Inspiration for Space 2.0 from Autonomous NanoTechnology Swarms Concept missions towards Autonomic Robotic Craft

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ABSTRACT

This paper introduces at a high level the concept of Autonomic Robotics based on the Autonomic Computing paradigm with the aim to achieve a systematic means to obtaining self-managing and autonomous robotic craft software for future space missions. It briefly reflects on the author’s research that took place in the noughties with NASA GSFC, in particular on the ANTS concept mission Autonomic Computing stream before briefly highlighting the authors research streams in the twenty-tens moving towards NewSpace or Space 2.0. Three specific streams of research within this area are summarised; cooperation between the autonomic robotic craft, an autonomic robotic architecture (and case-studies to derive such) and the development of an Autonomic Systems capability model for CubeSats.

KEYWORDS: Autonomic Systems, Autonomic-ANTS, Autonomic Robotics, Autonomic CubeSats, Self-Managing Systems, Autonomous Systems.

1. INTRODUCTION

During the noughties, significant research went into the NASA ANTS (Autonomous NanoTechnology Swarm) concept mission [1],[2]. A stream of this was inspired by the Autonomic Computing concept, to create self-managing systems, as a specialized and separate layer from the mission task-oriented autonomy that the majority of Autonomous System research focuses on [3].

ANTS (Autonomous Nano-Technology Swarm) is a NASA concept mission, a collaboration between NASA Goddard Space Flight Center and NASA Langley Research Center, which aims at the development of revolutionary mission architectures and the exploitation of artificial intelligence techniques and the paradigm of biological inspiration in future space exploration [1],[2]. The mission concept includes the use of swarm technologies for both spacecraft and surface-based rovers, and consists of several submissions such as SARA (The Saturn Autonomous Ring Array), PAM (Prospecting Asteroid Mission) and LARA (ANTS Application Lunar Base Activities).

Autonomic Computing and Communications are inspired by the biological nervous system and properties of homeostasis and responsiveness The general properties of an autonomic, or self-managing, system can be summarized by four objectives—self-configuration, self-healing, self-optimization and self-protection—and four attributes— self-awareness, self-situation (environment & context awareness), self-monitoring and self-adjusting [4],[5],[6],[7],[8]. Essentially, the objectives represent broad system requirements, while the attributes identify basic implementation mechanisms. The autonomic paradigm assigns an “autonomic manager” to a component utilizing a sensors and effectors and a closed control feedback loop to provide the self-management. Autonomic Mangers communicate and cooperate to provide system wide self-management. AMs may communicate and cooperate through a combination of various means; self-managing event messages, heart-beats, pulse signals, RPCs, and mobile agents.

In terms of the ANTS mission, Autonomy, for instance, results in a worker having responsibility for its scientific mission goals. To achieve these goals many autonomic self-* properties such as self-configuration will be necessary, as well as utilization of heart-beats, pulse signals and reflex reactions within Autonomic Managers [3].

'SPACE 2.0', 'NewSpace', 'Astropreneurship' or "the new space race" are terms for what has been described as a movement and philosophy, combining the methods and optimism of the information age with the nostalgia, poetry and epic narratives of the space age, while delineating from traditional, or 'mature space' [9]. Space 2.0 is best thought of as a new wave of entrepreneurial activity emerging over the past decade, where ambitious startups have begun to establish new commercial models in space related domains - such as launch, Earth observation, ground services and big data. This new wave of activity is beginning to challenge the incumbency of traditional players - in other words, big government agencies and big aerospace - who have for half a century dominated the sector [9].

This paper considers the extensions of our noughties research on Autonomic-ANTS for SPACE 2.0, where the research conducted by our PhD researchers during the '10s essentially falls under "Autonomic Robotics" (research to apply the Autonomic Computing paradigm to the self-management of robotics/crafts) specifically for SPACE 2.0; fitting with the grand vision that SPACE 2.0 could see the fulfilment for the ANTS exploration concept, for instance, could CubeSats become the real fulfilment for the ANTS crafts? It briefly starts with reviewing the AC paradigm and how this fits with Robotics. The paper then reports on three ongoing and concluding streams of the authors' research, innovation and development; 1) Autonomic Inter-Cooperation, 2) Autonomic Intra-Cooperation and 3) CACM-CubeSat Autonomic Capability Model to engineer Autonomicity into Space 2.0 missions.

2. AUTONOMIC COMPUTING

In 2001, IBM launched the Autonomic Computing initiative. IBM's Paul Horn likened the needs of large scale systems management to that of the human Autonomic Nervous System (ANS). The ANS, through self regulation, is able to effectively monitor, control and regulate the human body without the need for conscious thought. This self-regulation and separation of concerns provides human beings with the ability to concentrate on high level objectives without having to micro-manage the specific details involved. The vision and metaphor of Autonomic Computing is to apply the same principles of self-regulation and complexity-hiding to the design of any system that has at its heart a computer (aka a computer-based system), in the hope that eventually computer controlled systems can achieve the same level of self-regulation as the human ANS. This vision of creating self-managing and self-directing systems has become mainstream in both the academic and industrial research community under the Autonomic and Autonomous Systems (and related) initiatives [3]-[8],[10]-[12].

The ANS is that part of the nervous system that controls the vegetative functions of the body, such as circulation of the blood, intestinal activity, and secretion and production of chemical "messengers" (hormones) that circulate in the blood. The sympathetic nervous system (SyNS) supports "fight or flight", providing various protection mechanisms to ensure the safety and wellbeing of the body. The parasympathetic nervous system (PaNS) supports "rest and digest", ensuring that the body performs necessary functions for long term health.

The general properties of an autonomic (self-managing) system can be summarized by four objectives: being self-configuring, self-healing, self-optimizing and self-protecting, and four attributes: self-awareness, self-situated, self-monitoring and self-adjusting. Essentially, the objectives represent broad system requirements, while the attributes identify basic implementation mechanisms [7].

Self-configuring represents a system's ability to re-adjust itself automatically; this may simply be in support of changing circumstances, or to assist in self-healing, self-optimization or self-protection.

Self-healing, in reactive mode, is a mechanism concerned with ensuring effective recovery when a fault occurs, identifying the fault, and then, where possible, repairing it. In proactive mode, it monitors vital signs in an attempt to predict and avoid "health" problems (reaching undesirable situations).

Self-optimization means that a system is aware of its ideal performance, can measure its current performance against that ideal, and has defined policies for attempting improvements. It may also react to policy changes within the system as indicated by the users. A self-protecting system will defend itself from accidental or malicious external attack. This necessitates awareness of potential threats and a means of handling those threats.

In achieving such self-managing objectives, a system must be aware of its internal state (self-aware) and current external operating conditions (self-situated). Changing circumstances are detected through self-monitoring and adaptations are made accordingly (self-adjusting). As such, a system must have knowledge of its available resources, its components, their desired performance characteristics, their current status, and the status of inter-connections with other systems, along with rules and policies of how these may be adjusted. Such ability to operate in a heterogeneous environment will require the use of open standards to enable global understanding and communication with other systems.

