Development of a Nanosatellite Using Smartphones' Capabilities for the Fulfillment of Space Missions

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***Abstract*— One of the most pivotal challenges faced while developing space systems is the need for a high level of technology and to expend a substantial amount of money in order for achieving such technical knowledge. This has led to the development of space products being costly and time-consuming. One progressive approach to evolving space systems is the exploitation of commercial subsystems and components in order to abate the costs and the time required for technological development to occur. In the present research, the development of a Nanosatellite by the exploitation of commercial smartphones' capabilities as a platform for reducing the technological development costs and time is studied. To that end, a ground setup similar to a test table with the aim of integrating the satellite's software and hardware architecture is developed. The results demonstrate that the use of a smartphone as the central core and flight computer of a satellite is capable of diminishing the pertaining costs and time, and also the number of design loops to be followed in order for developing a satellite.**

***Index Terms*— Satellite, Commercial Technology, Smartphone, Space Technology**

I. Introduction

The expansion of space technologies being exploited in various missions has led to prominent growth in such areas over the last decades. What is more, cost is a key factor in space missions becoming triumphant; in a manner that different corporations are always looking for ways by which they can diminish their costs. Among satellite platforms, Micro and Nanosatellites have been able to provide extensive capabilities while keeping the costs low. The significance of lowering the costs has led to some optimization practices, by the utilization of creativity factor, in the field of Micro and Nanosatellites with low costs in recent years. One consequential factor of such creativity is the exploitation of commercial equipment in order to develop space products. This has made a substantial contribution to lowering the cost and time required for fulfilling a project requirement. During the last decade, commercial equipment and subsystems have made their way toward satellite production industry. In 1999, M. Day, from the University of Surrey, carried out comprehensive research into using commercial electronic equipment for space missions [1]. Looking into the literature in terms of using commercial equipment for space missions, M. Day evaluated the parameters affecting the utilization of such pieces for space missions.

Furthermore, developing PhoneSats, as a platform for Nanosatellites, has been capable of implementing the use of commercial equipment in order to manufacture satellites at a system level; the aforementioned has been started by NASA since 2009 [2, 3]. In 2010, Pignol, from CNES in France, examined the possible exploitation of commercial electronic equipment for space missions; specifically, for satellites. He finally declared that such utilization would provide great opportunities for future space missions [4]. As regards the risk of using commercial equipment for space missions, an article was published by a team from NASA in 2014. In the article, the use of commercial equipment for Space Launch Vehicles (SLVs) and spacecraft was studied in respect of risk and reliability. The approach was also considered as a tool for decreasing the costs [5]. In 2016, another team from NASA examined the requirements, standards, conditions, and methods by which the use of commercial electronic equipment on satellites can be implemented. In this research, reliability and availability were introduced as two fundamental factors [6]. Studies have demonstrated that electronic technologies during the last decade have advanced dramatically. The epitome of such developments could be observed in electronic devices like cellular phones. Even though the size of these phones has become smaller, their capabilities have increased manifold. This has led to an increasing trend in the application of such gadgetry to various missions; such exercise is observed in the implementation of smartphones for space missions known as PhoneSats. By virtue of capabilities found in smartphones, these small satellites have been able to bring down the number of design and manufacture loops leading to a reduction in the development costs. Such a system is comprised of four main parts: firstly, the cellular phone, which is responsible for gathering, processing, and sending information. Secondly, the transmitter for transmission of the data to ground station; thirdly, a receiver for reception of the data through waves and also its delivery to

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a processing system; and lastly, a laptop or specific equipment for recording, looking at and analyzing the data (as well as decision and exercising commands if required).

One very significant piece of research has been done to investigate the attitude determination of Phonesat. Zhao and his colleagues achieved the attitude information by using smartphone's sensors such as gyroscope, accelerometer and Global Positioning System (GPS) [7]. To improve the precision of the strategy, a quaternion based Kalman Filter was derived and illustrating reliable attitude information. Also in a similar study Zhao [8] used smartphone sensors to control and navigate PhoneSat satellite.

