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New Directions: SWANS – Sensor Wireless Actuator Network in Space

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ABSTRACT

Progress in low power miniaturized electronics and wireless technologies have enabled many innovative applications. Of particular interest is the Internet of Things (IoT) that has dominated the world of ICT in the last half a decade enabling many smart systems and applications. At the same time, we also see much enthusiasm with respect to space missions and applications including terrestrial applications, apart from exploring the universe. We believe that innovations in the domain of IoT will significantly influence the space related activities – both research and development. In this article, we chart out the innovations in space and the vision with respect to embedded and wireless systems for space applications. In particular, we bring in the notion of *Sensor Wireless Actuator Networks in Space* (SWANS) and *Space Pixels* to explain IoT in space. We explain with examples what we envision for the next decade and also the challenges therein. We briefly put forth our four major targets in the next five years.

CCS CONCEPTS

• **Hardware** → Sensors and actuators; Wireless integrated network sensors; Communication hardware, interfaces and storage;

KEYWORDS

Space IoT, Internet of Things, Sensor Wireless Actuator Network in Space, swarms, nanosatellite, femtosatellite, Space Pixels

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1 INTRODUCTION

With the advent of low-power miniaturized electronics supporting high-end computations and advances in wireless technologies, it is certain that Internet of Things (IoT) has become one of the key technological enablers for smart-* systems in this decade. As an enabler for the Cyber Physical Systems [21], IoT is making a great impact on our lifestyle and the way we interact with others, environment, and even machines. Current IoT comprises of embedded devices, and a network of such devices having sensors and actuators, leveraging the existing wired or wireless infrastructures for communication and control of physical environment and electronic systems.

Space is the next frontier for innovations. Space is becoming more enthralling by the day, for example, SpaceX is planning tourism around the moon [8], and many students will be able to launch their own satellites [13] in the near future. The next step, which is just around the cornerstone, is to involve space in IoT applications. This step will help to solve few challenges in terrestrial IoT deployments. A single satellite in space can communicate with many sensor nodes and gateways over a vast area on Earth simultaneously than a single gateway on the ground. With a network of such satellites orbiting around Earth, it is possible to get a global coverage for IoT devices even in areas such as Arctic and Antarctic regions, mountains, oceans and remote places that have little or no infrastructure. Companies such as Magnitude Space [5] are in the process of employing such methods not only to cover remote areas but also provide global coverage for IoT devices even in densely populated cities. Magnitude Space, with their proposed system "Low-power Global Area Network", envisions to use many satellites speak directly to their proprietary sensor nodes connected to IoT devices on ground, and upload data to the cloud [22].

Further, a satellite is already a collection of different sensor and actuator systems such as gyroscopes, magnetometers, solar panels, antennas, star and sun sensors, reaction wheels, magnetotorquers, and propulsion systems. They are connected by wires (also called *harness*) within a satellite, which adds to the weight and size (note that the mass and size of a satellite are important parameters that deeply impacts its cost including its launch) of the satellite. Replacing the wires with wireless without sacrificing its performance will make a satellite a sensor wireless actuator network in space (SWANS)[1]. Together with its external communication system, we extend SWANS to include a group of satellites in order to enable several applications including *swarms of satellites.* We envision that, in the near future, SWANS will impact the space industry significantly including the traditional space applications. The main driver for SWANS is the miniaturized, inexpensive, low-power network of satellites. We provide some examples here:

(a) Swarm of autonomous small satellites (or tiny wireless smart sensor networks) deployed around moon or planets can collect more data with respect to deep space exploration than any observatory station on Earth.

(b) Precise measurements for smoke and aerosol concentration in the atmosphere can be done easily and effectively using a swarm of

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[1] The extended version of this paper can be found in http://www.es.ewi.tudelft.nl/papers/2017-Narayana-SWANS-TR.pdf

tiny satellites orbiting in very Low Earth Orbits (LEO) than having a bulky equipment on Earth.

(c) With swarm of robots, space robotics can be improved significantly to control robots from Earth with much lower latencies for targeted autonomous applications than the state of the art. These are a few major visions of the space industry for the coming years [9].

