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IMPACT OF DIDACTIC SATELLITE IN SPACE MATURITY IMPROVEMENT: A REVIEW PAPER

Space technology is becoming increasingly important in modern society. It participates in the construction of the future and the welfare of humanity through many applications in daily life. These factors lead to the need for training, research, and development in this area of space exploration. This paper reviews the use of small satellites to acquire basic knowledge of the space sector. Further development of this knowledge leads to the creation of space missions, which, in turn, ensure the progress of the space technology readiness level (TRL), defined by the international measurement scale. It is able to estimate technological maturity. The review concludes that the use of low-cost or didactic satellites could contribute to space mission development and demonstration. We reckon that embedded components with functions similar to smartphones can be used to achieve this goal. Two types of embedded components are discussed to demonstrate their efficacy in space engineering.

Keywords: *Cubesat, data analysis, didactic, satellite, space engineering, TRL.*

1. INTRODUCTION

Space technology is beneficial in many areas, such as climate and meteorological monitoring, access to health care and education, water management, transport efficiency and agriculture, peacekeeping, security and humanitarian aid. The list of space applications impacting life on Earth is virtually endless, and many more contributions are currently under development or studied.

Unfortunately, the space sector continues to be affordable only to large national projects or extremely wealthy organizations. In this context, small organizations and emerging countries are adopting small satellites as their means of space exploration [1—5]. These satellites are often dedicated to scientific or amateur operations. This leads to a higher technology readiness level (TRL) to develop missions in the space domain. It is obvious that this work made it possible to advance technological maturity on satellite missions based on different platforms. This is an excellent educational idea to validate possible missions but also breaks new issues related to reliability, the life of a mission, and its reconfigurability. Despite the limitations present in the didactic project, it offers a reliable platform to access the space domain promoting TRL.

Technology Readiness Levels (TRLs) are a systematic metric that provides an objective measure to communicate the maturity of a particular technology among program executives, system developers and technology researchers, and individuals from different organizations. Generally, it aimed to monitor the maturation of technology. In addition, the use of TRLs can provide a needed foundation for developing and communicating insight into the risks involved in advancing a new system and its constituent new technology components [6].

Indeed, TRL is originally developed by NASA, and therefore, it is widely used as a reference in aero-

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nautical and aerospace projects. NASA, therefore, reached the top level of TRL, which opens the door for defining a higher TRL category. S. Jeremy considers the need of defining the TRL 10 as a new category [7].

In fact, developers need big budgets to reach a progressive TRL, mostly in the space domain. This creates a gap for emerging countries and small organizations that lead to the birth of a new class of satellites around didactic projects. This innovation provides a reliable platform to improve the maturity of the space sector. Thus, this paper reviews the impact of didactic satellites to develop TRL and therefore encourages universities and emerging countries to explore the space domain and benefit from its wide applications.

2. TECHNOLOGY READINESS LEVEL

Science, technology, and space data can directly or indirectly contribute to the achievement of all the sustainable development goals. Space science encompasses those scientific disciplines focused on the exploration of space and the study of natural phenomena and physical bodies in space, including astronomy, aerospace engineering, space medicine and astrobiology. Earth observation by satellites, satellite communications, and satellite geolocation involves space science and technology. This is also the case with weather forecasting and technologies that involve the use of remote sensing, global positioning systems, satellite television and communication systems, as well as scientific fields such as astronomy and science of the earth.

These factors lead to acquiring basic knowledge about space technology. It encompasses three main segments, which are space, user, and ground station. Thus, NASA provides an architecture to define space engineering in constructing a mission [8]. Indeed, acquiring an adequate definition of space mission leads to improving basic knowledge and therefore progresses the TRL. It is composed of nine levels defined by NASA and European Space Agency (ESA) for space applications. Table 1 summarizes the TRL's levels [6, 9].

