A realistic simulation environment as a teaching aid in educational robotics

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***Abstract*—The experimental component is an essential method in Engineering education. Sometimes the availability of laboratories and components is compromised, and the COVID-19 pandemic worsened the situation. Resorting to an accurate simulation seems to help this process by allowing students to develop the work, program, test, and validate it. Moreover, it lowers the development time and cost of the prototyping stages of a robotics project. As a multidisciplinary area, robotics requires simulation environments with essential characteristics, such as dynamics, connection to hardware (embedded systems), and other applications. Thus, this paper presents the Simulation environment of SimTwo, emphasizing previous publications with models of sensors, actuators, and simulation scenes. The simulator can be used for free, and the source code is available to the community. Proposed scenes and examples can inspire the development of other simulation scenes to be used in electrical and mechanical Engineering projects.**

***Index Terms*—Robotics Simulation, Dynamics Simulation, SimTwo, Engineering Education, Education 4.0, STEM.**

I. Introduction

It is highly beneficial for engineering students to have practical experiences to understand and learn engineering concepts, especially in more practical and abstract subjects, where only the theoretical explanation is insufficient. When access to the hardware is not possible, simulation can be used to assist the practical experiments. In addition, simulation can allow the remote study of such subjects and the optimization of the development of projects, especially in the software/hardware prototyping stages.

Robotics is a multidisciplinary area where students learn and apply concepts of electronics, control theory, mechatronics, computer science, mathematics and physics, among other disciplines, to progress in this area of knowledge. In fact, robotics is one of the areas of knowledge that fits very well in the learning methodology of Science, Technology, Engineering and Mathematics (STEM).

In the context of learning robotics, students should test and validate the software and mechanical designs in real scenarios. A realistic simulation with rigid-body dynamics is key to performing tests without real hardware. In other words, students can perform the tests with the convenience of not needing to go to the university's laboratory to test their projects and increase the projects' development efficacy for reasons already mentioned in this section. In later development stages, the students can test on the real scenario when the project has matured, speeding up the development process, lowering the costs, and possibly preventing real-hardware damage. Even more, the COVID-19 pandemic pushed the need for simulation due to social distancing rules.

There are several different types of robotic simulators available on the market with their features, similarities, and differences. Some works already performed reviews on these simulators, analyzing their usage, performance, and features available [1]–[4]. Authors in [1] compared V-REP, Gazebo and ARGoS robot simulators feature and performance-wise. Furthermore, a comparison of humanoid robots was done in [2]. An analysis and comparison of 3D robotics simulators was performed in [3]. In addition, a systematic literature review of realistic simulators applied in educational robotics context was developed in [4]. The authors concluded that one important feature was simulators with multiple simulation purposes where SimTwo was included in the list. Moreover, SimTwo was also included among the simulators that can be easily applied in the educational context.

In this reasoning, SimTwo is an open-source robotics simulator that uses Open Dynamics Engine [5] as the physics motor, a well-known and realistic physics engine for rigid-body simulations. Moreover, all SimTwo tools are integrated in the same software and there are several scientific publications regarding robotic applications, and sensors and actuators mathematical modelling (noise, non-idealities, among others), providing superior motor and sensor models relative to other simulators. For these reasons, SimTwo becomes another pow-

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erful educational tool for engineering.

Therefore, this paper aims to present a simulator environment with rigid-body dynamics and its features and compile the scientifically developed research works with it over the years of its existence. Some of them is the possibility of developing a robotics project in a hardware-in-the-loop approach with real microcontrollers. The simulator also supports several communication types such as serial, ZMQ, and UDP, allowing the previously mentioned feature and the support of any programming language by ethernet protocol. In this way, an overview and overall explanation of the simulator, along with several previous scientific publications made with this simulator, are presented. Finally, the default robotic scenes that the developers provide are shown to demonstrate the extent of the development possibilities of the SimTwo simulator since users can develop their robots and simulation scenes, fostering new users of this application software.

Simulation in a virtual environment has become necessary in the context of enabling the ability to perform tests and search for robotic solutions, bringing an increasing development of software for this area, both for research and educational purposes. The purpose of making simulation with robots as close to reality as possible is to conduct research and find solutions without damaging the actual robot while it is being developed.

In this context, SimTwo [6] was developed to be an environment that allows tests and projects in different scenarios and robots. According to the developers, in [7], the purpose of creating a new simulation tool is to insert new capabilities and characteristics of robots that were not found in commercial software. In this new environment, it is possible to prototype your own robot, in order to seek superior performance and be ever closer to the required reality.

