Orbital Robotics: A new Frontier in Education

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***Abstract*—As part of its Education Programme, the European Space Agency (ESA) is taking several steps towards the development of Educational activities and platforms that use Space Robotics as a mean to support and reinforce STEM (Science, Technology, Engineering and Mathematics) school education in Europe. In this paper the on-going development of an Orbital Robotics educational prototype platform is presented, consisting of a hardware-developed physical platform and an accompanying set of curriculum-based lessons (IB Physics curriculum) that target upper secondary students (16-18 y/o target group). The hardware, a friction-less air-hockey table (physical platform) engineered for this purpose, will be used by students to interactively acquire the necessary experience of the dynamics of space systems, as the environmental conditions and physical constraints that are characteristic of on-orbit systems are emulated. The students will be able to manipulate space robot (satellite) mockups performing basic tasks such as docking, landing and grasping space debris. Additionally, a smartphone application has been implemented to allow the interaction with the platform, via a dedicated User Interface (UI). The lessons are inquiry-based and are structured so that the students are actively engaged in the learning process according to a learner centered approach. The project is jointly undertaken by the ESA Education Office and the ESA Automation and Robotics Section, with the support of the Control Systems Laboratory of the National Technical University of Athens. The development is taking place at the facilities of the Automation and Robotics Laboratory (ARL) of ESTEC, ESA's European Space Research and Technology Centre in the Netherlands.**

I. Introduction

The use of robotic applications in education is increasing rapidly, after the realization of the various benefits they introduce in the learning process. These include both the motivational and pedagogical value provided by a direct hands-on and interactive experience that put the learner at the centre of an educational journey of discovery; during this journey the learners critical and innovative thinking is stimulated, leading to a deeper acquisition and understanding of physics and technological principles [1].

Currently, the approach to STEM (Science, Technology, Engineering and Mathematics) Education in Europe is still extensively based on passive learning (theoretical knowledge transmitted through lecturing); to a large extent, it still lacks the practical, inquiry-based and learner-centered dimension needed by the students to become an active part of the learning process. This leads to an efficient integration of theoretical knowledge into an experimental process of direct acquisition of this knowledge. The current approach also often lacks the context for students to work in groups and develop soft skills such as effective communication and teamwork, qualities needed to work in interdisciplinary research or industrial environment nowadays. Not completely adequate STEM teaching in school is considered by several recent European studies one of the key factors responsible for the relative decrease of the young peoples interest in STEM-related studies and professions in western countries today.

A recent study [2] shows that active learning leads to better student performance and raise of the average grades. By contrast, in traditional lecturing, failure rates are higher. Results from an Interactive Robotics Education Program implemented in the Curriculum of a Mechatronics course in Pontifical Catholic University of Peru (PUCP) [3], show a raise of motivation from the students of different age groups for completing their project, as well as the development of their teamwork, project management, documentation and communication skills. Furthermore, collaboration, cognitive skills, self-confidence, perception, and spatial understanding are some of the skills that the students achieve to learn through the implementation of robotics tools in education [4].

Being aware of the various benefits that educational robotics can bring into learning, combined with the recognized inspirational and interdisciplinary value that the space context can bring into STEM education, the European Space Agency (ESA) has kicked off the development of several space-robotics educational projects, including prototype activities such as the one presented in this paper, and a space-robotics training school for primary and secondary education (the *ESA e-robotics lab - space robotics in the classroom*, that will officially start its activities in Autumn 2015). Space has always been one of the most wondrous subjects for children: by integrating the space theme with educational robotics, ESA's objective is to raise the students motivation and performance in STEM subjects, as well as to raise the awareness about space and space applications, together with their benefits for modern society, among the young population in Europe. An example of a recent successful ESA space robotics activity, strongly connected with the concept of this project, was the docking of ESA's Automated Transfer Vehicle (ATV-5) to the International Space Station (ISS), as seen in Figure 1.