Indeed, maturity is a concept used in several areas. The term maturity implies a final state following development. The development principle considers a series of phases, passing from an initial stage and some intermediate stages before reaching maturity. This concept proposes to qualify or quantify the development of a given subject. It offers the potential to measure the acquisition of specific capacities at levels of development. This assessment makes it possible to identify the skills to be acquired in order to reach the desired level. Thus, development towards maturity can be described in the form of maturity models allowing the level to be measured in the form of benchmarking. These virtual models are characterized by the use of a scale of progressive stages, or maturity levels (Table 1). This led to describe each level for determining the adequate TRL of such technology's development which is explained as follows:

- TRL 1: This is the lowest level of maturity of a technology. We begin to evaluate applications of scientific research, for example, in the form of publi-

Table 1. **Technology Readiness Levels**

TRLs	Stage	Definition
1	Basic knowledge about the technology	Report and observation of basic principles
2		Concept of the technology
3	Feasibility research	Analysis for concept's proof
4		Validation in laboratory environment
5	Development and demonstration of the technology	Validation in relevant environment
6		Development of the prototype demonstration in space or on the ground
7		Test of the prototype in space environment
8	Systems development, test, and operation	Development of the flight model
9		Launch and operation

cations analyzing the fundamental characteristics of the technology.

- TRL 2: It defines the beginning of the invention phase. From the observation of the basic principles, it becomes possible to envisage practical applications. There is no evidence or detailed analysis to confirm them. We are still only at the paper studies stage.
- TRL 3: It presents the launching of analytical studies and laboratory work concerning the validation of certain elementary building blocks of the technology in order to concretely validate the forecast studies.
- TRL 4: During this phase, the basic constituents of the technology were integrated, but in a relatively "unrepresentative" form of a possible system, for example, in the form of a "mock-up" or prototype in the laboratory.
- TRL 5: This step serves to represent sharply increasing subsystems. The building blocks are integrated into a complete package allowing the testing of the technology in a realistic simulated environment, for example, in the form of a "very representative" laboratory integration.
- TRL 6: Here, we try to test in a representative environment a representative model or a prototype of a system, much more complete than what was tested in step 5, and this represents a key step in demonstrating the maturity of a technology, such as, for example, the testing of a prototype in a laboratory which reproduces the environmental conditions very precisely, or the conditions of operational use.
- TRL 7: This level serves to provide a demonstration of a prototype system conforming to the operational system or very close. Represents a strong progression from step 6, with the demonstration of a real prototype in an operational environment, such as, for example, a vehicle or an aerial platform, for example, an aircraft test bench. Information will be gathered at this stage to obtain the suitability to support this technology.
- TRL 8: Here, the technology has been proven to work in its final form and under the expected conditions of use. This step is, in most cases, the end of the demonstration, with, for example, the testing and evaluation of the system within the planned system in order to know whether it meets the specifications requested.
- TRL 9: It is the stage of application of the technology in its final form, and under representative mission conditions, such as those which may be encountered during operational tests and evaluations, and reliability tests, which includes, for example, employment under operational mission conditions.

3. WORK RELATED TO HIGH TRLS ACHIEVEMENT

Relying on TRLs estimation methods, many organizations integrated their capacities to reach high TRL enhancing techniques and methods. Indeed, this review focuses on analyzing the challenges and opportunities of TRLs related to space mission applications.

Technological evolution in the space domain is a complex process: technologies are interconnected into systems, and these, in turn, are intertwined and interdependent, both with each other and with the physical, social, and institutional environment. Each technological revolution is a set of technological systems, which gradually create the conditions necessary for the emergence of new systems, all following comparable principles and benefiting from the same external factors. The process of multiplication of technological innovations and systems explains the enormous growth potential of each of these constellations of new technologies. This process opens up a new and vast territory for innovation, expansion, and growth. The initial innovations mark the discovery of this territory, while its complete occupation corresponds to the phase of maturity and exhaustion.

Indeed, NASA was among organizations that opened the door for space missions' innovation and development. It focuses on progressing the level of technology maturity by developing systems related to space applications. Among, we quote those that reached the TRL 5 as an example of achieving the medium level in the scale [10]. It defined the way to achieve this level by developing a conductively cooled 2-micron laser transmitter for a coherent doppler wind lidar system. Here, it provides an adequate platform to progress the TRL towards level 6.