These mechanisms are not independent entities. For instance, if an attack is successful, this will include self-healing actions, and a mix of self-configuration and self-optimisation, in the first instance to ensure dependability and continued operation of the system, and later to increase the self-protection against similar future attacks. Finally, these self-mechanisms should ensure there is minimal disruption to users, avoiding significant delays in processing [7].

2.1 Autonomic Element

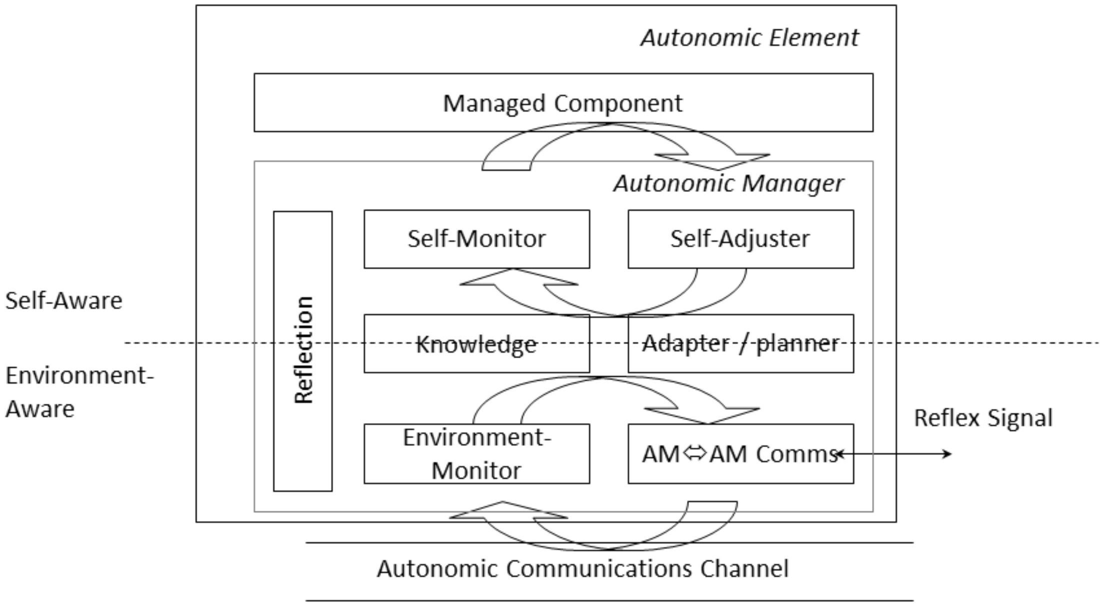


Figure 1. Autonomic Element.

At the heart of the architecture of any autonomic system are sensors and effectors. A control loop is created by monitoring behaviour through sensors, comparing this with expectations (knowledge, as in historical and current data, rules and beliefs), planning what action is necessary (if any), and then executing that action through effectors. The closed loop of feedback control provides the basic backbone structure for each system component. Figure 1 highlights that there are two conceptual control loops in an Autonomic Element – one for self-awareness (around the Managed Component) and another for self-situation (environmental awareness, situation and context-awareness) [8].

IBM represents this self-monitor/self-adjuster control loop as the monitor, analyze, plan and execute (MAPE) control loop. The monitor-and-analyze parts of the structure process information from the sensors to provide both self-awareness and an awareness of the external environment. The plan-and-execute parts decide on the necessary self-management behaviour that will be executed through the effectors. The MAPE components use the correlations, rules, beliefs, expectations, histories, and other information known to the autonomic element, or available to it through the knowledge repository within the AM [11] (this is also referred to as MAPE-K loop).

2.2 Autonomic Environment

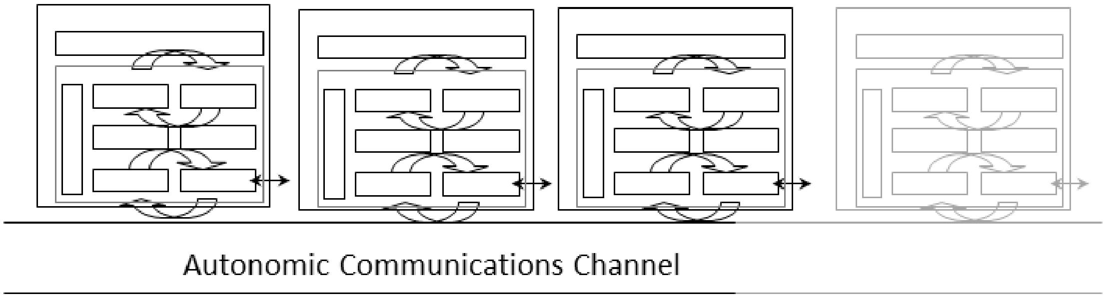


Figure 2. Autonomic Environment.

The autonomic environment requires that autonomic elements and, in particular, autonomic managers communicate and cooperate with one another concerning self-* activities, in order to ensure the robustness and self-management of the total system (system of systems) as depicted in Figure 2.

Some interpretations of the original AC paradigm's vision is that it should be a peer-to-peer approach, yet many of the solutions still operate on a client-server/slave-master basis. The NASA ANTS concept mission goes to the other end of the spectrum using the SWARMS paradigm [27],[24]. The ideal form of cooperation is one of the topics of our research and discussed later.

2.3 Autonomic Robotics

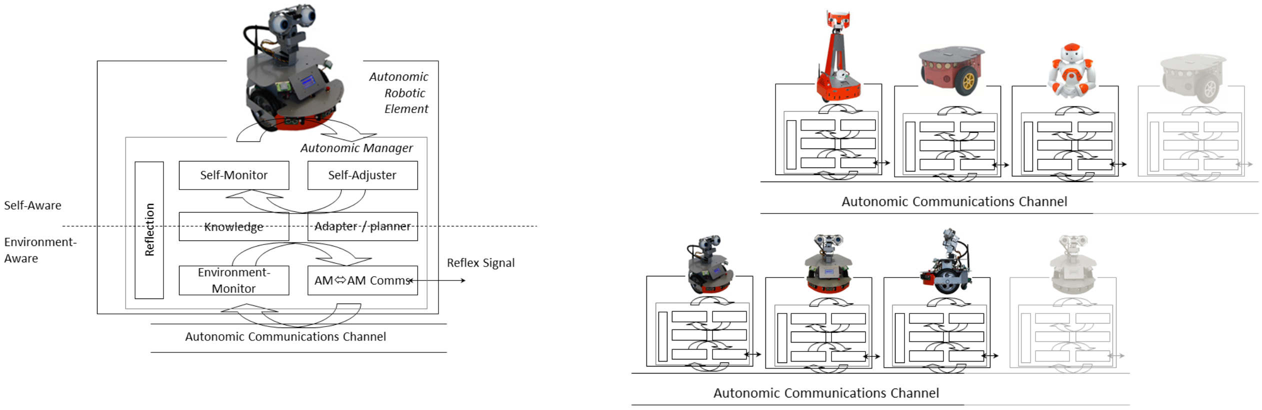


Figure 3 Autonomic Robotic Element (left-hand side) & "Autonomic Robotics" Environment (right-hand side)

Upon consideration of Figure 1 it may be noted that an Autonomic Manager is monitoring/adjusting an MC (Managed Component). In the majority of AC (Autonomic Computing) cases these are computer systems. We have hypothesised in the past that this should be extended to all computer-based systems, and that all CBS should be autonomic [25]. In this case the MC is the robot (Figure 3 LHS). We are researching the potential for the AC paradigm to offer a systematic approach to autonomy through its specific form of self-managing collaboration (Figure 3 RHS).