Another innovation in this field is the use of smartphone's camera as a tool for image telemetry [9]. A suitable camera module of a certain commercial smartphone is adopted after precise calculation and the product selection process.

In addition to subject proposal, considerable research has been done on the utilization of smartphone capabilities in different other fields. Specht and his colleagues [10] measured positioning accuracy of Samsung Galaxy nine series mobile phones in an athletic stadium for sport purposes. The study demonstrated significant differences in positioning accuracy of particular GNSS receivers in Samsung Galaxy series mobile phones while allowing their accuracy to be unambiguously assessed.

In the present work, utilization of smartphones as a commercial system and for the purpose of serving as the central core of a Nanosatellite has been studied. In this regard, a ground software and hardware setup, similar to a test table, has been developed, assessing the integration of the developed software into the smartphone's hardware and also with the transceiver system.

II. An Introduction to PhoneSats

A PhoneSat is a satellite making use of a smartphone, developing an affordable platform for remote sensing satellites. The PhoneSat Project was first initiated by NASA. In principle, a PhoneSat is a Satellite possessing a plunged cost of design and manufacture with the help of a smartphone. Such a platform is a CubeSat made up of multiples of 10 cm^3 cubic units and a weight of approximately one to two kilograms. The cost reduction experienced in the platform is due largely to the exploitation of commercial technologies being already present in smartphones. The technologies and capabilities required in satellites to a certain extent, such as a fast central processing unit, an open-source multipurpose operating system, different miniature sensors, appropriate memory for storing information, high spatial resolution cameras, GPS antennas; these phones are able to provide for numerous requisites of the satellite with no changes made. In the present research, not only will the merits of using smartphones as the central processing unit and the main platform of a Nanosatellite be studied, but also the exploitation of commercial technologies at the system level of a spacecraft will be discussed. The following are being reviewed in detail:

- The merits and demerits of utilizing commercial technologies for space missions.
- As regards the merits,
  - ✓ Reduction in research and development (R&D) costs.
  - ✓ Reduced amount of time for preparation and delivery, and reliability.
  - ✓ Performance germane to the mission's aims.
- Turning to the demerits and challenges,
  - ✓ Particular operating conditions and environments.
  - ✓ Operating lifetime.
  - ✓ Standards used by different manufacturers not being identical.
  - ✓ A broad domain of operating environments in terms of requirements.

A. *Mission objectives of PhoneSats*

The following are the most prominent mission objectives of PhoneSats:

- Development of a Nano-Satellite platform with an approach to cost reduction.
- Reduction in R&D costs of the satellite's subsystems.
- Reduction in design and manufacture time.
- Development of a platform that could be easily launched in a piggyback arrangement.
- Exploitation of commercial technologies for space missions accompanied by an increase in reliability at a system level.

B. *Identification of possible missions and their corresponding architectures*

According to studies carried out, a PhoneSat is a CubeSat capable of imaging, sending out telecommunicational and radio signals, aggregating various sensors' data, testing out the Electrical Power System (EPS), testing software capabilities of the smartphone, testing out the solar panels, and testing out the Attitude Determination and Control System (ADCS).

In accordance with the investigation carried out, it will be attempted to use the platform's own capabilities, adding no further complexities to the satellite; especially in terms of the ADCS. Besides, in the present work, it will be attempted to adopt the simplest and the most operational mission possible, leading into a satellite possessing a simpler architecture. By and large, the mission adopted for the satellite is to do imaging by the utilization of the smartphone's camera and send out the images taken to the ground station using the satellite's antenna in a ten-day operational lifetime. To do so, the smartphone's battery must be removed, and a new pack of batteries must be installed. Also, two pieces of hardware comprised of an

Arduino Uno as shown in Fig 1, using the Microchip Atmel ATmega328 microcontroller and performing the function of a guard circuit, and a radio antenna sending out signals.