II. SimTwo environment

SimTwo was developed to be a simulator capable of supporting different types of terrestrial robots that contain rotating joints, or wheels [6]. The robot is divided into rigid-body parts and electric motors, thus bringing to the simulator their dynamic realism. Fig. 1 shows SimTwo in operation, consisting of several communication and visualization windows.

The windows, letter-labelled, shown in Figure 1 are explained in alphabetical order. Thus, the “main view window” displays the simulated world with graphical aspects.

The “sheets window” creates customized action buttons or read/write cells to interact with the “code editor”.

The “config” window is where it is possible to change the general settings of the simulator, such as robots’ states control, graphics, debugs, physics engine, and external communication.

The “cameras window” allows visualizing the cameras that were configured in the “config window”. It is also possible to save images in JPEG format to be exported later.

The “chart” window allows the plotting of graphs with the available states of each robot, such as position, and speed, among others.

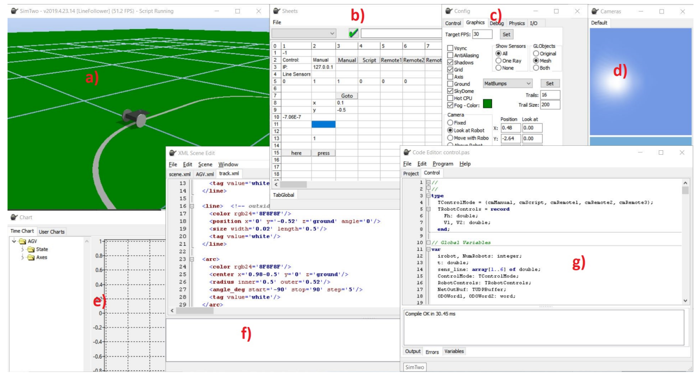

Fig. 1. SimTwo simulation environment. a) main view window; b) sheets window; c) config window; d) camera view; e) chart window; f) scene editor; g) code editor.

The simulation scene is created using XML files in the “scene editor” window, where it is possible to define the conditions of the simulation environment, the parts of the robot, and the sensors, among others.

Finally, the “code editor” is where the robot control program will run. The window is an integrated development environment (IDE) for high-level programming based on the Pascal language.

A. Communication

It is of high importance that SimTwo can interact and communicate with other applications or processes. The simulator provides USB (Serial COM port), Modbus, ZMQ, and UDP communication protocols, as described in this section.

1) Serial Port: hardware-in-the-loop: This methodology provides a feature to develop the code responsible for controlling all actions of the real robot but controlling the virtual robot instead. It uses the Serial (USB) communication established with SimTwo. In other words, the simulator will provide the sensor data to the embedded controller in the hardware, which will process the data and send back the control signals to the virtual robot. It is a way to develop and test a robot with a microcontroller’s memory and processing constraints and use the same code in the real hardware since the microcontroller is the same used for both situations. More information can be obtained in [8] and [9].

2) ZMQ: ZeroMQ or ∅MQ is a high-performance asynchronous messaging library aimed at distributed and concurrent applications. In this reasoning, it supports several messaging patterns such as publisher and subscriber, request and reply, client and server, and other examples, among several types of transports (TCP, in-process, inter-process, multicast, WebSocket, and others) [10]. Thus, this library is used in several different environments, such as financial services, game development, embedded systems, academic research, and aerospace [11].

SimTwo simulator provides support to WebSocket communication through the ZMQ library for the transmission of 32 BGRA Bitmaps with a resolution of 640×480 pixels. The transmission frequency can be configured in the "XML" file where the camera is defined in the simulated world.

3) Ethernet UDP: The simulator provides communication using UDP protocol. SimTwo can be configured in the I/O tab to listen to a defined port. The script provides functions to read and write UDP datagrams, such as $ReadUDPData()$ and $WriteUDPData()$. This method of communication is a powerful strategy to use other languages or programs to control the scene, for example, C++, Matlab, Python, or even ROS (Robot Operating System) [12]. The script should be used to decode the received UDP packet.

B. Sensor and actuator Modeling

SimTwo, as described in Section II, is a simulation environment that allows the user to create the robot and scenario according to its needs. With this, it becomes a very extensive software in the area of simulations for developing, testing, and validating new prototypes. This chapter presents a list of works that were developed using SimTwo's environment.