Therefore, its research was conducted to reach the TRL 6 by developing systems for space applications such as solar sail [11, 12] and platform for testing hardware in flight environments [13]. Otherwise,

R. Pierce et al. developed a laser system for space application reaching the TRL 6 [14].

Despite the difficulties surrounding space missions, many projects succeeded in reaching the TRL 9, defining the ways to achieve this goal. A survey provided a summary of systems able to reach level 9, including Guidance, Navigation, and Control (GNC) subsystems for small satellites is presented in [15]. This survey as well concerns sensors and actuators such as Star Trackers, Magnetometers, Sun Sensors, Earth Sensors, Gyroscopes, GPS Receivers, Reaction Wheels, Magnetorquers. In addition, it defined the performance needed to reach this high level. Otherwise, the development of the On-Board Computer (OBC) for small satellites can lead to the progress of the TRL towards level 9 [16]. Besides, didactic project-based rocket development can deal with this objective [17].

Table 2 summarizes the space projects related to TRL enhancement.

Indeed, this domain represents a real gap in achieving a high level of technological maturity regarding complex systems. Ironically, the benefits shift to countries with few financial resources at the precise moment when the production process is characterized by more intensive use of capital. We could therefore think that only companies in advanced countries have the necessary knowledge in this phase. Yet while new products are part of the early stages of a technological revolution, the knowledge required tends to be in the public domain (available in universities, for example). The only proof of this is the recent case of didactic projects around satellite missions' demonstration and development.

Therefore, it seems possible to devise a strategy for accumulating technological capabilities using mature technologies and then using them to access new and dynamic technologies, but this ability is highly dependent on the specific opportunities created by successive technological revolutions. A thorough understanding of technological developments in advanced countries can be useful for developing countries wishing to design viable strategies. This opens the door for the birth of new amateur and didactic projects based on satellite systems to enhance the TRL of space technology domain.

Table 2. **TRL reached for space missions**

Mission name	Developed system	TRL achieved
Conductively Cooled 2 Micron Laser Transmitter for Coherent Doppler Wind Lidar System [10]	Conductively-cooled single-frequency 2-micron laser	5
Solar Sail design [11]	Solar sail configuration to address NASA's future space propulsion needs	6
Solar Sail [12]	Solar sail propulsion	6
Satellite Servicing Capabilities Office Testing [13]	Platform for hardware testing	6
Stabilized Lasers [14]	Stabilized Lasers for a satellite application	6
GNC components for small satellites [15]	Star trackers	9
	Magnetometers	9
	Earth sensor	9
	Sun sensor	9
	GPS receiver	9
	Gyroscope	9
	Reaction wheels	9
On-board computer (OBC) [16]	Power-efficient, low-Cost, and flash FPGA based OBC for small-satellites	9
Rocket [17]	Hybrid sounding rocket HEROS	9

4. TECHNOLOGY READINESS LEVEL BASED ON DIDACTIC PROJECTS

Regarding the complex systems related to space applications, the improvement of TRLs in this domain may present challenges for achieving a high level. A survey performed in [18] extracted the difficulties observed in TRL implementation, which can be summarized into three categories: system complexity, planning and review, and validity of the assessment. Thus, didactic projects present a promoting solution to fill the gap in space missions' demonstration and development.

The CubeSat was developed for research and education as the first step for amateur satellites toward the accumulation and test of space applications [19, 20]. This satellite reduces the mission's cost providing an adequate system for space exploration. This is proven by the hundreds of CubeSats launched into orbits [21]. These missions were developed around nano and pico classes of satellites providing an adequate platform for demonstration projects aimed at increasing the maturity of satellite technology.

In fact, the accumulation of space technology knowledge relying on didactic projects leads to developing skills for the construction of pico and nanosatellites [22—24]. In addition, these systems can provide a reliable platform for the development of satellite subsystems such as attitude determination and control systems [25—27].

On the other hand, "what can we do when our students are bored during the activities, or they are not interested in the topic? The Arduino board based on ATMEGA chipset or similar devices with few sensors or robotics can be the solution", said Maria Peto [28]. Thus, this kind of system presents an adequate amateur platform to demonstrate satellite development steps. It provides the necessary knowledge to develop a real satellite using low-cost commercialized components. This idea led to the announcement of the birth of a new tiny satellite, such as CanSat, which was proposed by Prof. Robert Twiggs [29]. CanSat systems were developed to avoid barriers to constructing a real satellite, including a similar environment for construction, test, and launch.