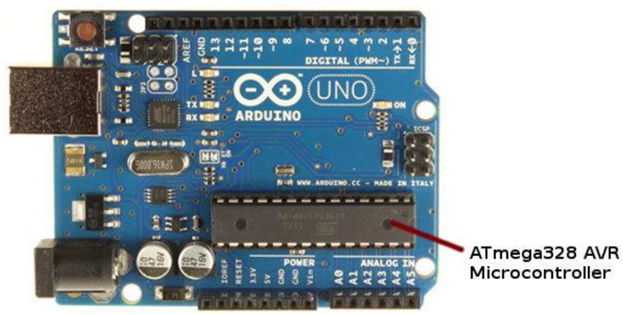

Fig 1 : Arduino Uno using the ATmega328 microcontroller

In general, the schematic of a small satellite’s architecture is illustrated in Fig 2. The aforementioned demonstrates the connection between the On-Board Computer (OBC) and other subsystems along with connectional complexities existent in satellite development. This is while there is no such architecture in a PhoneSat, and that is due to the fact that many of these connections are already integrated into the smartphone itself, creating an advantage for the PhoneSat and leading to fewer connectional complexities in such a platform.

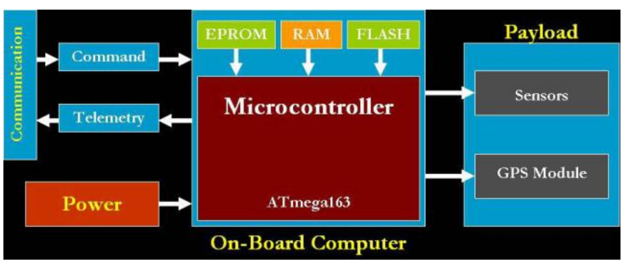

Fig 2 : The schematic of a Nano-Satellite’s architecture

The architecture of a PhoneSat is designed in two categories: hardware architecture and software architecture. Regarding the planned mission, Fig 3 shows the hardware architecture of the PhoneSat which is the most straightforward design.

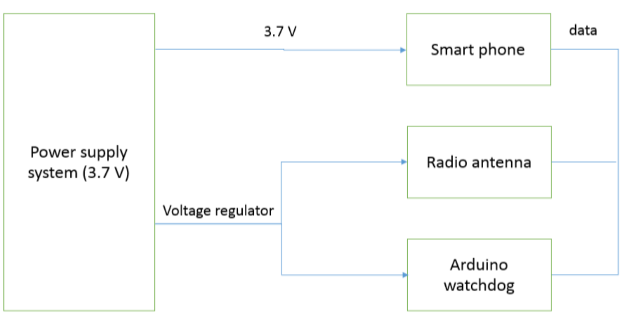

Fig 3 : Hardware architecture of the PhoneSat

The software architecture of the PhoneSat is based upon the open-source Android operating system. In case of the PhoneSat’s software management, an application has to be developed, (a piece of software) possessing consistent architecture with the hardware and also the mission of the satellite. In principle, the software architecture of the PhoneSat is a piece of software functioning within the Android operating system.

Considering the mission objectives defined, it is anticipated that the PhoneSat will be able to gather data, utilize its equipment such as the camera and the sensors, and send them out to the ground station. Overall, the tasks which the PhoneSat is supposed to perform are limited, and the designed software must be capable of managing missions like imaging, selecting images, and sending them out to the ground station.

Moreover, missions like restarting and sending out some pieces of data must be consistent with the software. The telemetry subsystem not only sends out images, but also is able to send out some pieces of data concerning batteries’ voltages and temperature of the cube. In terms of sending out images, there will be an algorithm implemented, selecting images having a higher resolution, transmitting them to the ground station while erasing the others. Schematically, the software architecture of the PhoneSat has been deemed as shown in Fig 4.