3. AUTONOMIC ELEMENT INTER-COOPERATION (EXTERNAL)

The main purpose of this PhD research programme stream was to investigate co-operation strategies that will enable an Autonomic Paradigm/Protocol change; i.e. self-recognition (of the need) and then self-configuration, such as from swarms to constellations to clusters of robots to enable correct paradigm/protocol collaboration to perform their mission without human involvement.

Reconsidering the Autonomic Computing (self-managing systems) paradigm, it accepts that components and elements will fail but intends that the system does not by providing self-healing, self-configuring and reconfiguring, self-protecting and self-optimising strategies through the cooperation of the elements within the system.

Cooperation between elements seems straight forward when you consider the logical Autonomic architecture in Figure 2. An AE (Autonomic Element) consists of an Autonomic Manager (AM) and the Managed Component (MC), where in this case the MC is the robots and their supporting architecture with each having its own AM and thus referred to as an ARE (Autonomic Robotic Element). Yet this logical view hides substantial complexity, especially when one considers the spectrum of cooperation, they range from client-server/master-slave, through peer-to-peer, to the extreme of SWARM computing modes of collaboration or cooperation between elements.

For instance, Grid Computing systems tend to follow a client-server approach but recommendation have been made to become more proactive in recognising faults by incorporating more of a peer-to-peer and Autonomic approach [26]. As has been highlighted, we have worked with NASA Goddard Space Flight Center (GSFC) on SWARM based approaches for future concept missions e.g. ANTS [3],[24],[27] yet once the mission configures into a sub-swarm to do the actual exploratory science, it very much resembles a client-server/master-slave or P2P cluster approach, not a SWARM.

We are investigating the best scenarios and scalability ranges for each of these cooperation paradigms with Robots [13]. Autonomic Computing also has self-adaptability and self-organisation as part of its mandate, as such we are also investigating the potential that the nature of the system can change depending on the situation facing it. For instance, taking the NASA ANTS PAM concept mission as an example, the 2.5 year flight of 1000s of robotic craft to the asteroid belt may best be achieved in a Swarm operational mode. Upon reaching the belt switching to peer-to-peer paradigm may be best while surveying for potential asteroids of interest. And then upon scientific study of specific asteroids of interest, self-configuring into a client-server/master-slave mode with sub-swarms or clusters having a ruler directing the operation and communicating with other sub-swarm leaders, to for instance, share rare resources (as up to 80% of the craft may have been lost in the 2.5 year journey resulting in scarce craft types amongst the sub-swarms).

In this research stream, early research explored using 4x X80-H robots and then moved onto building a swarm simulator to obtain large scale scenarios of 1000s of SoftBots (Figure 4).

As has been highlighted, the Autonomic Computing paradigm aims to ensure that the *system of systems* or *mission* continues to operate even under fault conditions by self-adapting (and accepting this will be at less than optimal performance). As such the Autonomic System requires contingency strategies at its disposal. One example scenario we explored was total failure of communications between robots and attempting to communicate by semaphores through flashing lights and then extending this to robots reading messages from each other's display screens (Figure 5) [14].

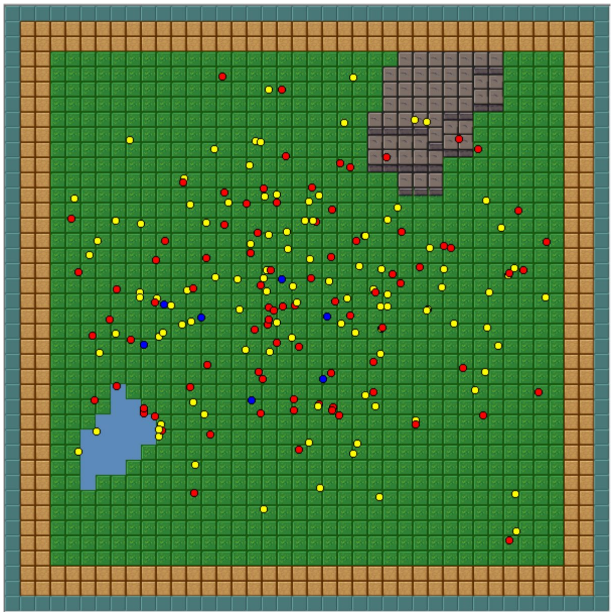


Figure 4. Autonomic Robot Swarm Simulator.

Figure 5. X80-H and X80 communicating under comms fault conditions [14].

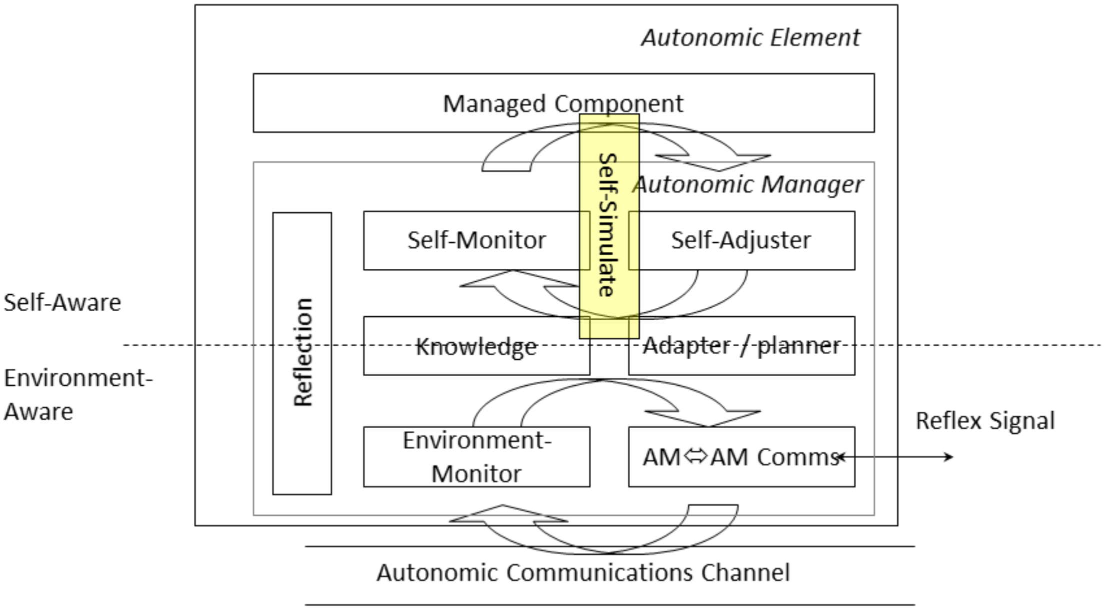


Figure 6 Extended Autonomic Element with Simulation before adjusting/adapting put into action.