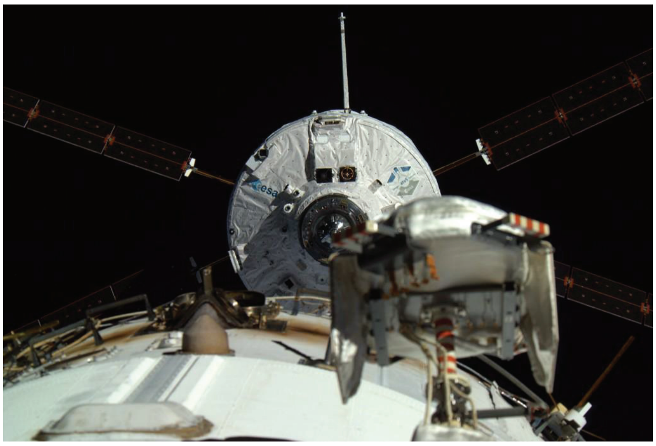

Fig. 1. ATV-5 docking with the ISS, 12 Aug 2014

Under this scope, ESA's Educational Project Orbital Robotics: A new frontier in Education, in collaboration with the Control Systems Laboratory (CSL) of the National Technical University of Athens (NTUA), Greece, aims to provide an active-learning tool for physics and technology under the concept of orbital mechanics and space dynamics. The project, aimed at the upper secondary school target group (16-18 years old), includes the development of an educational space environment emulator using air levitation (planar space emulator platform) and a set of space robot mockups (the 'satellites'), which can float on its surface. A set of lessons, which for the prototyping phase are based on the International Baccalaureates (IB) Physics guide, is also being developed.

In Section three the approach to the educational goals and its application to the lessons structure are presented. Section four illustrates the design and development of the physical platform based on the requirements set by the educational goals. Section five illustrates the lesson plan and how the learning objectives are achieved. Section six presents the authors conclusions, and mentions the next steps in the development of the project.

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II. Pedagogical Approach

'For the things we have to learn before we can do them, we learn by doing them.'

Aristotle, 350 BC

The methodology consists in deploying a set of inquiry-based lessons that gradually builds the knowledge and the skills needed to complete the final lesson, which makes use of the principles introduced in the previous ones. The learning process and the lessons, whose goal is teaching physics through the students experience of a 2-dimensional representation of space dynamics, implement cognitive neuroscience research and developmental psychology (MBE [5] - Mind, Brain and Education Science). Through an interactive use of the physical platform, the learning process also introduces the hands-on experience.

Methodologies derived from the belief that the human brain is constantly searching for meaning and seeking patterns and connections are being implemented, while the main focus remains on reaching a deep understanding of the basic school physics concepts that lie in the fundamentals of space and orbital robotics.

The lesson plan is based on the 4MAT Theory [6], a use of the extensive research on brain-based teaching methods. The implementation of the 4MAT Cycle into teaching engages the students through all the steps of the learning experience. The movement around the 4MAT cycle represents the learning process itself; it is a movement from 1.experiencing, to 2. reflecting, to 3.conceptualising, to tinkering and problem solving, to 4.integrating new knowledge with the self.

The intention is to provide the students with the chance to perceive information both directly and abstractly and process it reflectively and actively. The different combinations of information acquisition and the path the mind follows to process it, define the four types of *learning types*: Type one learners are those whose mind is searching for the why? in what they see, perceiving information directly and process it reflectively; the type two learners asks for the what? in the stimuli they are given, perceive information abstractly and process it reflectively; type three or how does it what seekers, perceive information abstractly and process it actively; while the fourth, more intuitive type, is interested on the what if , and perceives information directly and processes it actively.

The lessons are structured to stimulate all the channels that these different type of learners use to perceive and process information; they are built upon the Umbrella Concept and follow a Concept-Based Learning. In other words, the learning objectives for every lesson refer to a greater concept that the students can relate to: new subjects are gradually introduced be referring to the students previous knowledge, and experiences and feelings to it, so that the learning experience becomes personal.

All the *personality types* (according to the Myers Bricks type indicator [7] are equally respected. Some people, the sensing types, perceive what is happening around them making logical connections in their mind (the door is wooden), opposite to the intuitive types who use their intuition (the door reminds me of the wood we have at home). Some others take decisions based on their logic and some on their emotions (thinkers and feelers), while for some, the decision making process is more difficult than for others (perceivers and judgers). Personality types also account for the different channels one uses to express oneself: for the extraverts, the source of energy is external, while for introverts it is internal.