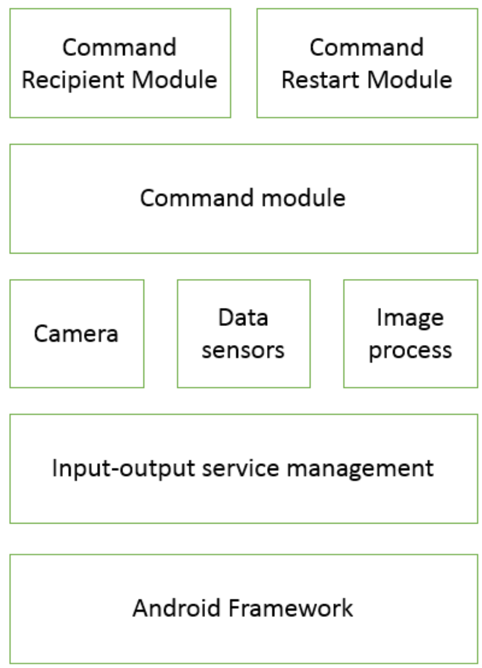

Fig 4 : Software architecture of the PhoneSat

III. USE OF SMART PHONE SENSORS AS A MEANS OF ATTITUDE DETERMINATION FOR THE SATELLITE SYSTEM

The new generation smartphones posses a wide range of efficient sensors. These sensors include accelerometer, gyroscope and GPS. Reading raw sensor data and measuring them during operation is one of the major challenges of this project. Fig 5 and Fig 6 demonstrate the raw data reed from gyroscope and accelerometer sensors of smartphone, respectively.

Error reduction algorithms have been used to reduce the measurement error of the sensors. Data fusion of the sensors is used to reduce the measurement error, with the Kalman filter is utilized to this end as shown in Fig 7.