Currently, most of the existing satellites in space are bulky, expensive but ultra-reliable and designed for a particular mission. Instead, a swarm of networked, small, low-cost satellites can form a wireless sensor actuator networks in a distributed way to achieve the same desired features [19]. These swarm of small satellites can communicate with each other and also with ground stations in order to perform better than a big satellite. Such swarms in space can provide advantages such as redundancy, fault tolerance, and low-cost production and deployment, autonomous, incremental deployment and massively distributed. Hence, small satellite technology can be a key element to the future vision of Space IoT.

Though there have been advancements in satellite building and launching technologies, access to space has been expensive and many scientific challenges still exist [15]. An important question is how these existing sensors and actuator systems in satellites should be adapted to form SWANS so that the solution is inexpensive, reliable and efficient. Since the beginning of the satellite era, there always has been demand for mass production, miniaturization, low-cost solutions, innovative system designs, reliable inter-networking of satellites, etc., for space applications but much exploration is yet to be done to meet these requirements. Compared to the terrestrial applications, the implementation of SWANS in the form of wireless networked satellite systems, constellations of (tiny) satellites in space or inter-satellite communication and computing requires innovation, optimization of space and weight, and higher levels of reliability. They should withstand the harsh space environments such as extreme temperatures, high mobility, power constraints, and undesirable perturbations which influence their operation significantly. The wireless communication between two modules in the network will rely on the inter-satellite link or intra-satellite link, whose establishment and stability are impacted by the satellite orbit and attitude, antenna configuration, link range, mobility or the layout of spacecraft. If the communication range of each node is limited, the nodes may use multi-hop communication to send their data to the destination. This requires a complex control, and should adopt an auto configuration [17] and routing strategy to ensure time and/or energy optimization as they are resource constrained.

In this paper, we present our vision on SWANS. Majorly we discuss three important broader themes, which have long-term research and innovation potential: (i) Wireless sensor actuator networks in space for deep space and Low Earth Orbit (LEO) missions and applications. This is an exciting new frontier. The idea is to automate and connect multiple modules within systems such as satellites, planet rovers, etc.; (ii) Satellite swarms will be the order of the future because of widespread deployment of mobile systems. Swarms will be part of any future space missions since it allows the incremental buildup of large space missions using smaller, yet complete systems that are individually accomplishing some of the tasks; (iii) Space robotics is an important topic since they can be autonomous and will be crucial for space explorations. We describe these topics with our initial studies and experiments while listing their umpteen challenges in this article.

2 MINIATURIZATION OF SPACE SYSTEMS

Access to space has always been expensive. It takes around $20,000 to place 1 kg of payload (satellite) in orbit with an altitude of around 500 km [15]. At this cost, even a small satellite with 10 kg would cost $200,000 just for the launch when a rocket carries the bulk of them. Most of the existing satellites in space are big, too expensive and single mission-oriented. Once the mission is complete, the satellites are nothing but space debris and cannot be reused for another mission. Even during the mission if there is a failure in the satellite's sub-system, it is difficult to fix it. In fact, physical repair or upgrade after the launch is very tedious and expensive, and in some cases next to impossible. Hubble telescope is the only space telescope that has been serviced in-orbit till date. NASA dropped the plan of such missions as the upgrade cost is of the order of a new satellite itself [7]. Such problems in space missions have led to a vision in the space industry to develop space systems that are low cost, flexible, multipurpose, and reusable.

Due to the recent advancements in technology, miniaturization of satellites has been the principal method to reduce space mission costs. Evolution of small sensor and actuator systems with MEMS technology has made it possible to shrink the size of many satellite components and in turn, reduce the size of satellites dramatically from 1000 kg in the 1960s to 10 kg now. Alongside, small satellites such as Swiss Cube[11], STRaND-1[10], Delfi-C^3[12], etc., have proven that Commercial Off-The-Shelf (COTS) components work in space, thus providing low cost solutions and fast access to space. It may be easy to clear such small satellites compared to the big ones once they become debris [23]. Table 1 lists a classification of satellites in terms of deployed mass that has been generally adopted in recent years [16]. The current trend in the space industry targets nanosatellites and CubeSats (10 cm x 10 cm x 10 cm volume with mass around 1 kg) that has many advantages over large satellites such as, (i) less production time and low launching and development cost because of reduced mass and COTS approach; (ii) suitability for small, short-time missions and (iii) tremendous potential for scientific research, and technology development and demonstration. Thus we envisage a large number of these small space systems that are agile being very low cost alternatives to dominate the space. With this background, we next describe our vision.