The lessons follow a pattern that provides the students the opportunity to acquire the knowledge in the way that is the easiest and most preferable for them, and are meant to favour the development of their communication skills.

In conclusion, the students are led through interactive activities into the basics of physics principles and of their specific phenomenology in the space environment. Every lesson is structured around a themed assignment, or mission, that make use of orbital robotics and that they have to accomplish as a team. At the end of the assignment, the students have to present the process they have run through, the results of their mission, and the outcome of their teamwork in which every member had specific tasks. Under the guidance of their tutor, they then have to engage into an open discussion to share the trade-offs made, the challenges overcomed, the lessons learnt both individually and as a team, etc. Through this process, the students gain a first-hand understanding and direct experience of the curricular subjects introduced, an experience of project management and teamwork, and the development of their communication skills, self-confidence and awareness in a learning environment that respects the wide variety of personality and learning types.

III. The physical Platform

A. Design requirements

In order to achieve the educational objectives set for this project, the physical platform had to meet a set of requirements:

- emulate the behavior of space robots on orbit, resembling in a 2-dimensional environment the experience and the effects of the 3-dimensional zero-g environment on the bodies;
- allow students interactivity;
- remain small, low-cost, low-weight, low-noise and safe for use in a classroom environment;
- ensure its sustainability and reusability by different generations of students.

These requirements and constrains drew the design decisions and trade-offs made during the development of the prototype: the final layout, the selection of the materials, and the functionality of all the components, have been designed always in correlation with the educational scope of the project. As a 3D emulator is impossible to build easily, a planar space environment emulator that allows space robot mockups to hover on top (a friction-less air-hockey table), simulating a zero gravity and zero friction movement, was selected as a good alternative. This allows a very effective 2-dimensional representation of satellites movement in space.

The planar platform also had to provide working space for two space robot mockups to effectively perform operations on its surface. The mockups had to be light and have small footprint, and be capable of performing basic space tasks resembling at the same time real satellites with a good degree of fidelity. A great effort has been put into reducing to the minimum the power and mass budget requirements of both the satellite mockups and the planar platform.

B. The Planar Space Emulator

From the early stages of the development, one of the main challenges was the design and construction of a system able to simulate free-fall environment conditions, while at the same time taking into account all the project requirements as well as the physical limitations.

The chosen design incorporates the benefits of the planar simulators already developed in the USA (MIT, NASA, Stanford), Europe (U. of Padova, U. of Southampton, National Technical University of Athens) and Japan (Tokyo Institute of Technology, Tokyo University), scaled down to a low-power-budget and simplified system that does not need compressed air. Planar simulators using air bearings are perhaps the most versatile and less expensive method for emulating zero-g environment, in comparison to other methods, and allow for repeated and thorough testing of control algorithms and verification of dynamics [8]. They require minimum preparation compared to other simulation methods and are easier to upgrade and adapt to alternative scenarios.

These systems usually use a thick and heavy (e.g. granite) or fragile (e.g. glass) material as the surface where the air bearing space emulators hover, which however are not suitable for a classroom environment. Moreover, the direct use of air bearings would have introduced a considerable weight, cost and complexity to the mockups due to the required payload for air supply. Therefore it was decided that the platform should follow the example of planar simulators using air bearings, although this time the method of hovering should be reversed: the air flow will come out from the hovering table instead from the mockups. For this reason the planar educational space emulator developed and presented, follows the air hockey principle and consists of an assembly of additive manufacturing derived parts. It also has a custom layout, implementing results from both theory and testing, for optimization of the flow and maximization of the output pressure.

The model prototype that has been created was based on the high level requirements and having two main issues to overcome: lifting a space robot mockup weighing approximately 600g and being made of a low friction material. Moreover, the surface had to be flat and smooth and create a homogenous film of air on its surface to allow smooth hovering of the mockups. The stiffness requirement of the platform sets the manufacturing options for a stable and rigid assembly, using low-cost and easily accessible resources.