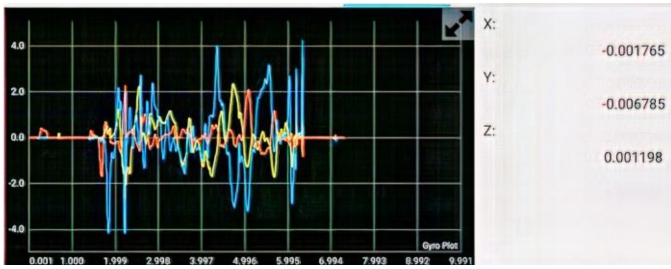

Fig 5 : Raw data read from the smartphone’s gyroscope Sensor

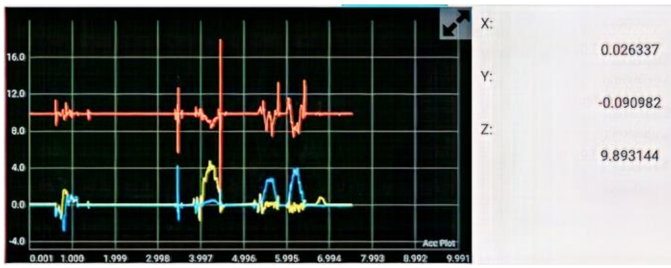

Fig 6 : Raw data read from the smartphone’s accelerometer Sensor

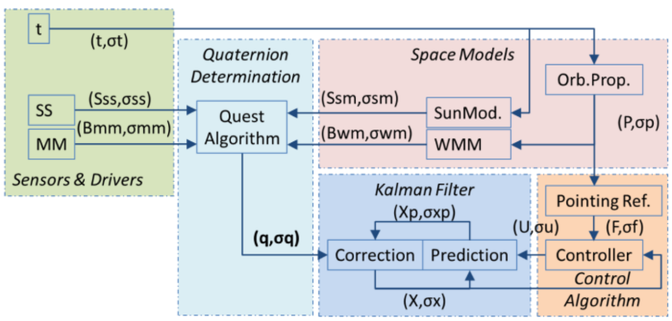

Fig 7 : Schematic of the sensor’s architecture and error reduction algorithm

IV. STUDYING THE IMPLEMENTED SETUP ON THE GROUND TEST TABLE

In order to carry out initial tests on this system, the Zigbee Module, among the modules existent in the market, was chosen because of its satisfactory range and yet having a low price. Zigbee is the name of a communicational wireless protocol recognized as a global communicational standard in Machine to Machine (M2M) Networks. It needs small spaces, low power consumption, and has a low price Fig 8. The Zigbee standard operates at the frequency of 2.4 GHz, under the physical properties of the standard “IEEE 802.15.4”. The Zigbee technology is the low-cost type of wireless networks such as Bluetooth and Wireless Fidelity (Wi-Fi). This enables the Zigbee to be exploited in several different practices like smartification of houses, traffic management systems, and controlling various industrial devices.

Fig 9 delineates a communicational network embedded in this module comprising a coordinator as the central element, one or more End Devices as the transmitters of the sensors’ data, and a couple of routers as relay for extending the range of these modules by consecutive receiving and sending out of the data.

Fig 8 : The Zigbee transmitter, with implementation of changes in terms of circuits’ disposition and mechanical strengthening [5]

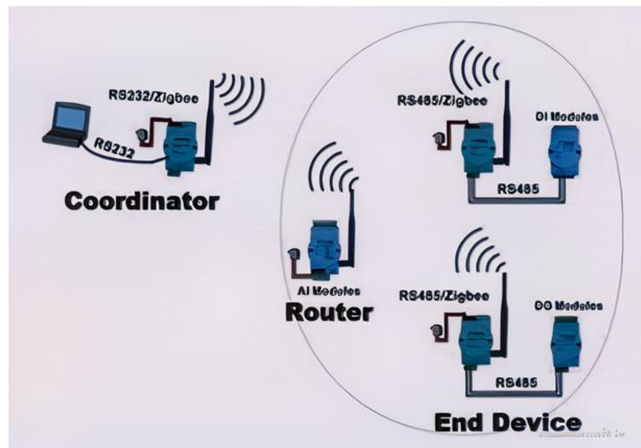

Fig 9 : The structure of a communicational network utilizing the Zigbee module

The power supply of the Zigbee module is provided by a 1350 mAh battery with a voltage of 3.7 V. Serious attention has been given to the system being affected by noise, in respect of the disposition of the battery and the power supply wires (passing by serial communication wires) and strengthening of the circuits. In this manner, problems with the noise are fairly removed, and the circuits within the transmittal box will not be impaired by intense agitation.

The functions of the Android software are as follows:

1. Getting permission to access the camera and the location of the device.

2. Getting started on taking images at pre-defined time intervals.

3. Storing the images with their original resolution on the device’s memory.

4. Compressing the images to the required limit, for lowering the data packet’s volume to be sent out.

5. Encoding the images using Base-64.

6. Fractionating the data packet, for removing the maximum buffer limit in the transmitter and smartphone.

7. Sending out the data packet obtained from the previous stage and pausing for an amount of time well suited to the rate at which the packet is being sent out.
8. Sending out the location at the end of each image.

In order to set the time intervals between images to be taken, the intended amount is input based on milliseconds, and, after having been stored, the images are sent out in succession.

The software provided for the computer is developed via Java programming language, hence having no limitations to be operated on various operating systems. The procedure pertaining to the software is as follows:

1. Opening the serial port and implementation of the serial device's settings.
2. Waiting for receiving information via the serial port.
3. Keeping the information until the entire file of an image downloads.
4. Decoding the received packet and demonstrating the image on the computer.
5. Storing the received image on the computer.
6. Receiving and demonstrating the location.

The platform programmed for the ground station (on the desktop environment) is shown in Fig 10; demonstrating the received and stored image, accompanying the coordinates of its location.