Category	Mass in kg	Approximate size in m
Large	> 1,000	50 x 10 x 10
Medium	500-1,000	15 x 10 x 5
Mini	100-500	10 x 5 x 3
Micro	10-100	3 x 3 x 3
Nano	1-10	0.3 x 0.2 x 0.1
Pico	0.1-1	0.1 x 0.05 x 0.05
Femto	< 0.1	0.03 x 0.03 x 0.02

Table 1: Classification of satellites by mass

3 VISION OF SWANS

SWANS represent the next generation space missions, which are agile, networked and wireless communication enabled closed-loop control systems to autonomously accomplish multiple missions. The vision of SWANS is that it addresses not only smaller issues, for example, cable harness in satellites, but also the future potential of easy access to space in general. The idea is to automate and connect multiple modules within and between systems such as satellites, planet rovers, etc. We take a big leap into space and list three important topics below covering many important aspects of SWANS. These topics invariably involve sensors, actuators, and wireless communications.

The following three topics using SWANs have long-term research and innovation potential: (i) *Satellite Swarms* will be the order of the day because of widespread deployment of mobile systems on Earth and space in future. Swarms of satellites will be part of any future space mission since it allows the incremental building up of a large space mission using smaller, yet complete systems that are individually accomplishing some of the tasks; (ii) *Radio Interferometry (RI)* requires multiple, spatially separated low frequency RF antennas to mimic optical telescope on the ground. The size of the antennas in RI is expected to be very large compared to their mountings. RI can be used in deep space as well as low Earth orbit (LEO) missions. RI in space requires distributed computations, pointing and orientation (involving micro-thrusters), and synchronization to mention a few. This is an exciting new frontier; (iii) *Space robotics* is an important topic since humans are not in a position to live in outer space yet without daily consumables; we need robotic limbs/extensions or a swarm of rovers to work on future outer planet explorations. We expand on these topics in the sections below.

3.1 Satellite Swarms

The concept of small satellites (comprising of nanosatellites, picosatellites, and femtosatellites) is not new. Though space technology have advanced immensely, a small satellite may not replace large ones in terms of mission capacity. However, a constellation of small satellites can provide much higher functionality and flexibility for many important future missions, providing equivalent performance of a bigger one or even better. For instance, a large satellite with huge antennas used in radio astronomy can be replaced by multiple small satellites providing the same performance but at very low cost and power. They form constellations of satellites ('satellite swarms') and are distributed in space forming a specific orbital geometry, and are interconnected. In general, these swarms are nothing but a flexible distributed networked sensor actuator systems in space that can maneuver, self-organize and execute specific tasks together. Such a swarm system can adopt star topology where small satellites are connected to a single gateway, that can be a large satellite which communicates to Earth, or a mesh with multiple gateways. If the satellites in a swarm are bound to a specific control algorithm to maintain relative navigation with respect to each other by enabling communications amongst themselves or with a leader, it results in *formation flying*. Small satellites orbiting in close formations can target their mission at low cost and low-power compared to multiple bigger satellites, with enhanced reliability compared to larger single platform operations.