1) Laser Scanner: Light Detection and Ranging (Lidar) sensors have been used in industry and mobile robot applications that measure distances relative to the sensor in different scanning patterns. They are applied in navigation tasks of robots to perform localization and obstacle avoidance, even for safety reasons. Measurements from LiDAR depend on several aspects that should be modelled, for example, target colour dependences, noise, limits, time constraints, and target angle functions. Model for different sensors are validated and detailed in [13] and [14].

2) Spray Painting: In [15], the simulation of spray painting is done in SimTwo, proposing techniques for improving the trajectory algorithm, highlighting the simulation's advantages of not wasting paint, parts, and energy. The project was validated through a real-world experiment.

3) Motor EMG30: The EMG30 is a popular motor model in mobile robotics and is used by most teams in the Robot@Factory competition. Because of its importance, mechanical and electrical modelling of the actuator was developed in [16] in the SimTwo environment.

4) Robotic Joint: As cited in [17], in robotic performance, one of the factors that are simple to deal with is the position and velocity control of the joints, but some nonlinearities make this process difficult. Using the SimTwo simulation environment, a scenario was created to test the different control methods proposed by the authors, consisting of a motor fixed to a tower and a load attached to the motor shaft. The Internal Model Control method presented a new speed controller tuning approach and a second-order Bessel prototype as a tuning approach for a position controller. In addition, different control methods, such as Parallel and Cascade PIDs combined with feedforward and dead zone compensation, were tested. An actual implementation was done to validate the result, which stressed that the best result obtained was the Cascade PID controller with Dead Zone Compensation (DZC) and Inverse Dynamics Feedforward.

5) Humanoid Robots: Similarly, humanoid robots can be simulated in SimTwo's environment, ensuring a realistic simulation, taking into account the real limitations and dynamics of the robot. In the work developed in [18], the simulator was used to propose methods to minimize power consumption. Moreover, the work developed by the authors in [19] was to create a simulation environment for humanoid robots, taking into account the parameters closest to a real robot, like dimension, mass, inertia, and joint speed.

6) LEGO Mindstorms NXT: The LEGO Mindstorms NXT line is a line of robots aimed at technology education, allowing different robots to be created. It was proposed in [20] the simulation development of these robots in SimTwo to improve the student experience with these robots.

III. Provided Scenes

This section is dedicated to mentioning the different scenes that SimTwo provides to the students, followed by a brief explanation. A limited number of scenes are presented due to space limitations. Other scenes, such as Micromouse [9] [21] [22], hybrid (legs and wheels) robots [23], plotter XY and others are available either online or contacting the authors. Source code is also available to the community.

A. Autonomous driving

Inspired by the autonomous driving competition, the scene proposed by Fig. 2 was developed to test mobile robots to follow a road, avoid obstacles, and parking to stress the manoeuvres.

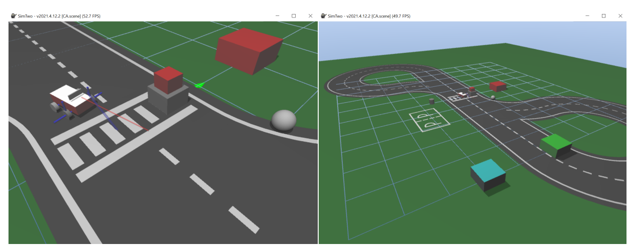

Fig. 2. Autonomous driving competition.

B. Unmanned Aerial Vehicle

SimTwo makes it possible to preliminarily evaluate the performance of different methods and techniques in unmanned aerial systems, adding other types of sensors and cameras to meet the simulation criteria. In this way, techniques related to sensory fusion, artificial vision, navigation, obstacle avoidance, precision landing and others can be analyzed in SimTwo simulations (as presented in Fig. 3) to be implemented in a real environment [24].

https://github.com/P33a/SimTwo

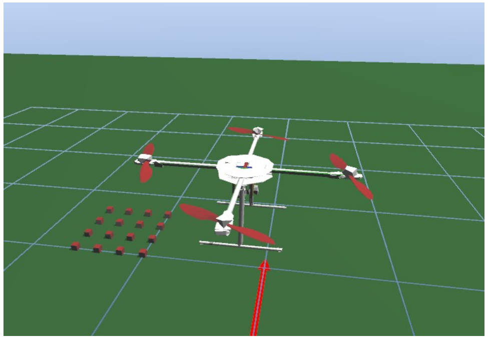

Fig. 3. Unmanned Aerial Vehicle.