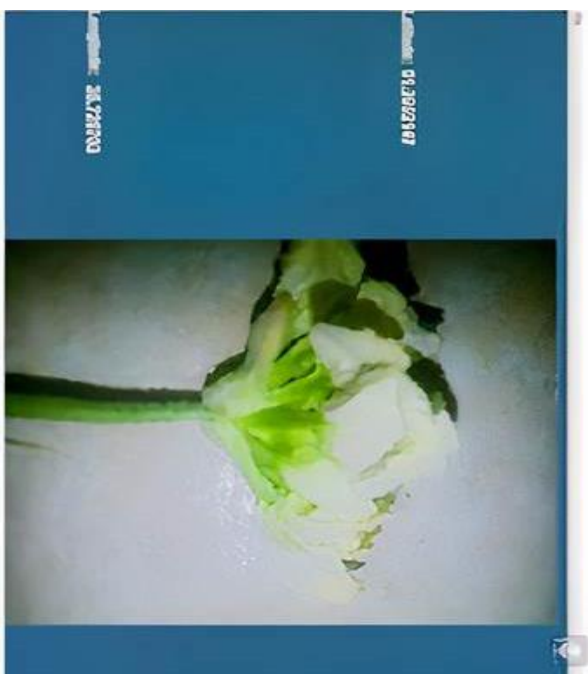

Fig 10 : The platform programmed for the ground station.

The system implemented has passed the initial tests flourishingly, and its overall performance has been approved. By the exploitation of a broadband, long-range transmitter and receiver, the final performance of the system is measurable. A similar version of this setup has already been implemented in the NASA PhoneSat project as shown in Fig 11.

In the ultimate system, the following will be given due considerations:

1. Designing a body appropriate for the satellite.
2. Adding more accurate sensors in order for receiving particular ambient data.
3. Ameliorating the ground station.
4. Analysis of the received data.

Fig 11 : The Development Model (DM) of PhoneSat-1, operated by NASA [5]

V. PhoneSat's Conceptual Mission

In case of the mission concept establishment and design, this ought to be referred to the mission objectives and its requirements. Since PhoneSat is an experimental satellite, and that its main objective is germane to imaging, the satellite's mission concept is established based upon the aforementioned. One of the most significant factors in a satellite's mission is its orbital height. Since the orbital lifetime of the PhoneSat is approximately ten days, there is the capability to insert it into lower orbital altitudes; this is to avoid the atmospheric drag which is predominant in satellites possessing longer orbital lifetimes. With regards to the aforementioned and the launch capability of our country's SLV, a quasi-elliptical orbit possessing the orbital height of 250 Kilometers above sea level has been considered for the satellite Fig 12. Basically, there are four principal phases in the satellite's operation. These phases are listed here and elaborated in subsequent paragraphs:

- Climb
- Separation and orbital insertion
- Carrying out the imaging operation and communication with the Earth
- Passivation and de-orbit

A. *The Climb Phase*

At this phase, the satellite is switched off, and there is no communication of data. The SLV will carry the satellite up to a specific altitude; this is followed by the separation of the fairings and the satellite in succession, preceded by the SLV stages having burned out.

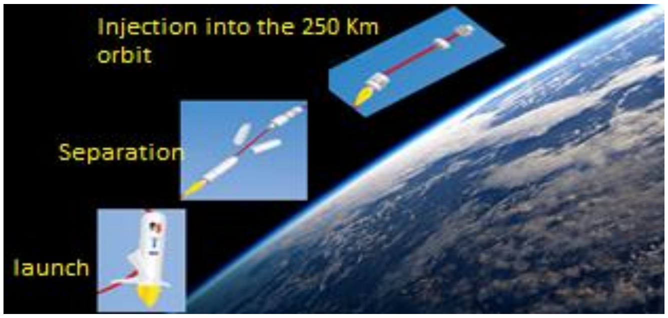

Fig 12 : PhoneSat's concept of operations

B. The Separation and Orbital Insertion

After the satellite separation occurs, the satellite goes through tumbling and then detumbling for some time before final stabilization. In accordance with calculations carried out, this procedure takes about 45 minutes to an hour. In later design phases, this number will become more accurate through numerical simulations, and it will be integrated into the final design. After the detumbling is completed, the designed guard circuit takes charge for turning on the satellite, under any circumstances. This point onwards, the satellite becomes fully operational in orbit.