This stream of research contributed to the Autonomic Computing & Autonomic Robotics, two main themes;
– Autonomic Paradigm change and
– Self-simulation as part of the autonomic control loop (Figure 6).

More detail about this research stream can be found in [29] (which won best paper award), [13],[14],[30] & [48].

4. AUTONOMIC ELEMENT INTRA-COOPERATION (INTERNAL)

The main purpose of this PhD research programme stream was to investigate self-* healing strategies and to determine if 3 tier Intelligent Machine Architecture had something to add to the MAPE-K architecture for Autonomic Robotics (Figure 7).

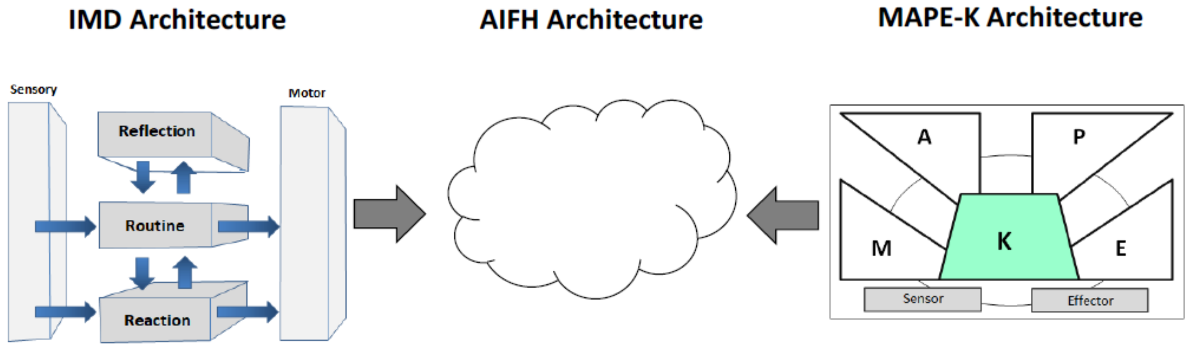


Figure 7. Autonomic Robotics Architecture.

In pursuit of future space exploration, researchers have described the concept of moving from missions based on single rovers towards multiple rovers and indeed in the ANTS scenario potentially 1000s of flying rovers; this concept is based on the fact that multiple rovers are capable of completing more tasks and covering a larger area than a single rover. However, the amount of expenditure put into each rover is likely to be greatly reduced compared to that of a single mission rover. At the extreme Swarm end of the spectrum the crafts will be expendable. These lower spec. rovers could be more vulnerable to hardware faults. However, if the software system built into each rover is based on autonomic principles, then the ability of the rover to continue to operate would be greatly increased, as well redundancy provided through the Autonomic Cooperation.

These approaches require that the ARE is evaluating its own health (Figure 1 self-awareness control loop) but at more than one dimension. For instance, self-configuring (sC), self-healing (sH) and self-optimising (sO) in reaction to an immediate danger is very different to sC, sH and sO in relation to a reflection process, that being from analysing data patterns over several weeks and identifying a better operational mode.

Note we have already incorporated the Reflex Reaction (via Pulse Monitoring [16]) and Reflection into our AE (Figure 1). But this also clearly operates at a system level and not just within an AE.

This has led us to research into a suitable architecture both internal (intra-cooperation within the AE) and intra-cooperation between layers or vertical orchestration within a system. One approach we had considered in the past was VSM or Beer's model [18]-[20]. VSM offers a valuable way to model the total system from a cybernetic model of the organization yet we found it difficult to translate into the bottom up approach depicted in Figs. 1 & 2. It still has value in looking at the overall complex design [17],[21]. We found another simpler approach related better from an older perspective for an intelligent machine design Figure 8 [22],[23].

The layers are:

1. Reaction—lowest level, where no learning occurs but there is immediate response to state information coming from sensory systems.

2. Routine—middle level, where largely routine evaluation and planning behaviours take place. Input is received from sensors as well as from the reaction level and reflection level. This level of assessment results in three dimensions of affect and emotion values: positive affect, negative affect, and (energetic) arousal.

3. Reflection—top level, receives no sensory input or has no motor output; input is received from below. Reflection is a meta-process, whereby the mind deliberates about itself. Essentially, operations at this level look at the system's representations of its experiences, its current behaviour, its current environment, etc.

Input from, and output to, the environment only takes place within the reflex and routine layers. One may consider that reaction level essentially sits within the "hard" engineering domain, monitoring the current state of both the machine and its environment, with rapid reaction to changing circumstances; and, that the reflection level may reside within the AI domain utilizing its techniques to consider the behaviour of the system and learn new strategies. The routine level may be a cooperative mixture of both (Figure 8).

This high-level intelligent machine design is appropriate for autonomic systems as depicted here since the case has been made for the dynamics of responses including reflex reactions and also for reflection of the self-managing behaviour.

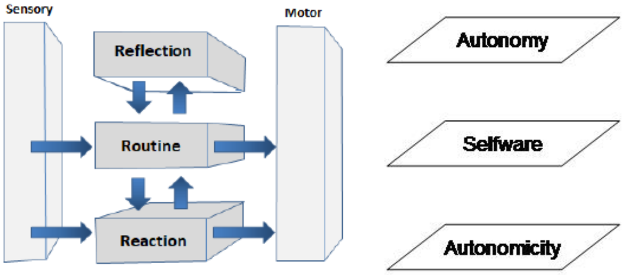


Figure 8. Comparing intelligent machine design and system level autonomy and autonomicity

Some researchers hold the perception that autonomic computing resides solely within the domain of the reaction layer. This is understandable due to the metaphoric link with the autonomic nervous system, where no conscious or cognitive activity takes place. These researchers would point to other biologically-inspired computing (also referred to as nature-inspired computing, organic computing, etc.) as providing such higher level cognitive approaches, for instance as in swarm intelligence. Within the autonomic computing research community, autonomicity is not normally considered to imply this narrower view. Essentially, the autonomic self-managing metaphor is considered to aim for a user/manager to be able to set high-level policies, while the system achieves the goals. Similar overarching views exist in other related initiatives and, increasingly, they are influencing each other.