C. Manipulator

The simulator also allows the creation of manipulator robots, as in the example in Fig. 4. This type of simulated robot, commonly used in industry and education, comes very close to reality through the ability to recreate its axes, joints, sensors, and other characteristics in the simulator. Through SimTwo, it is possible to create scenes and test situations that allow the validation of projects using a manipulator robot.

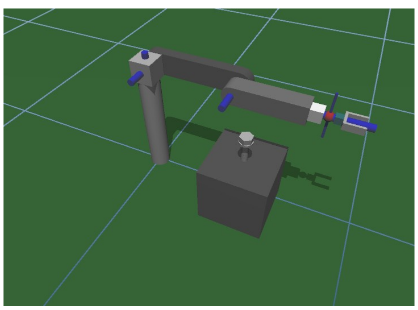

Fig. 4. Five DoF manipulator with a screwdriver tool end-effector.

D. Middle Size League

A well-known robotics competition all over the world is the RoboCup. A wheeled robot designed for that competition is presented in Fig. 5.

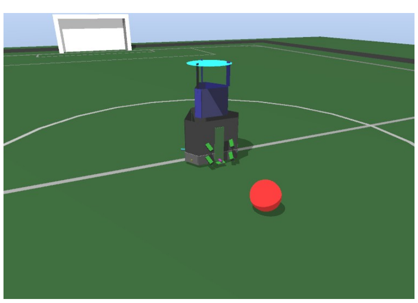

Fig. 5. Middle Size League - robotics soccer competition.

E. DOBOT Magician

SimTwo can support a dynamics-based simulation environment that can be used to teach, test, and validate solutions from robot manufacturers [25]. With STL files (provided by the manufacturers), it is possible to create any scene. For example, the DOBOT Magician robot (an educational model developed by DOBOT [26]) is digitalized using SimTwo. Fig. 6 shows the real and virtual robots, which is possible to see the similarity between each case.

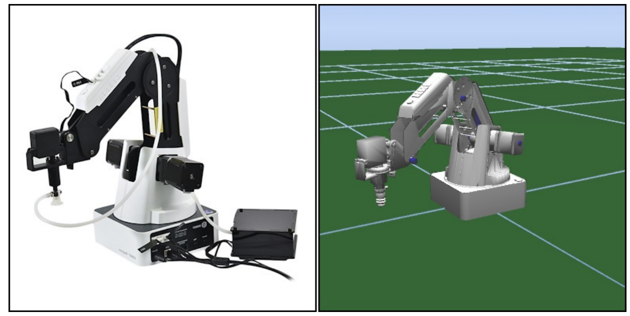

Fig. 6. DOBOT Magician - real (left) and simulated (right) [25], [26].

F. Mecanum wheels - Omnidirectional

The simulator also supports omnidirectional dynamics for mobile robots, and one of the wheels available to set up in the robots' design is the mecanum wheel. The mecanum wheel is a regular wheel with rollers attached to the middle of it in a $45°$ angle. They must be assembled so that the rollers form an "X" shape if looking at the robot from a top perspective. In that way, they will allow for movement in any direction. Fig. 7 displays an Autonomous Mobile Robot (AMR) with mecanum wheels assembled in SimTwo.

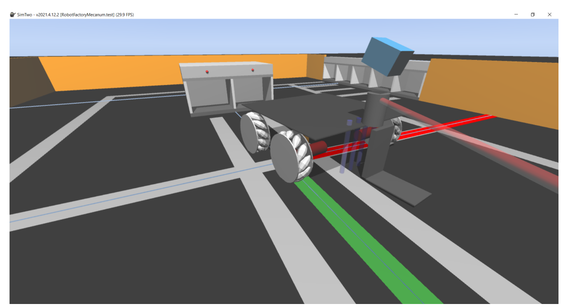

Fig. 7. Autonomous mobile robot with four mecanum wheels, characterizing a four-wheeled omnidirectional drive architecture.

G. Conveyor belt

Industrial automation requires the transportation of raw and processed materials between different workstations. One of the methods that can be used is conveyor belts. SimTwo also owns this transport system, as presented in Fig. 8 where a cylinder is being transported to reach the laser sensor.