Indeed, CanSat offered a fruitful platform as an educational system to practice space engineering knowledge [30—32]. In addition, it allowed the practicing of space operations such as ground station development [33], construction and testing of subsystems [34, 35], and launching techniques [36, 37]. Besides, it opened the door to the development and testing of space missions, such as data communication techniques and analysis [38, 39], and satellite operations and applications [40, 41].

Table 3. **TRL achieved by CanSats**

Mission	Stage reached	TRL achieved
Development of a didactic satellite for training and research [22] Educational satellite [25], [26], [27]	Validation in laboratory environment	4
Disaster victims monitoring [28]	Validation in relevant environment	5
OPEN prototype design and test [20] Ground station for the CanSat mission [33]	Development of the prototype demonstration on the ground	6
Prototype of CanSat with auto-gyro payload [30] Rover-back CanSat [31] Educative practice of space engineering [32] Data analysis mission for the CanSat [34], [35], [38], [39] Control system for CanSat landing [36], [37] CanSat for monitoring application [40], [41]	Development of the prototype demonstration in space	6
AeroCube 2 lanching [19] CanSat launched to suborbit [42]	Launch and operation	9

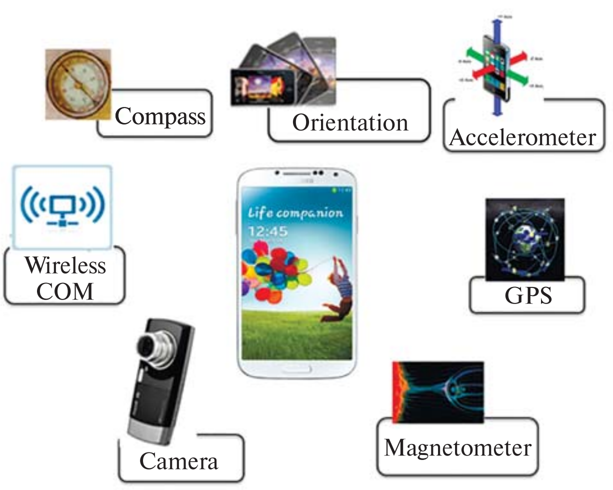

Fig. 1. Smartphone device components

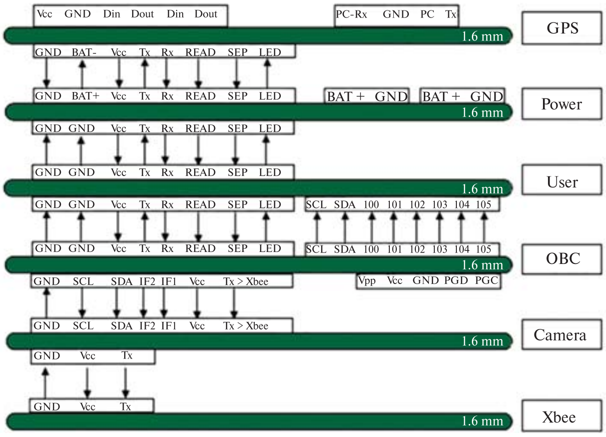

Fig. 2. CanSat Interfaces and boards

CanSat projects proved their efficiency to enhance the maturity of the space technology that reaches a high TRL encompassing all the steps to develop a real satellite [42]. We can consider that this tiny satellite has the potential to reach a high TRL despite its educational purpose. It succeeded to develop and practice knowledge of space engineering. Thus, it seemed reasonable to estimate the TRL of didactic projects to prove their impact on increasing the maturity of space engineering. Therefore, relying on TRL estimation tools, table 3 summarises the TRL reached by the presented examples.

5. DISCUSSION

TRLs have become a necessary tool to develop in the engineering domain, including the space engineering field, that presents a vital element of satellite application developments. Due to the gaps in related investments in this domain, many organizations and universities have developed systems around demonstration tools, such as satellite-based smartphones [43, 44] and CanSat systems that offer reliable platforms to acquire and practice knowledge about space engineering using affordable tools. These projects can be classified into two categories: device-based integrated/collected components.

5.1. *Device-based integrated components.* This system can be summarized in one tool of smartphone type that includes new software features, a camera, GPS receiver, and many miniaturized sensors, as presented in figure 1.