In terms of autonomy and autonomicity, autonomy may be considered as being self-governing while autonomicity is considered being self-managing. At the element level, an element will have some autonomy and autonomic properties, since to self-manage implies some autonomy, while to provide a dependable autonomous element requires such autonomic properties as self-healing along with the element's self-directed task. From this perspective, it would appear that the separation of autonomy and autonomicity as characteristics will decrease in the future and eventually will become negligible. On the other hand, at the system level if one considers again the three tiers of the intelligent machine design (reaction, routine, and reflection) and accepts the narrower view of autonomicity, there is a potential correlation between the levels. That is, the reaction level correlates with autonomicity, and the reflection level with autonomy, as in self-governing of the self-managing policies within the system. In the end, different classifications or different perspectives on the matter will be academic unless they assist and inspire new means to achieve the self-managing vision [23][49].

This perspective has enabled us to build in reaction, routine and reflection into the Autonomic Robotic Element and resulting system. One such example is that of monitoring the path of the robot over time and self-adjusting in field any misalignment [15].

This stream of research contributed to the Autonomic Computing & Autonomic Robotics;

– 3x case studies investigating self-* healing strategies and a 4th confirmatory case study;

- Robot Wheel Alignment Fault
- Robot Sonar Sensor Faults
- Robot Battery Degradation Fault
- Stereo Vision Camera Fault – Confirmatory Case Study

– Autonomic Robotics Architecture derived from IMD (Robotics) & MAPE (Autonomic Computing) architectures, which is also referred to as AIFH: Autonomic Intelligent Fault Handling (Figure 9 & Figure 10). Much of this “Autonomic Robotics” research was influenced by the operational constraints on Mar’s Rovers.

Figure 9 shows how the Autonomic Robotic Manager (containing the three layers, awareness, analysis and adjustment), adopted from MAPE & IMD, is integrated with the System Manager. Figure 10 shows this in much more detail where the System Manager is responsible for executing commands to the mobile robot via the effectors and sensors. The System Manager is also responsible for running task procedures and health check monitoring. The Autonomic Robotic Manager provides a mechanism for detecting faults, analyzing faults and providing policies that can compensate for faults. The ‘autonomic intelligence’ in the awareness layer not only flags component faults but also provides a means of monitoring sensor data and reporting to the User/Mission Control, if certain component behaviors may indicate an impending fault. Within the Analysis layer, there are policies that can adjust tolerance thresholds. These policies are important as an over-sensitive tolerance value may lead to faults being reported continuously within the Reaction loop (between the Awareness and Analysis layers), therefore creating an infinite fault state.

More detail about this research stream can be found in [15], [31]-[34].

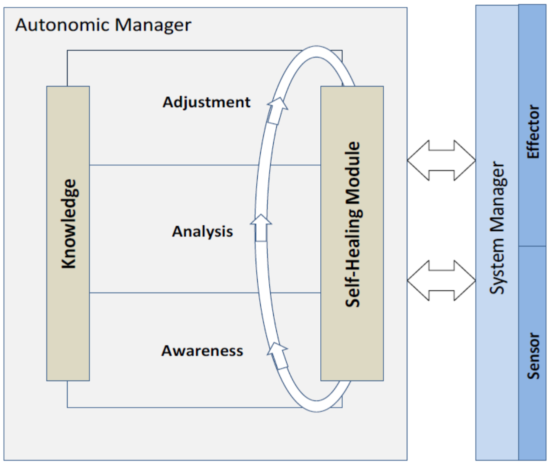


Figure 9 Autonomic Robotics Architecture high-level conceptual 3xA’s control loop

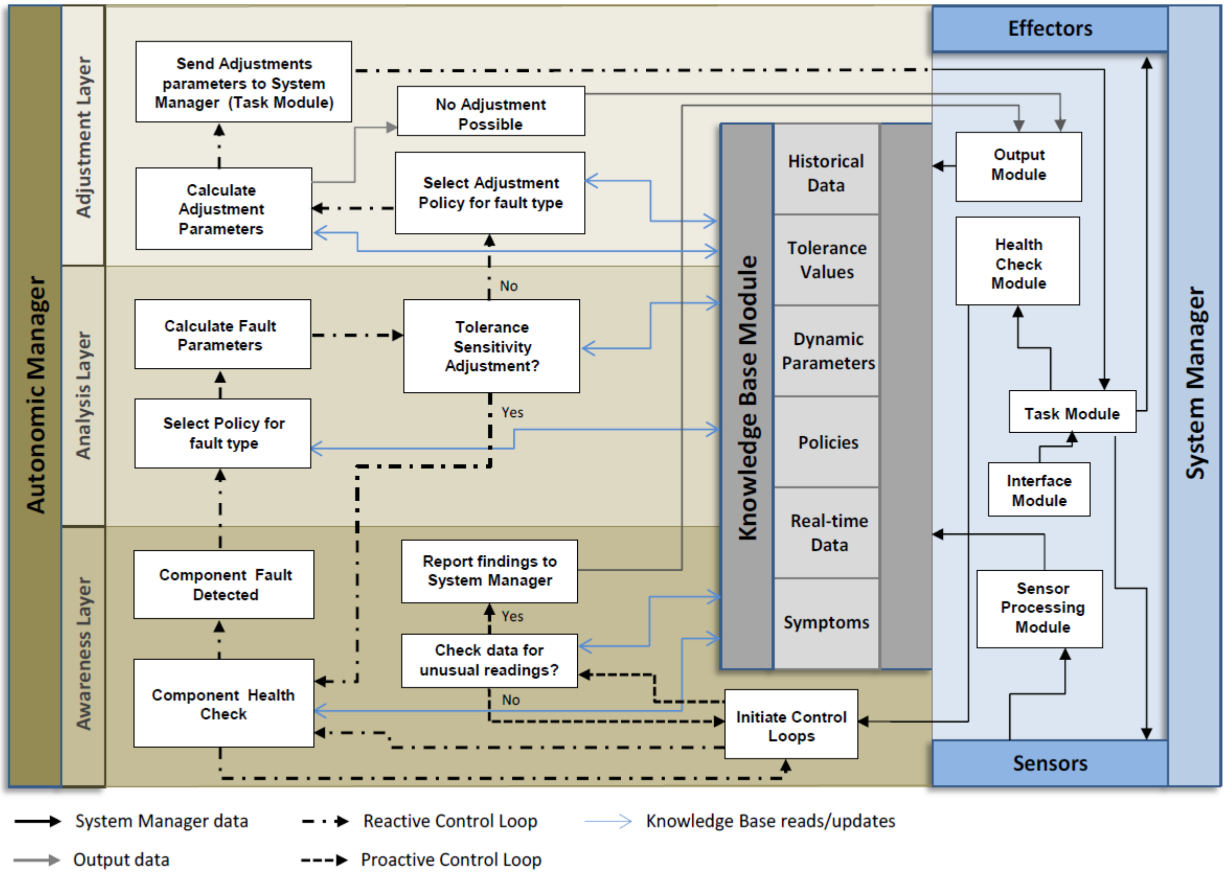


Figure 10. AIFH Autonomic Architecture for Fault Handling in Mobile Robots (*Autonomic Robotics*) [34]

5. AUTONOMIC COMPUTING FOR CUBESATS

The main purpose of this PhD research programme stream was to investigate if and how the Autonomic Computing paradigm could contribute to CubeSats.

