determined as 394 K, after applying Stefan-Boltzmann’s law for a black body encountering a solar energy flux of 1,360 W/m2 at 1 AU from the Sun. The typical range of temperatures has been found to be from  -170 ˚C to 123 ˚C in LEO. The upper-bound temperature (equivalent to 396 K) in the noted range is close to the value obtained from Stefan-Boltzmann’s law. The lower-bound temperature of -170 oC in the noted temperature range, however, is far lower than the average Earth infrared temperature of -18 oC.

The aim of this research campaign paper is to frame useful research objectives on automation and artificial intelligence capabilities in LEO platforms, with the purpose to realize important goals that are of current interest, which are: the operation of robots in temperatures that are dangerous to human presence, the operation of supercomputers in spacecraft, the performance of real-time simulations of materials in the supercomputers, and the adaptation of space module surfaces for physical integration (or accommodation) of the supercomputers. The conditions that have been described in LEO are accounted for in the derivation of the research objectives.

1. **Operation of Robots at Temperatures that are Dangerous to Human Presence**

To operate a robot in temperatures that are dangerous to human presence will require increasing the level of autonomy of the robot to enable it to independently respond to external stimuli that result from extreme temperature conditions. The robot should be, thus, designed to self-regulate its temperature to acceptable ranges that are defined by factors such as the operating temperatures of the electronics, and the wear and tear of the robot materials. A case scenario of temperature regulation in an untethered robot is in the operation of a soft robot muscle that reduces the robot temperature in hot conditions through sweating [4]. In the described scenario, the sweating mechanism is initiated by a temperature stimulus. In [[5](file:///C:\Users\marshall.DESKTOP-4BECME1\Documents\NASA\BIO%20AND%20PHYSICAL%20SCIENCES%20DECADAL%20SURVEY\AI%20and%20Automation%20in%20Materials%20Research\Effect_of_temperature_variation_on_repeatability_positioning.pdf)], untethered soft robots are designed to make programmed responses to thermal stimuli by modifying their shape and volume. The response function of the robot can be updated in order to improve the response in subsequent stimuli. This would involve an artificial intelligence (AI) algorithm that records the data of the response to stimuli, learns from the data, and updates its response function in order to engage actions that result in improved thermal regulation. Research objectives to be pursued in the operation of robots in LEO environmental conditions dangerous to human presence can thus be summarized. **Objective** **1.1)** **Increase in the level of autonomy of the robot to enable it to independently respond to external stimuli that result from extreme temperature conditions. Objective 1.2) The development of AI algorithms that update the robot response to thermal stimuli in order to improve thermal regulation.**

Electronic hardware that engages the actuators or electric drivers for mechanical motion in a robot is typically embedded in the robot. Electronic devices and components are designed to operate optimally within a certain range of temperatures defined by the manufacturer. In addition to having to manage the amount of heat that transfers to the electronics from the space environment, the heat generated from the operating electronics has to be managed. Typical electronic hardware for collecting and processing information include sensing capabilities, processing units, and data storage (or memory) units. Sensing capabilities typically include amplifiers and filters. The operating temperatures of sensors, amplifiers, and filters must be observed in the thermal management and control of the robot operating systems. Processing units are predominantly made of logic gates. Memory unit technologies can be static RAM (SRAM), dynamic RAM (DRAM), and ROM or its programmable variants. The operating characteristics of the logic families, e.g. transistor-transistor logic (TTL) or complementary metal oxide semiconductor (CMOS), that constitute the digital hardware must be observed in the thermal management and control of the robot operating systems. When radiation collides with the electronics, they can change the contents of memory cells, cause spurious currents to flow, or even burn the devices. For integrated circuits to resist the effects of radiation, it usually involves redesigning the chips so that they are protected from the harmful radiation.

Spacecraft in LEO may orbit for about 90 to 130 minutes, depending on the altitude. During this time it encounters both hot and cold regions. In extreme cold regions, it may be too cold for the sensors to register the temperature, and this will in turn prevent the robot from receiving signals that initiate temperature regulation. Apparently, most temperature sensors operate as low as - 40 oC. This is well above the coldest noted temperature of -170 oC in LEO. **Objective 1.3)** **This reveals the need to advance technologies in temperature sensing that enable their operation beyond current operating limits, or to compensate for the failure to sense beyond these limits during operation of the robot or the electronics.**

Given the occasional prevalence of temperatures that are beyond operating limits of a robot or spacecraft in LEO, a thermal control system is a necessity for sustaining operation in extreme temperature conditions. Thermal control systems (TCS) can be categorized as: passive TCS that require no mechanical moving parts or moving fluids and no power consumption; and active TCS that require mechanical moving parts or moving fluids or electrical power [3]. To maintain temperatures below maximum operating temperatures, a cooling mechanism is required. In a passive TCS, this can be achieved by heat distribution along the structure of the robot, and by multi-layer insulation on the surface of the robot. Variable emissivity and absorptivity of surface coatings have also enabled the management of thermal loads. Contrary to metals that quickly dissipate heat, synthetic materials retain heat. In a robot with synthetic materials, a means to release the heat retained has to be devised without adopting costly procedures that lead to increase in weight and volume, such as installing a fan inside the robot. In [4], internal cooling of the robot is attained by perspiration of the robot at hot temperatures. The mechanism involves the engagement of actuators above a certain temperature to result in the squeezing of water from lower layers towards perforated upper layers of the synthetic material which dilate to enhance evaporation of the water.