The planar prototype platform was designed taking under consideration the constraints set by the limitations of the 3D-printing technology, and the material used which, in this case, is Polylactic Acid (PLA). It is a modular structure consisting of four smaller modules, as shown in Figure 2, which shall be glued together to provide a working surface (top surface of the upper part) with dimensions 380x300mm. The modules has been, tested and optimised to meet the requirements. The upper part of the module is a box-shaped element with custom-made nozzles on top, which produces the air film. The intermediate part is used for the mounting of the fan (air flow source), while the lower parts used for the support of the whole construction. This way it provides the structure with sufficient support and distance from the ground, while using the least possible amount of material.

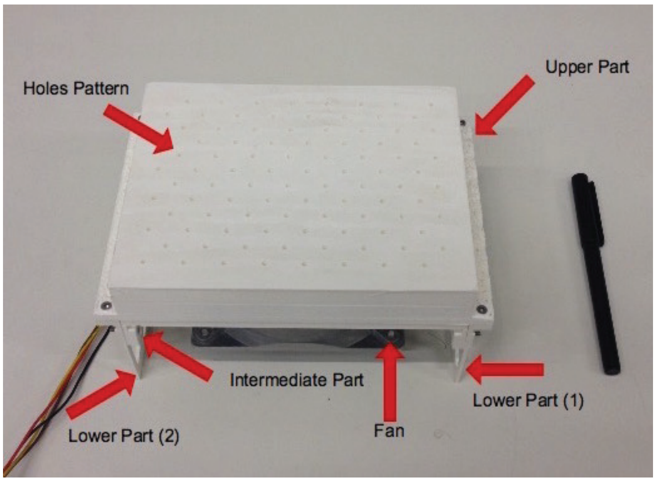

Fig. 2. The module (1 out of 4) of the planar space emulator prototype

The airflow had to be optimised to assure minimum air escape and enough thrust to lift the satellite mockups for undisturbed motion, i.e. there is a small pitch distance between the surface holes where the air flows. For that purpose, the Bernoulli concept was exploited, in order to achieve an increase in pressure [9]; that is, to provide the external airflow through a gradually diminishing-diameter nozzle before escape into the environment, in order to increase the dynamic pressure of the output airflow, and thus increase the velocity, and therefore the thrust, which is the main objective and only known value. Additionally, since the air is not provided directly through a simple cylindrical hole, but it escapes through a carefully designed route (the nozzle), special care was taken in order to decrease its internal friction.

C. The satellite mockups

The space robot mockups represent the bodies orbiting in space they can also represent mini satellites as their basic operational principles are the same. The observation of their movement and the results of the interaction with other objects on the planar space emulator environment are meant to allow the students to study the dynamics of orbiting bodies.

The goal is to make the mockups as light and small as possible. This will enable them to be lifted by the film of air created by the space planar emulator platform and at the same time decrease the required minimum dimensions of the upper surface due to additive manufacturing limitations. Note however that as the resemblance with real satellites is required, their translational and rotational motion should have been generated by thrusters. This would introduced the problem of using compressed air and the need to add a pneumatic system, that would have increased the mass and power budget, not to mention the complexity.

Instead, the use of small fans enclosed in nozzles was selected, in order to resemble real thrusters without sacrificing considerably the accuracy. The fans only function in a pulse-like mode, so as to emulate rocket propulsion (propulsion through momentum transfer), therefore reducing significantly the inertial issues that emerge additionally their weight is minimal making the previous assumption reasonable. The first system implementation incorporates four fans, as seen in Figure 3; more can be added to allow angular motion.