Most of the future missions planned by the space industry will include small satellites and formation flying [3, 5, 6]. The advantages and use cases of future swarm of satellites are many: (i) Swarms can take remote sensing to the next level. Multiple interconnected small satellites can achieve remote sensing simultaneously and get complete three dimensional mapping of the globe in less time; (ii) Measurements such as aerosol, smoke and ozone concentration in atmosphere, seismic activities using magnetic sensors, greenhouse effect, and dynamics of Ionosphere with respect to radiation and communication at very low Earth orbits (for instance at 250 km altitude) are very expensive and time-consuming with a single large satellite as the lifetime of objects in these orbits varies from several days to a few months. Satellite swarms being low cost and providing quick results are the sought-after solution in such situations; (iii) they can provide reliable communication and broadband services to remote areas; (iv) best services in military applications such as tracking soldiers and navy ships with shorter re-visit times; (v) communication with a single larger satellite is possible only when it is visible to the ground station whereas in case of swarm, communication with non-visible satellite is possible because of inter-satellite links; (vi) high expandability, autonomy, reliability, and redundancy are built-in. If one satellite fails others can work intelligently without breaking the formation, whereas, a failure of single large satellite ends the entire expensive mission. A number of satellites can be added to the swarm whenever necessary, and (vii) small satellites also provide the opportunity to test new scientific experiments because of lower cost of production.

Space companies such as NASA have come up with a wealth of new ideas for future, targeting small satellites. NASA's Cube Quest Challenge to design small satellites[3], OneWeb's vision for global Internet service with small satellites in 2020[6], the concept of PCB-Sat and Satellite on Chip from Surrey space center[14] provide a way to the vision with satellite swarms and miniaturization technology. Moving one step further, we have the Starshot program by Stephen Hawking[4], a future project where a satellite in the form of a wafer-sized chip is shot to distant starts at ultra-high-speeds away from the Earth, using highly concentrated laser beams fired from the Earth. This shows that there is a need for much advancement in miniaturization and sensor technology to make the mission successful. For missions such as Starshot program, there has to be a huge advancement in the existing satellite technology to produce a tiny sensor and actuator chips that are ultra-low-power which can communicate with one another and with ground stations. Thinking big, to be small, the complete satellite should be embedded in a single pixel shaped miniaturized chip which we call "*Space Pixels*". With a size in the range of 1 mm x 1 mm and weigh less than 1 gm, Space pixels can be analogous to Smart Dust[24] containing low-power, processing, sensor, actuator, and communication units onboard. Their weight and size make it easy to release thousands of them in different orbits by a high altitude balloon from ISS or a small satellite where experiments such as RADAR reflectivity, atmospheric coloring and gas concentration, and meteor impacts can be done almost instantly. Not only in Earth orbits, a swarm of Space Pixels can also be used in deep space explorations. They can be used for near-field atmospheric measurements in other planets and space objects such as moons, asteroids, and space stations by throwing them into the orbit from landers or rover robots. In the case of remote sensing, multiple Space Pixels with micro cameras can get a bigger image in interplanetary explorations. The source of energy for these pixels can be solar or RF based. In the case of solar, there can be a tiny solar panel and in the case of RF, a large satellite or lander/orbiter on other planets can power these with continuous RF bursts. Space pixels can indeed be an important vision for IoT.

3.2 Radio Interferometry

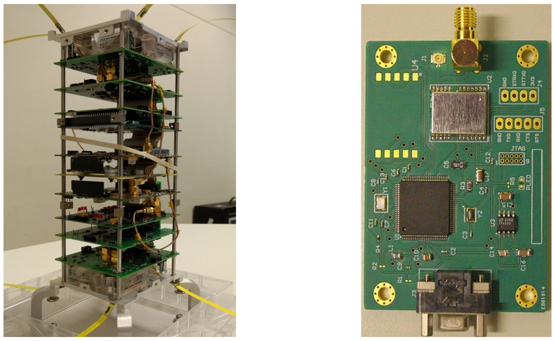
One of the most foreseen expectations with the development of small satellite technology is taking radio astronomy into space. Though many complex radio telescopes are installed on Earth, there are many problems in listening to the RF signals from the deep space: low radio frequencies are absorbed or refracted by Ionosphere, high frequencies are absorbed by oxygen and water in the atmosphere, man-made interference on Earth, atmospheric phase fluctuations, and pointing offsets due to Earth's rotation, etc. Even though space beyond Ionosphere is suitable for radio astronomy, the technology involved in placing radio telescopes out there is different than that on the ground. Projects such as Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) aims to collect low frequency signals (0.1 - 30 MHz) from far galaxies that can reveal information about solar, planetary bursts and the events from *Dark ages* after Big Bang, which is still unknown to us[18]. OLFAR cannot be accomplished on Earth or in Earth orbits as man-made RF interferences from Earth can reach as far as the Moon. Hence, the dark side of the moon – where there is a lack of atmosphere to interfere with radio waves – would be a favorite place for radio astronomers. RF Telescopes on Earth have antennas with a diameter between 25 m - 500 m [2] and has an angular resolution of $\frac{1.22\lambda}{d}$ where λ is the wavelength of observation and d is the diameter of the antenna. Further, lower the radio frequency larger the required antenna. Hubble space telescope has an angular resolution 14μ deg. Therefore, for low frequency radio measurements in space, a 5 km diameter antenna has to be placed in orbits which are nearly impossible with the current technologies. However, a novel approach with a swarm of small satellites in a constellation can realize the dream of radio astronomy in space.