Early research explored carrying on from the Palmer Autonomic & Apoptotic demo on Arduinos [35] with DemoSat equipment (Figure 11).

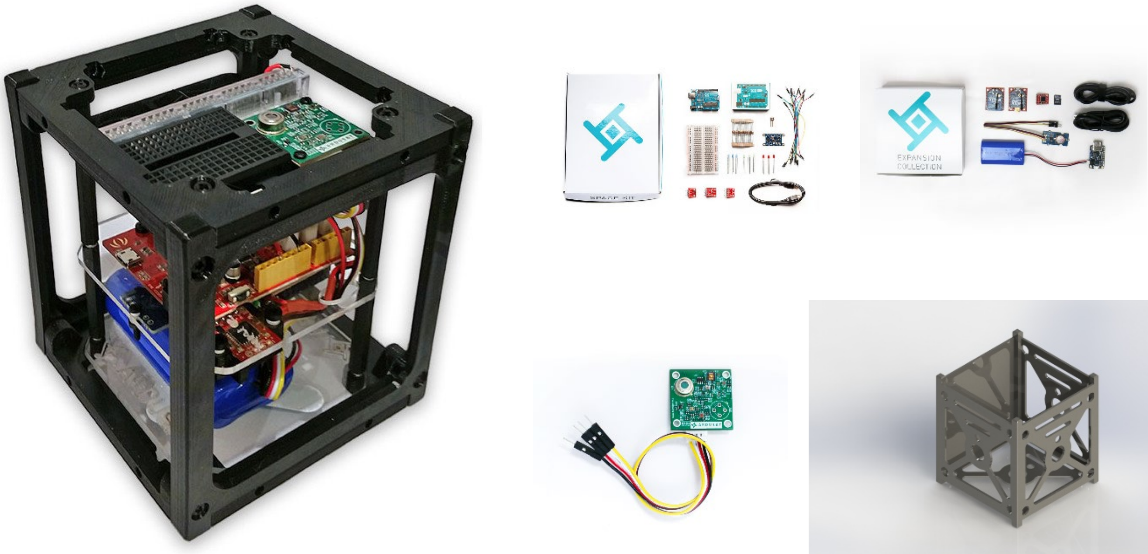


Figure 11 ArduSat DemoSat equipment

Later the research moved towards defining a Cubesat Autonomicity Capability Model (CACM) as a roadmap for future autonomic cubesat development [36],[37] and an exemplar “killswitch” (Apoptotic Computing) application to prevent the CubeSat becoming space debris.

CACM derives inspiration from various models; the IBM 2001 Autonomic Maturity Model, Autonomy Levels Framework, the Automotive Driving Automation Levels model, and the SEI Capability Maturity Model Integration (CMMI) [38]-[41].

Cubesats are a type of microsatellites / nanosatellites that came out of a collaborative endeavour between California Polytechnic State University and Stanford University in 1999 [42]. The original vision for developing cubesats and standardizing them was to develop the necessary skills for creating satellites intended for Low Earth Orbit (LEO) and also limit the size and number of science instruments that could go on-board spacecraft. The cubesat form factor specification was standardized to 10cm x 10cm x10cm (1U) with a mass of about 1.33kg [43]. Other form factors include 2U (10cm x 10cm x 20cm), 3U (10cm x 10cm x 30cm), 6U, 12U, etc. The low cost and faster development of cubesats has been the result of accelerated technological advances in spacecraft miniaturization in recent years [44]. Traditionally, spacecraft consist the main payload, which conducts space experiments or tasks, and vehicle support systems, like communications, propulsion, attitude determination and control, electric power system, and data storage [45]. Cubesats, however, can only implement some of the features of monolithic satellites due to their physical size limit, electrical power availability and processing power [45]. Nowadays, these microsatellites are utilised to accomplish LEO missions that were previously performed using monolithic satellites and this has resulted in huge mission cost savings [46].

This research after initially working on DemoSat hardware to, for instance, pre-programme a death by default (apoptotic computing) safety mechanism [35], focused on defining autonomic (self-managing) pre-defined & pre-programmed capability that could be built in to CubeSats for individual missions (with increasing autonomicity from levels 1-3) and self-managing capability that could be achieved from a constellation of CubeSats (levels 4 & 5). A sample of the levels can be viewed in Figure 12 & Figure 13.

The 2nd part of this research stream is to validate the CACM model utilizing a simulated exemplar to assist discussions with industry experts. A visualization of this is shown in Figure 14

This stream of research contributed to the Autonomic Computing & Autonomic Robotics;

- A CubeSat Autonomic Capability Model
- An exemplar pre-programmed death by default ("killswitch"), that is Apoptotic Computing enforced by Autonomic Computing, application to prevent the CubeSat adding to the space debris escalation.

More detail about this research stream can be found in [35][36][37].