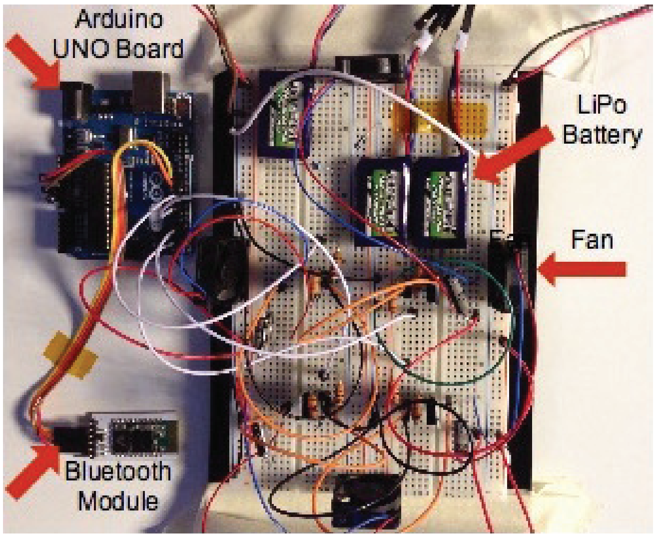

Fig. 3. The space robot mockup in development stage

The fans are connected to an Arduino® system, which is an open-source physical computing platform based on a simple microcontroller board [10], controlled remotely through Bluetooth by use of an android smartphone application, as seen in Figure 4.

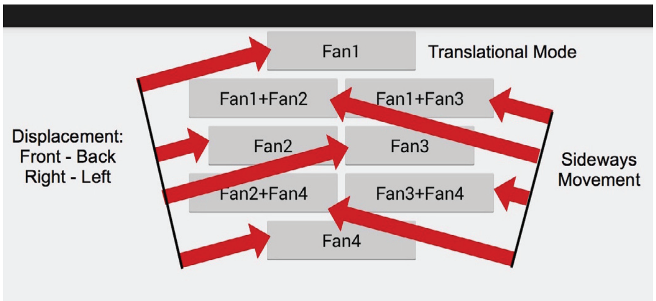

Fig. 4. The Android Application User Interface for moving the robot mockups (communication via bluetooth)

The User Interface of the smartphone application is structured with buttons, each of them representing the operation of a specific fan, which produces the corresponding impulse force for translational motion.

Finally the mockups disk-shaped base was made of a slightly flexible plastic plate (as thin and light as possible). The base is large enough to allow the mockup to move and to provide enough space for the robotic mechanisms that will be added by the students in the future. LEGO® baseplates will be mounted over the base surface, allowing the students to add LEGO® technic parts, to assembly their robotic mechanisms that they will be asked to make during the lessons.

Figure 5 shows the one Degree Of Freedom (DOF) LEGO® robotic arm assembly used for the docking exercises, and the corporation with a pico-servo motor (weight 4.5g) able to move the mechanism on the z-axis (yaw).

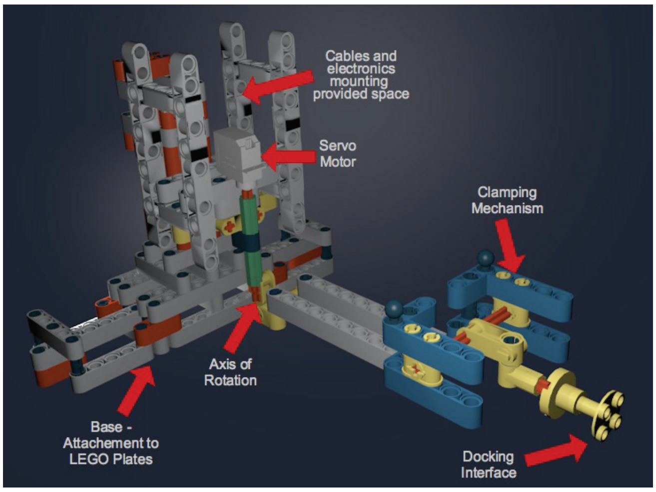

Fig. 5. LEGO® robotic arm with docking mechanism and servo motor

IV. Lessons Plan : Achieving Learning Objectives

The challenge during the lessons is to raise students' interest and engagement in STEM subjects; this is achieved by guiding the students through the application of physics principles in the space environment - a context usually fascinating to children. For example, as the teacher demonstrates a physical phenomenon like rolling a ball on the table which stops at some point, he/she asks the students to describe what they saw and to explain what happened. In this way, the teacher can introduce Newton's Laws and friction. On the same time and in order to highlight the difference between space and Earth dynamics, the teacher shows a video of a satellite on orbit, of landing on an asteroid and of docking between two objects in space.

During such a lesson, the students are called to describe both what they saw and to notice the differences that exist between the bodies behaviour on the Earth and on orbit; this way the students start to think about what they have just experienced. Meanwhile, the teacher keeps stimulating the active learning process by asking questions such as 'where does space begin?', 'why man first wanted to go to space?' or 'when did that happen?'. This leads to the rationale behind a space mission, which aims to fulfill a specific human need. A mission statement thus is introduced together with a top-level definition of its concept, operations and benefits.