To achieve a single, big and virtual radio telescope in space with an angular resolution equivalent to that on Earth, an array of smaller telescopes can be used. This technique is called as Radio Interferometry (RI). The design considers spatial separation between small satellites in the form of swarms carrying small telescopes, pointing at same source of interest. The distance between two antennas is the baseline which is nothing but the diameter of the virtual giant antenna in space. Since the radio signal from a distant source arrives at the antennas at slightly different times, the cosmic address of the source can be calculated provided that the distance between small telescopes (satellites) is known. The signals from all the telescopes (at least two) are correlated to eliminate noise and obtain the signal. Though the concept of RI in space is already proposed, it is not yet demonstrated in space. RI can also help in searching for signals such as Fast Radio Bursts (FRBs) and gravitation waves from distant galaxies or *Black Holes* that span for a fraction of a second. Till date, only 25 FRBs have been discovered since its first detection in 2007[1]. There are a number of key technologies that are still to be developed for such missions using small satellite swarms with precise formation flying, high speed inter-satellite communication. If a stage can be set for RI in space, then a very high redundant, low complexity, highly scalable, autonomous radio astronomy can be realized.

3.3 Space Robotics

Space robots are advantageous in many ways: they can collect fine samples in space, can work towards in-space assembly and in-space maintenance, as a human assistant, mining, satellite deployments, refueling and orbit maintenance, constructions, repairing, re/de-orbiting, etc. Since the previous decade, robots have done a lot when it comes to space exploration. The state of the art space robots includes landers, rovers and manipulator arms. Rosetta comet lander, Pathfinder, Opportunity and Curiosity Mars rovers and Remote Manipulator System in ISS have proven that robots work in space[20]. However, in some cases, a swarm of robots can perform collective space exploration with coordinated motion and pattern formation, completing the mission quickly. Future space missions involving swarm robots can perform multiple tasks simultaneously that is beyond the capabilities of a single one. Swarms provide improved performance, distributes sensing and action, offer redundancy and fault tolerance. If one robot fails, the other robot in action can repair it autonomously.

One of the major challenges in space robotics is teleoperation where the robot is controlled by humans in space or on Earth. Communication latency is one of the major issues that NASA is trying to handle. It takes between 5 - 15 minutes to send commands to Mars rover and to receive telemetry from it. The major delay is because of the distance from the Earth and cannot be reduced unless we discover something that can travel faster than light. Therefore, researchers are finding a way to make teleoperation tactile for upcoming Mars missions. The best solution for future robots in space is to make them autonomous, reliable and self-repairable, and only receive new instructions or software upgrades from satellites if necessary. Space robots can come in many forms in the near future – they can be a bunch of self-deploying sensor networks such as humanoid robotics, manipulator arms, advanced rovers, plasma or rotor based drones, crawlers, climbers, etc. Their capability will be far beyond the potential of humans: Space pixels can be mass programmed for specific tasks shot by a space robot on a distant celestial object to study weather conditions and do atmospheric measurements; humanoids can replace humans in many aspects, rovers can perform mining for samples; crawlers and climbers can perform tasks on uneven surfaces where rovers and humanoids cannot step on; drones can travel farther distances at less time performing aerial mapping and measurements; swimming robots can swim (in liquid hydrogen and other fluids on Saturn and other planets), and many more. Missions with such types of robots pose unique requirements and opportunities but also new challenges. Planet's gravity, planet-quakes, and unknown obstacles can be challenging for a humanoid, unknown atmospheric perturbations can damage the drones, and unfavorable weather such as heavy winds can sweep away Space Pixels. With the rapid developments in space robotics, there is no doubt that the next inter-planetary missions will first have a footprint of a humanoid on the distant planet than that of a human. However, having painted a nice picture, to bring these visions to reality there are many challenges to be addressed pushing further the limits of robots in space.