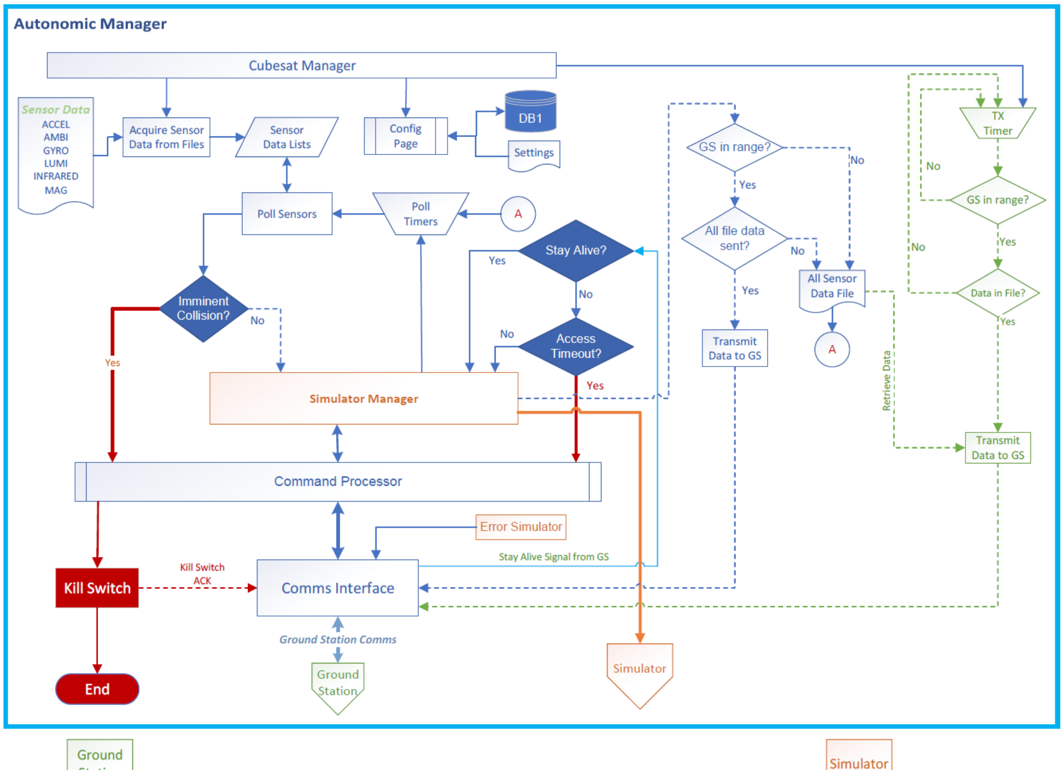


Figure 12 CubeSat Autonomic Capability Model – Level 1

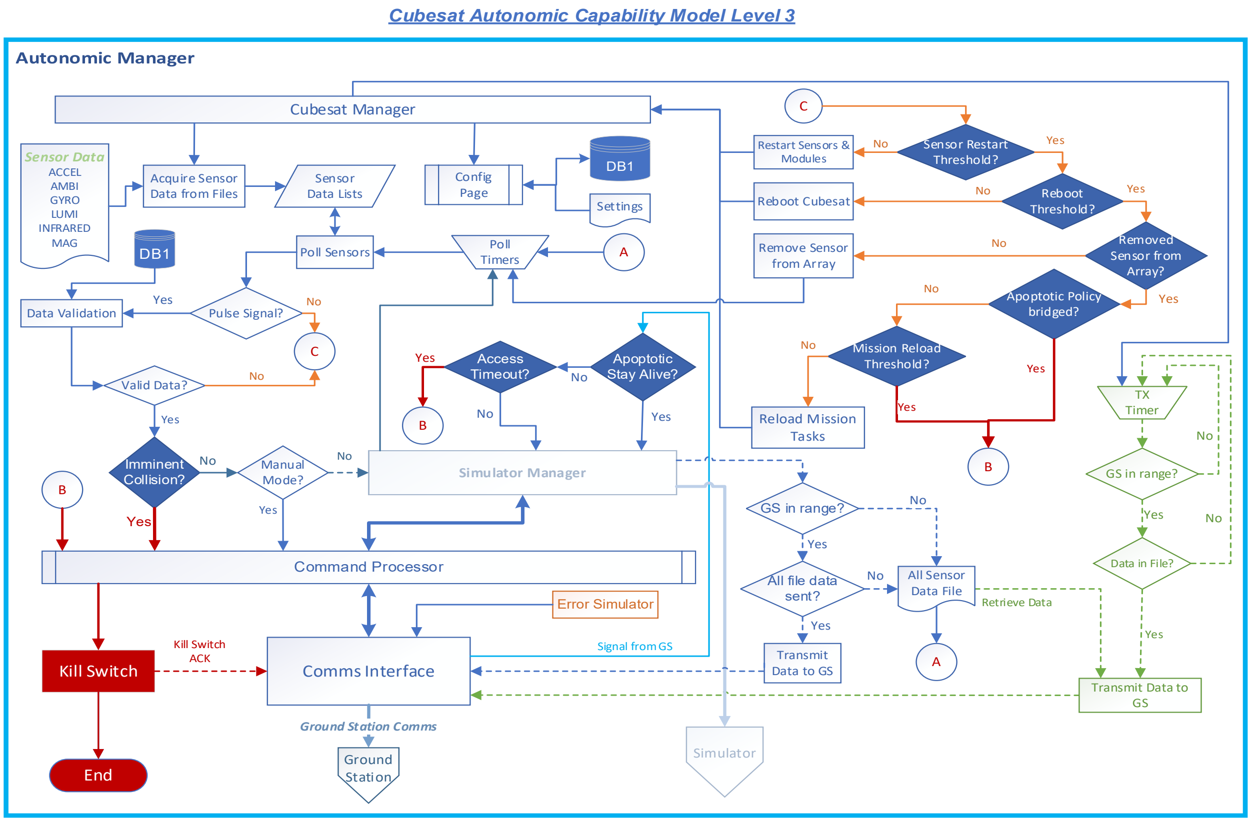
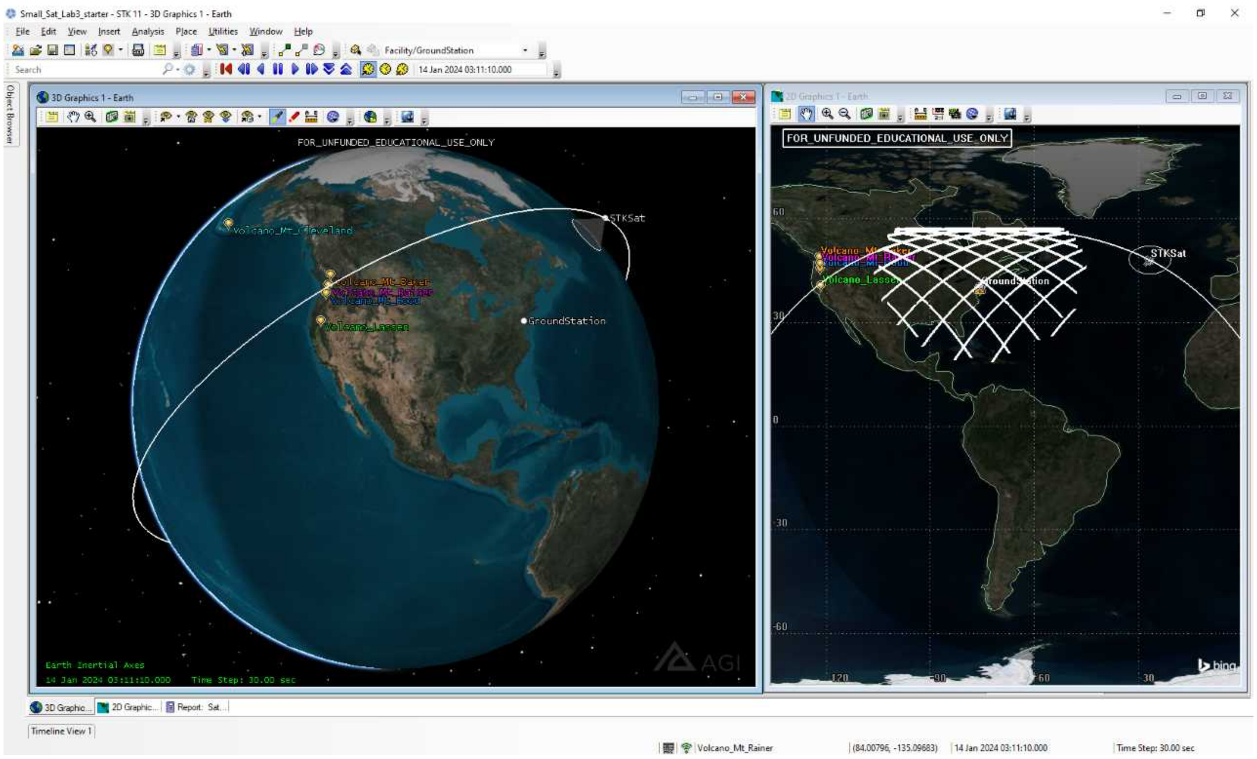
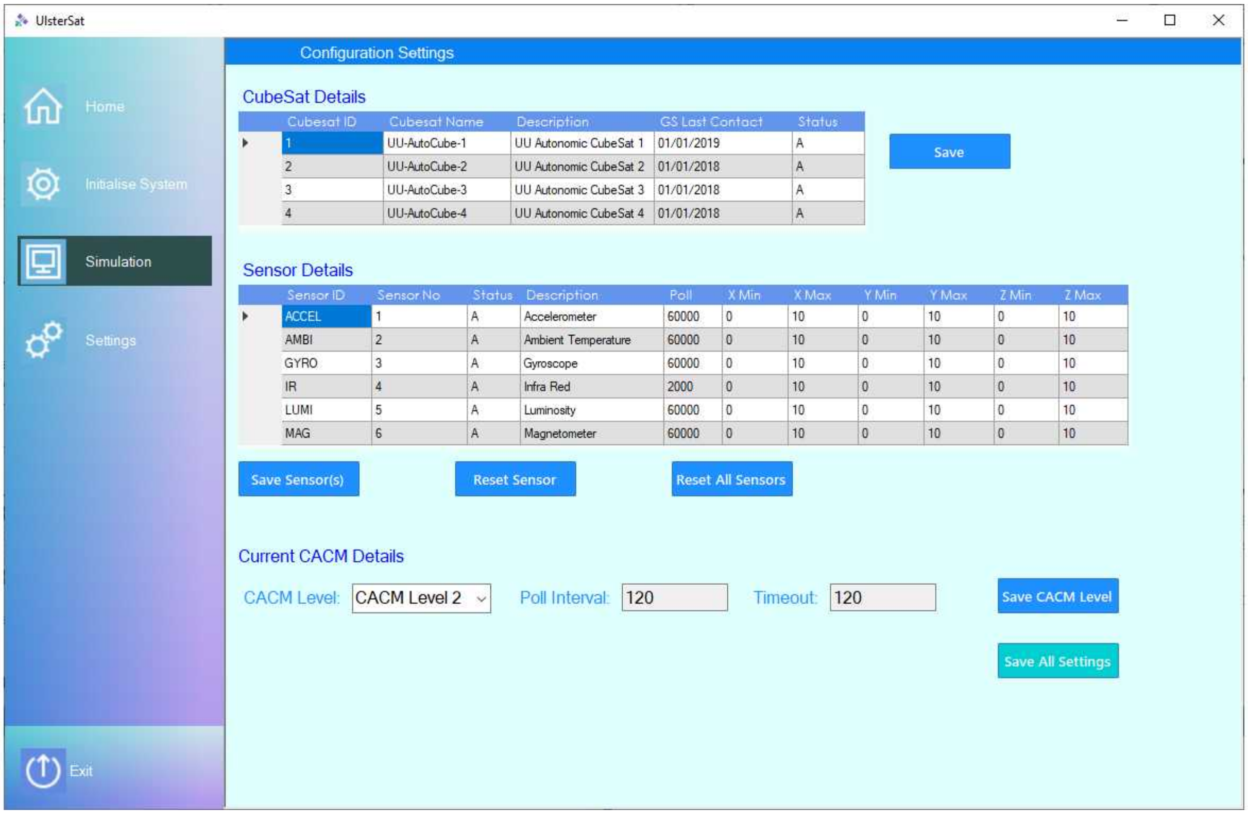