In each lesson, the students are grouped in teams and assigned a task which they need to execute, based on the previous inquiry-based educational approach. Preferably they are divided into teams which have equal number of: girls and boys, introverts and extraverts, judgers and perceivers, and thinkers and feelers. The students are asked to decide which are the phases of the assigned mission, which role each team member will play (e.g. Mission Management, Telecommunications, Operations, Science, etc), and what is each roles responsibility. The activity making use of the planar emulator will then commence, with the objective to achieve the assigned mission.

When the task is over the students are called to present their outcomes, choosing their preferred presentation method (whiteboard, flipcharts, papers, post-its etc); the teacher will call the rest of the students to engage into discussion on this presentation. At the end, they are called to talk about their experience working as a team, where the teachers will act as moderators in helping each other understanding and respect of the different personality types whilst favouring communication between the students.

The methodology developed seeks to trigger all the learning routes the students with different personality types choose to follow into perceiving, acting and decision-making. Feelers have the chance to act, so to involve action in the procedure of learning, and thinkers are given the time to reflect and process things in their mind before they can decide on the answer. The perceivers in the team will also seek for further investigation on the problem while the judgers will tend to take fast decisions. Moreover, extroverts will react more spontaneously, while the introverts will need some time to reflect before they choose to act.

Based on these principles, and making use of the physical platform, the set of lessons presented below has been selected. It has to be noted that the construction of the robot mockups will be done gradually by the students: throughout each lesson more parts will be added to meet the learning objectives. Further down we present Lesson 1, 'Introduction to Space'; this particular lesson does not make use of hardware, but provides an example of how all lessons are structured.

- **Lesson One - Introduction to Space**
  This is an introductory lesson about space, aiming to raise students interest about space and its applications. Additionally an introduction to space robotics will take place. This lesson will contain astronomical fun facts and basic knowledge about orbital robotics and space missions. Finally the students will be called to execute a space mission.
- **Lesson Two - Friction -or not**
  This lesson aims at achieving the realization of the difference between the concept of friction on Earth in comparison with its absence in space. It contains observa-

tional exercises on frictionless movement and momentum transfer.

- **Lesson Three - How Rockets Work**
  Here the concept of rocket propulsion using the Newtons 3rd law is explained. The main observation is the action-reaction principle.
- **Lesson Four - Inertial Momentum**
  Students are asked to add a robotic arm to the mockup and, by observing the movement of the whole body when trying to move the arm, the students understand the fundamentals of inertial momentum.
- **Lesson Five - Catch me if you can!**
  The students explore the observational concept by which, in a free-fall environment, when you just touch something it drifts away. The task is trying to the capture a static target object, finding a solution to avoid the drifting away and managing to capture it.
- **Lesson Six - Landing on a Comet**
  The objective of this lesson is to achieve successful approach of the target object and successfully anchoring to a planar surface placed in the simulation environment. The lesson introduces the basics of space propulsion.
- **Lesson Seven - Interacting in Space**
  This lesson presents by practical demonstration the difficulties of two-body interaction in space.
- **Lesson Eight - Space Debris Removal**
  Through this lesson the goal is to raise awareness on the space debris issue and the mechanisms used for cleaning space from space junk. The students are called to design a net mechanism to capture a moving body.
- **Lesson Nine - aMAZE me!**
  The students will have to construct a robot and drive it through a maze. The goal will be to avoid hitting the walls and get to the final destination in the shortest time possible, where the target they need to capture will be positioned.

Lesson Example (prototype)

Lesson 1: Introduction to Space

1) **Educational Objectives Fast Facts:**
   - **Age range:** 16-18 years old
   - **Type:** student workshop
   - **Complexity:** medium
   - **Lesson time required:** 45 minutes to 1.5 hours

   Students should already know:
   a) The concept of gravity
   b) The definition of weight (W = m g)
   c) The concept of vectors (size = value & direction)

   Learning outcomes
   a) Students should be able to make simple calculations using the equation derived from Newtons Law of Universal Gravitation.
   b) Students should be familiar with the concept of free-fall environment and the differences that lie with earth environment in daily applications.
   c) Students should understand how Universal Gravitation and space environment conditions affect the movement of objects in space.
   d) Students should realise why orbits have elliptical shape, based on Keplers Laws of motion.
   e) Students should be able to state benefits resulted from space exploration.