The Android platform is provet to withstand onboard flights in the atmosphere to low Earth orbit [43, 44]. Besides cost and power optimization, there are other benefits of adapting mobile device processors: better software development tools with better version control and a single power supply (typically 3, 3V) that presents the significant challenges of space applications. It has many integrated peripherals, such as magnetometers, accelerometers, and gyroscopes, to introduce and develop space applications for attitude determination and mission control. It contains several additional interfaces: the USB and the wireless connections (Wifi and Bluetooth), which create a convenient platform for data transmission while the satellite mission operates. Here, the novelty lies in the use of one tool to fully demonstrate satellite missions with achieving a high TRL.

5.2. *Device-based collected components.* This system presents a platform that connects many components with a central processing tool, such as the CanSat device. It is a small satellite fit within a soda can, which weighs less than 1 kg. This electronic device includes all development cycles in order to fabricate a satellite involving the design, fabrication, and launch [45]. It has been created to provide an opportunity to acquire the basic knowledge of space engineering.

Following the mission of the CanSat assembled and tested during the 6th CanSat Leader Training Program [35], we can learn all the necessary steps to build CanSats in order to fabricate, test, and launch a picosatellite. In addition, it presents a fruitful tool to enhance TRL in space engineering of a low-cost mission.

The CanSat contains 6 circular boards arranged as shown in figure 2, which illustrates the interfaces, boards, and the interconnection between them.

The CanSat has the same subsystems as a real satellite; the microcontroller board as an OBC (On-Board Computer), the GPS and sensors boards as an attitude determination subsystem, the Xbee module as a communication subsystem, the power board as a power subsystem, and the payload of this CanSat is a camera.

Based on this, CanSat can be considered a small satellite. This prototype demonstrates data management using a PIC microcontroller and attitude determination using a GPS receiver and an accelerometer, gyroscope, and temperature sensors. This fact makes it very efficient as a first step towards the development of a real satellite, including analysis, design, and implementation of subsystems' integration. This leads to achieving TRL 4.

The prototype was tested on the ground, including vibration and temperature tests. Finally, the flight model was developed and launched to about an altitude of 100 meters in order to be tested in a space environment achieving a high level of TRL [35].

6. CONCLUSION

The concept of maturity originates in the field of quality management. Many fields and disciplines have drawn inspiration from the concept of maturity to generate their own maturity model. Among all its types, they share one common aspect: Technology Readiness Level.

Despite the achievement of high TRL related to space technology, it is presenting a big challenge for emerging countries that are developing new tiny satellites as didactic projects. This innovation opens new and interesting perspectives within the framework of the mastery of space technology. In our review, we tried to substantiate the efficiency of satellite missions based on a didactic platform to enhance TRLs. It is an excellent educational tool for validating possible missions.

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ВПЛИВ ДИДАКТИЧНИХ СУПУТНИКІВ НА ВДОСКОНАЛЕННЯ ЗНАНЬ З КОСМІЧНИХ ДОСЛІДЖЕНЬ (КОСМІЧНОЇ ІНЖЕНЕРІЇ): ОГЛЯД

Космічні технології набувають все більшого значення в сучасному суспільстві. Маючи багато застосувань у повсякденному житті, вони зумовлюють подальший прогрес та добробут людства. Звідси витікає необхідність забезпечення відповідного рівня навчання, досліджень і розробок у цій галузі освоєння космосу. У статті розглядається використання малих супутників для отримання базових знань у галузі космічних технологій. Подальший розвиток цих знань веде до створення космічних місій, які в свою чергу забезпечують прогрес рівня технологічної готовності (TRL), визначеного міжнародною шкалою вимірювань. Цей рівень характеризує загальну технологічну зрілість суспільства. У огляді робиться висновок, що використання недорогих або навчальних супутників може сприяти вдосконаленню знань молодих інженерів і конструкторів та демонстрації важливості космічних досліджень. Ми вважаємо, що для досягнення цієї мети можна використати вбудовані компоненти з функціями, аналогічними смартфонам. В статті обговорюються два типи таких компонентів для демонстрації їх ефективності в космічних інженерних розробках.

Ключові слова: CubeSat, аналіз даних, дидактика, космічна інженерія, рівень технологічної готовності, супутник.