(a) Delfi-C^3 (b) Our low cost GNSS module

Figure 1: Delfi-C^3 and our GNSS module

4 CHALLENGES TO BUILD SWANS

In the previous sections, we explained the path towards the use of SWANS in space assisting many new applications and missions. We discussed three ambitious themes, which offer new directions in the coming years. All of them invariably require building networks within space objects (e.g., satellites) to connecting and coordinating multiple objects. Without mentioning these space objects have multitudes of sensors, actuators, low-power systems and embedded software modules. All these have stringent constraints during developmental as well as operational phases. Thus space related scientific endeavors have umpteen possibilities and challenges. Future SWANS needs cutting-edge technology in the field of miniaturization, energy harvesting, and distributed sensor networks. We consolidate many of the important challenges below which are highly interesting to the sensor systems community.

Distributed systems: Future SWANS should have a tight coupling between distributed sensors and actuator systems, and distributed computing and communication. The idea is to build and assemble independent modules that work towards a common goal. Within a space object, such as nanosatellites, or amongst multiple such objects, many modules should be able to accomplish a huge mission working in tandem independently but synchronously. Modules working well individually do not guarantee that the overall system is reliable, robust and adaptive to the harsh environments in space.

Miniaturization: Since access to space is expensive and requires enormous amount of resources (fuel, infrastructure, etc.), making space objects as small as possible is a must. Thus miniaturization of every subsystem is being targeted by academia and industry. However, miniaturization also poses challenges - constraints on harvested energy through small solar panels, power generation, control, and regulation. Though a small amount of energy is sufficient to power up systems such as Space Pixels, we do not have any miniaturized energy harvesters till date to fit entire power system in a tiny chip. With miniaturization, the hardware limitations such as radiation mitigation and thermal control, etc., becomes highly challenging.

Avoidance of cable harness using wireless: One of the ways to miniaturize the space object is to replace the cable harness by wireless systems. Indeed on an average, cables account for 5-10% of the total weight in small satellites as shown in Fig. 1a. In bigger satellites, this may even increase. Moreover, avoiding cables reduces the time for integration (building) of satellite time by 30%-40% while also avoiding errors and difficulties to reach every part of the space systems. It has been proved that wireless technologies such as BLE and ZigBee work in space, yet complete satellite has not been built using these wireless technologies. This is an area that needs close exploration. Major roadblock here is the reliability of wireless links. With wireless coming into the picture, challenging problems such as RF interference and higher power consumption because of the newly introduced wireless devices, should be addressed.

Handling a large amount of data: Any space mission these days requires high resolution data (for instance, data from remote sensing cameras). The data handling in large space systems involves maintenance and powering of the memory modules however the tough problem is to communicate the data back to Earth. In miniaturized space systems, it is also tedious to store data for longer duration because of less space, lower power, and less protection from solar flares, etc. Until now, not much work has been done on exploring this challenge; with distributed systems and requirement of high resolution data, data management and communication become an important bottleneck.

Synchronization: One of the major requirements in swarm based radio astronomy in space is synchronization between individual devices in SWANS. One of the easiest ways to achieve synchronization is by utilizing GPS signals available in the Earth orbits. With GPS, the synchronization can be achieved as high as nano-seconds with COTS approach. However, in non-Earth orbits such as the moon, GPS is not available thus clock synchronization is one of the major challenges if multiple modules or objects need to work in tandem. Further, some applications such as RI require multiple telescopes (antenna arrays) to be synchronized with a precision of pico-seconds. Typical COTS crystals may not provide such accuracy and are also affected with clock drifts unless it is atomic.