   Curriculum links
   - **Mathematics** (Vectors)
   - **Physics** (Satellites, Comets, Planets, Stars, Gravity, Friction, Newton's Law of Universal Gravitation, Keplers Laws of motion)
   - **Astronomy** (Movement of space objects)

   Outline
   In this activity students will be engaged in an active discussion which will essentially lead to the realisation of the conditions that define a space environment and its impact on the movement of orbiting objects and space applications. Students are also expected to come to an understanding of why space exploration is of vital importance to our daily life.

2) **Background** Astronomy in early 1600s, Aristotle's geocentric system, Ptolemy, Copernicus, Brahe, Kepler, Newton. First space applications developed, first satellite launched, first spacecraft, man on the moon, first mission on mars, first rover on mars, Rosetta! What it the urge that pushes humanity towards space exploration? What is there to learn and benefit from?

3) **Activity**
   - **Discussion**

   What defines the Earth Environment? Introduce the concept of gravity and friction and the importance of their results in our daily life (humans/animals and artificial constructions:cars, airplanes). Make the first reference to space environment conditions:

- Space: what? why? (different gravitational fields)
  – How do the laws of physics that apply on earth change, in the absence of friction?
  – The gravitational field around objects pulls free-floating objects towards it, and the pulling force is proportional to the mass (Newtons Law on Universal Gravitation).
- How does this affect objects orbiting in space?
  – A small object (satellite) orbits around a bigger one -its gravitational field can create a force large enough to cause the orbiting of an object around it.
  – But the orbit has a specific shape. Which one? What is the reason? (Keplers Laws of motion (1st and 2nd))
- Why do we go to space?

Students are divided into teams and called to fill in their worksheets and present their outcomes to the rest of the class. They are called to write down some arguments that prove correct the statement: *'Space activities are an essential part of modern society'*. Students shall think of society needs -derived by the evolution of technology- that led to the creation of space applications which established space activities as a necessary part of our daily lives and the world as we know today.

- **Discussion Extension**

Mission Scenario:

'You have to repair a solar cell that has been damaged on the rear edge of the ISS. What steps would you follow? Which are the difficulties you think you will have to face and how would that differ if it was taking place on earth'.

The students are involved in an active discussion, with the teacher facilitating the flow. The students are then divided into teams and are expected to write down and present their mission outline, along with the answers to the questions.

In the table below the content that by the end of the activity is expected to have been transmitted to students is presented.

Application	Reason
Telecommunications	Communication, instant access to large amount of information by everyone, eliminates physical distances..
Earth Observation	Meteorology, predict natural disasters..
Planet Exploration	Life on other planets, how life started..
Experiments in microgravity	Materials, fluids, biology, radiation testing..

- **Conclusion**

Talking about space always fascinates children. Through the active discussions and activities taking place in this course, students are led to a deep understanding of basic facts about space environment, orbits and space applications and their impact on modern society. They also learn how to work in teams while improving their communication and presentation skills.

V. Conclusion

The learning requirements and objectives set by ESA's educational project on orbital robotics were presented. The educational objectives are reached by the interactive use from students of a set of space robot mockups able to float on a planar space emulator platform. The students are led through a set of inquiry-based lessons, to a deep understanding of orbital mechanics and space dynamics concepts. This is achieved through the experience of a 2-dimensional representation of the physical phenomena happening in space in a 3-dimensional environment, that the manipulation of the mockups hovering on a space emulator is making possible. Additional fine-tuning of the design of the planar emulator platform and of the satellite mockups is intended. Furthermore, it is foreseen to produce a detailed manual on how the lessons can be replicated in a classroom environment. Throughout 2015 and 2016 the concept will be refined by ESA Education Office and tested with teachers in the context of the ESA e-robotics lab Teachers Training. It is expected that the activity may be rolled out for school use in late-2016/2017 (classroom of approximately 20 pupils).

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