C. Carrying out the imaging operation and communication with the Earth

At this phase, the satellite is in orbit, ready to carry out its mission. Imaging, categorization of the images taken, selecting the data, and sending them out to the ground station are the most paramount tasks to be performed. As scheduled, the satellite's camera will take one image per second. This requires that the satellite be able to continuously take images.

Nowadays, some smartphones in the market have been equipped with this capability. The satellite's software is required to hand-pick the images of high quality compared to the others every 20 minutes, storing them as a packet in the memory. The stored packets will be sent out to the ground station every 20 minutes as part of a larger packet comprised of the aforesaid images, housekeeping data of the satellite, and sensors' data (if there are any). After each and every communication, the satellite's software and guard circuit are required to monitor every subsystem's health, resetting the smartphone on the condition that a problem is detected. Regarding the fact that the smartphone's camera is only capable of imaging in the visible spectrum, the imaging schedule ought to be planned in a manner that the images would possess the appropriate resolution. The images sent out to the Earth must be stored to the smartphone's memory.

D. Passivation and de-orbit

At this phase, the satellite has completed its whole mission and sent out its data to the Earth. At this stage, the satellite is turned off and de-orbited.

VI. The Exploitation of Commercial Technologies for Space Missions

For the most part, due to some challenges such as operational environment, operational lifetime, and lower reliability, compared with products possessing space and military quality, commercial technologies are not satisfactory alternatives to space missions. However, in recent years, the development of knowledge, reliability and quality assurance has led to the capability of utilizing commercial parts for space missions without any problems; using military and space standards accompanied by some procedures.

The conventional and classic approach followed by NASA is carrying out environmental and performance tests on the parts based upon MIL standards. What is more, the aggregate reliability of the system, having installed the parts on the satellite, must not become less than that dictated by the requirements. For the purpose of exploiting a smartphone as the central core of a Nanosatellite, not only are the performance and functional tests of crucial importance, but also the environmental tests are of great significance. Shock, vibration, thermal vacuum, and radiation tests are the most vital tests for a satellite to pass. The reliability of the mission must be more than 95 percent, which is to be confirmed by performance tests.

VII. Concluding Remarks

In the present research, the exploitation of commercial technologies for space missions was discussed, and, specifically, the utilization of smartphones as the central core of a Nanosatellite was studied. The results demonstrate that the utilization of smartphones as the flight computer of a satellite decreases the costs germane to research and development carried out in the design phase, lowering the number of design loops to be followed. Unique capabilities of the new smartphones, comprising powerful processors, internal memory of high capacity, flexible open-source software, high-resolution cameras, and an independent power supply system, make them a satisfactory satellite platform. Having high-performance sensors is another feature of smartphones.

In this research use of gyroscope, GPS, and accelerometer sensors of a smartphone was considered. Furthermore, sensors' data fusion implemented and error reduction algorithms used to improve sensors' measurement. In terms of commercial technologies being operated in space, various environmental tests must be carried out with the aim of enhancing the reliability of the final product in space, making sure these are capable of being operated in space. The utilization of smartphones as the central core of a satellite, considering the particular environment of the space, requires serious consideration of reliability; that is why a guard circuit has been chosen to guard the system. For the future strategies of the project, efforts will be made to control and navigate the satellite using smartphone sensors. In addition, software upgrades will be considered to increase system's reliability and safety.

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