Figure 13 CubeSat Autonomic Capability Model – Level 3





CubeSat Details

Cubesat ID	Cubesat Name	Description	GS Last Contact	Status
1	UU-AutoCube-1	UU Autonomic CubeSat 1	01/01/2019	A
2	UU-AutoCube-2	UU Autonomic CubeSat 2	01/01/2018	A
3	UU-AutoCube-3	UU Autonomic CubeSat 3	01/01/2018	A
4	UU-AutoCube-4	UU Autonomic CubeSat 4	01/01/2018	A

Sensor Details

Sensor ID	Sensor No	Status	Description	Poll	X Min	X Max	Y Min	Y Max	Z Min	Z Max
ACCEL	1	A	Accelerometer	60000	0	10	0	10	0	10
AMBI	2	A	Ambient Temperature	60000	0	10	0	10	0	10
GYRO	3	A	Gyroscope	60000	0	10	0	10	0	10
IR	4	A	Infra Red	2000	0	10	0	10	0	10
LUMI	5	A	Luminosity	60000	0	10	0	10	0	10
MAG	6	A	Magnetometer	60000	0	10	0	10	0	10

Current CACM Details

CACM Level: CACM Level 2
Poll Interval: 120
Timeout: 120

Figure 14. CACM Exemplar using Analytical Graphics Inc. STK Simulator

6. DISCUSSION AND CONCLUSION

ANTS – Autonomous NanoTechnology Swarm was classed as a concept mission. At that time, concept missions were 30 years prior to launch. At the time the ANTS concept movie, visualising the Prospecting Asteroid Mission (PAM), was often referred to as Science Fiction when shown at conferences by sceptical audiences. Twenty years later, not only has technology moved closer to realising such a vision, but the actual shape of the Space industry is unrecognisable. One can now envisage CubeSats acting as those ANTS craft, the envisaged robotic factory at a lagrange point could now be replaced with 3D printers and the headache of autonomously managing 1000s of craft can be solved by autonomic and apoptotic software some of which discussed in this paper.

This paper introduced, at a high level, the concept of *Autonomic Robotics* based on the Autonomic Computing paradigm applied to Robotics and craft. This expanded on from research carried out in the noughties on Autonomic Systems, including work with NASA GSFC. It is the belief of the authors that the AC paradigm [25] will offer a systematic means to obtain self-managing and autonomous robotic craft software for space exploration.

The first area to be considered in this paper was the self-management collaboration and cooperation between system entities. Many space agencies, including NASA & ESA, are activity moving away from singular space craft mission paradigm to multiple craft missions. From constellation missions of three cooperating craft to the NASA "ANTS" (Autonomous Nano-Technology Swarm) concept mission with potentially 1000's of craft working as a swarm. With the larger the scale of entities, the more reliance on autonomy and self-management techniques. We briefly described how in this project we are investigating autonomic cooperation and collaborating strategies between elements from a small cluster to large swarm scale. The second area of interest was specifically focused on the internal self-managing cooperation within an entity and the best architecture to enable vertical orchestration within the system in a scalable fashion to enable the first. Lastly, a research project deriving an Autonomicity (self-managing) capability model for Cubesats (including constellations of Cubesats) to assist in deriving standard self-management activities and potentially providing standard software artefacts and middleware was briefly described.

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