Software defined systems: Making the swarms agile and programmable as well as transformable (with respect to their individual tasks) requires flexibility in designing and executing software modules. For example, RI requires constellation formation in different geometry based on the application or mission. Thus, SWANS can be a Software Defined Satellite (SDS) systems combining many results from software defined systems.

Onboard control systems: The celestial objects around which the satellites may orbit can have gravitational perturbations (gravity is not the same at all points). This makes the satellite change its orientation and altitude in the orbit. Hence, SWANS need autonomous control algorithms. It is highly necessary for formation flying and high speed inter-satellite communication systems. Eventhough mmWave and laser communication can provide high speed data transfer, they require precise beam forming the and attitude control to achieve line of sight. The embedded software needs to support such precision control algorithms.

Localization: Localization is a huge challenge in space, not only because of the vast volume to cover but also due to the fact that many space objects are moving at enormous speeds. Further, on other planets, mapping with miniaturized robots/systems is difficult as they do not contain any position sensors like GPS. Stitching the data from each of them to get a broader picture is highly challenging. Further, such localization algorithms require high amount of computations, which is scarce in miniaturized space objects.

The list above provides a sneak preview of some of the major challenges. Apart from them, there are many problems which are well known in Sensor Systems community, which are, energy optimization, harvesting, time synchronization, multi-hop communication, packet delivery improvements, localization, optimization of embedded code, etc., to mention a few. We next provide a short list of our plans for the next five years.

4.1 Work so far

When building the nanosatellite - Delft-C^3 (Fig. 1a) at TU Delft, many challenges in designing subsystems were noted such as power, on-board computer, attitude related sensors and actuators, low-power communication, etc. As a wireless technology demonstration in satellites, ZigBee was used in one of our satellite subsystems and we have the first results of it. We have built a low cost (approx $100) Global Navigation Satellite Systems (GNSS) receiver, shown in Fig 1b that provides location accuracy upto 10 m (3σ). We tested our in-house manufactured thin film solar cells that can lead us towards miniaturized energy harvester. The micro-propulsion system that we designed could successfully perform orbit correction 60 times in the orbit, proving the working of our sub-system. This can help us with our vision of establishing swarm formation.

4.2 Our Research in the Next 5 Years

Our plan for the next five years towards the goal of miniaturization i.e, building SWANS include addressing the following immediate problems for technology demonstration:

IoT in SWANS: Our first step towards the miniaturization is to explore the ways to avoid harness and connect the subsystems wirelessly. We will address the new challenges introduced as a result of wireless interconnection, such as RF interference, extra burden on the available power and guaranteeing reliability in this intra-communication network.

Power management: As the system gets miniaturized, the amount of energy harvested also reduces while the power consumption may not reduce proportionally. New power management techniques and embedded code optimization need to be investigated.

Communication: Miniaturization may end up with designing small antennas. With smaller antennas, communication using lower frequencies is not possible. Higher frequencies are power hungry which is going to be scarce with small harvesters. In coming years, we want to address such problems both in terms of hardware and communication.

Onboard control and synchronization: We plan to focus on optimizing onboard tasks scheduling in energy-constrained SWANS along with time synchronization between them when they are operational in the form of swarms.

5 CONCLUSIONS

In this article, we traced the new horizons for innovations in space embedded systems in the near future. We presented our vision on many innovations that are expected in space technologies in the coming years harnessing the developments in IoT. We envisaged that wireless sensor actuator networks will take over space systems in a big way. We mentioned examples of innovative applications showcasing our visions for the future, which will have a significant impact on science and technology. We provided some important challenges with respect to miniaturization, resource optimization, embedded software, algorithms, wireless communications, and networking. We also briefly mentioned our experience in this domain (though limited). Towards the end, we provided a list of problems that we would like to tackle in the next five years. We believe that space is largely an unconquered frontier where **sky is the limit** – literally and figuratively.

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