A robot can also be programmed to temporarily shut down or scale down its operation when it senses hot temperatures above certain limits. This has the result of avoiding the flow of currents in conditions that are detrimental to the electronic devices engaged in operation.

**Objective 1.4) A proposition that would enhance thermal regulation and efficient energy management could involve the construction of a thermal engine cycle that will store thermal energy that is conducted away from spacecraft when environmental temperatures are high, and supply some of the stored energy to maintain operation of the spacecraft when environmental temperatures are low**. **Mechanisms that enable scaling down or suspending operation of the robot in the most extreme conditions should be in consideration**.

1. **Onboard Supercomputer with Machine Learning Capabilities for Real-time Simulations**

Multi-core computing chips have been applied in space [6]: multi-core architectures have significant potential to implement scalable computing, thereby lowering spacecraft vehicle mass and power as the number of systems needed to implement onboard functions are reduced. **Objective 2.1) Given the minimal level of human intervention,** **multi-core computing systems have to be fault tolerant and subjected to control, allowing allocation and deallocation of cores to particular computations as some cores may instantly fail to perform**. In supercomputing, a computation is partitioned across the various cores in a distributed-memory or shared-memory distribution with the result of speeding up the computation. An alternative architecture that can increase computational speed is quantum computing. Quantum algorithms are exponentially faster than classical algorithms. NASA has made advances on quantum computing devices, such as the quantum annealing machine, which has control of ~ 72 qubits and has been used to solve combinatorial optimization problems in computer vision and machine learning [6]. Advances and realizations in quantum computing in ISS can be facilitated by cold atom studies in the Cold Atom Laboratory (CAL), in agreement with recommendations of the mid-term decadal survey in physical and biological sciences [7]. Another possible advancement in supercomputing in space is reconfigurable computing. In reconfigurable computing architectures, such as Field Programmable Gate Arrays (FPGAs), the hardware can be reconfigured in real time to meet actual data processing requirements. FPGAs can also be suitable targets for fine-grained parallellism, while coarse grained parallelism remains targeted at multi-processor computing nodes. **Objective 2.2) Supercomputing capabilities that include quantum computing, reconfigurable computing, and combinations of parallel computing technologies should be developed for application in space.**

Some current state-of-the-art approaches in supercomputing in LEO space platforms can be highlighted. Hewlett Packard Enterprise (HPE) Spaceborne Computer is a high-performance computer system that runs in excess of one teraflop at the ISS [8]. Unlike most space computers that incorporate hardware-based modifications to ensure reliability amid the radiation storms that periodically sweep through outer space, the Spaceborne Computer relies on a software approach that incorporates real-time throttling of system operations, based on current conditions. According to [8], it takes more than 430 trillion calculations per second (or 430 teraflops) to make it to the bottom of the usual Top500 list of the global ranking of the supercomputer processing speed. **Objective 2.3) Despite the impressive processing speed as a space application, space computers will have to up their game considerably in the future to reach the top of their performance**. In another state-of-the-art development, Microsoft has partnered with Hewlett Packard Enterprise to bring Azure cloud computing to the ISS. HPE’s Spaceborne Computer-2 integrates capabilities in edge computing, artificial intelligence and cloud connections [9]. The cloud and edge computing capabilities overcome the usually limited bandwidth between the ISS and Earth. *Machine learning capabilities could enable the anticipation of radiation storms that would upset operation of the onboard computer or the mission spacecraft.*

Machine learning algorithms can be integrated in computational material models. The microgravity environment in LEO provides conditions in which material properties can be better determined, given the relative perfection with which growth and formation of materials is realized. An illustrative example is the crystallization of protein crystals: although the growth rate of the crystals is significantly slower in LEO conditions than on Earth, perfect and bigger 3D crystals are obtained, providing more data points for computation than their terrestrial counterparts. A materials simulation approach will be to use results of experimentally determined material properties in the LEO platform to parametrize material models that are simulated in real time. It is important to recall here that a model describes the characteristics of the material, while a simulation emulates the behavior of the material described by a model. In parametrization, the model parameters are numerically fitted to known material properties. Machine learning involves the use of new data points to improve the model algorithm by continuously refining or correcting the model. **Objective 2.4) Material properties should be obtained from experiments conducted in LEO platforms, for later use in the parametrization of models that are simulated in real time. Machine learning will use newly obtained data points from experiments to refine or correct the material models**.

Adaptation or change of the space module surface for physical integration of the onboard supercomputer can be attained with surface material applications that are actuated to conform to a predicted shape and volume in response to a stimulus. Materials that can be actuated are designed to respond to a kind of stimulus. Liquid crystal elastomers (LCEs) respond to thermal stimuli by generating large, powerful, and repeatable deformations upon heating above their nematic-to-isotropic transition temperature [5]. Actuators based on graphene materials have shown a large displacement and rapid response to electrical stimuli [10]. Responsive materials based on polymer liquid crystal hydrogels can bend under light stimulation [11]. Some of the commonly noted limitations in the actuated response of the materials are the failure to support large loads, a slow response time, or the inability to output a large displacement. **Objective 2.5) There is need to advance the design of the actuating materials in order to meet the demands of physical integration of the onboard supercomputer.** *In situations where the mechanical pressure from the accommodating supercomputer is not a desired stimulus, a conversion to a non-mechanical stimulus can be enabled.*

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