H. Robot at Factory Lite

The Robot At Factory Lite competition challenges students and researchers to develop a solution for a logistics warehouse. In other words, the competition mimics the industry problem of a warehouse with several packages that must be organized

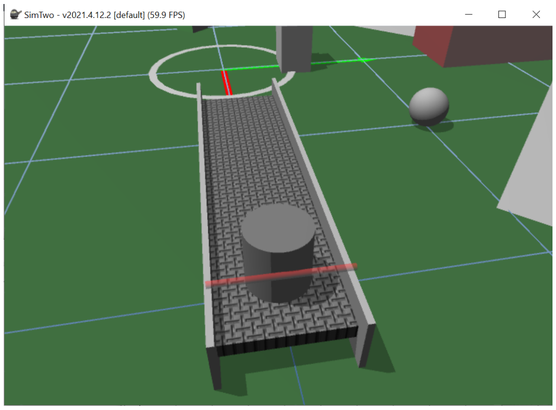

Fig. 8. Conveyor belt equipped with laser sensor with a moving material.

efficiently using automatic guided vehicles (AGVs). Therefore, the competitors must design, assemble, and program one or more AGV(s) to autonomously navigate, identify the boxes and transport them where they need to be delivered. Fig. 9 displays a snapshot of the competition floor with machines (the garages to the left and right of the robot) and the incoming warehouse, the entrance, represented by the garages further away from the robot. Finally, the AGV can navigate the competition floor following the black stripes shown in the picture [27].

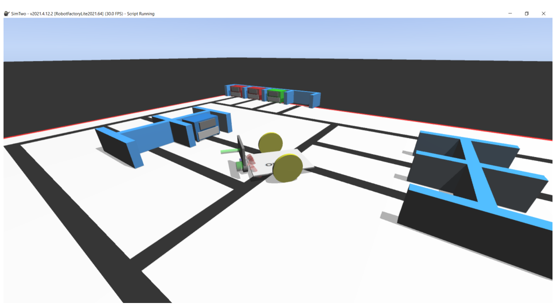

Fig. 9. Official RobotAtFactory Lite competition scene with a differential-drive AGV model as an example.

Some works were already published about this competition. In [8], the authors developed a hardware-in-the-loop approach for the simulation scene where the limitations provided by a microcontroller were inserted in the simulation loop, providing a more realistic simulation. Therefore, making the transition to the real scenario easier. In [28], the authors displayed their approach for the 2019 competition that they won, held in the Portuguese Robotics Open, Gondomar, Portugal.

I. Robot at Factory 4.0

In 2021, the Portuguese Robotics Society launched a new factory competition called Robot At Factory 4.0, an update and upgrade of the RobotAtFactory (discontinued) and a more complex version of the RobotAtFactory Lite competitions. This new version focus on the Industry 4.0 concept that has been happening for the last decade, employing AMRs and not AGVs in the industry area. In this way, the factory floor was updated to have fiducial markers instead of black stripes to aid the robot in the localization, following the I4.0 trend. It is important to note that the competitors are not bound to the markers for localization. They can use any localization system as long as it fits the rules. The organization offers, too, an official simulation scene in the Simtwo Simulator to aid the competitors in developing their solutions without the necessity of a real robot and an official floor at all times, easing the developing time, difficulty, and cost. Fig. 10 displays the simulation scene [29].

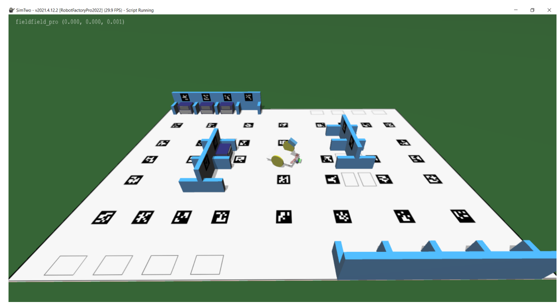

Fig. 10. Official RobotAtFactory 4.0 competition scene with a differential-drive AMR model as an example.

There is already one published work regarding this new competition [30]. The authors developed a ROS framework for the simulator where the framework and the simulation scene communicate essential data for the robot's control, such as the sensors readings and the robot's states, among other data.

IV. Conclusion and Future Work

This paper addressed the SimTwo simulation environment used for Engineering Education, mainly in robotics areas, such as mobile and manipulators. Several scenes were presented as examples as inspiration to users to design new ones according to their needs. The presented collection includes models for commercial sensors and actuators that students can use. Previous publications of authors are summarized and can help with more details. This is a free powerful tool to be used in Engineering Education courses. In future work, more scenes, sensors and actuator models will be introduced to help students in further developments. A Modbus protocol will be implemented as an interface to connect programmable logic controllers.

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