Feature and performance comparison of the V-REP, Gazebo and ARGoS robot simulators

Lenka Pitonakova[1,2], Manuel Giuliani[1], Anthony Pipe[1], and Alan Winfield[1]

[1] Bristol Robotics Laboratory, University of the West of England, Bristol, UK
[2] contact@lenkaspace.net

Abstract. In this paper, the characteristics and performance of three open-source simulators for robotics, V-REP, Gazebo and ARGoS, are thoroughly analysed and compared. While they all allow for programming in C++, they also represent clear alternatives when it comes to the trade-off between complexity and performance. Attention is given to their built-in features, robot libraries, programming methods and the usability of their user interfaces. Benchmark test results are reported in order to identify how well the simulators can cope with environments of varying complexity. The richness of features of V-REP and the strong performance of Gazebo and ARGoS in complex scenes are highlighted. Various usability issues of Gazebo are also noted.

1 Introduction

Simulation is a useful scientific tool that can complements more traditional experimental approaches [1]. Choosing a suitable simulator is important, as different simulation environments offer different performance, model detail and built-in features, all of which may affect the success and the merit of a simulation-based study. In this paper, features and performance of three open-source simulators for robotics, V-REP [2], Gazebo [3] and ARGoS [4], are thoroughly analysed and suggestions about what types of projects they are suitable for are provided. All of the three simulators allow for programming in C++, allowing us to make reasonable comparisons between their features and performance. At the same time, the simulators represent clear alternatives when it comes to the trade-off between simulation complexity and speed.

Other simulators, such as Matlab [5, 6], Webots [5, 6], Player/Stage [5, 7–9], Gazebo [5, 7–9], USARSim [5, 8, 9], SARGE [8] and TeamBots [7], have previously been described and compared. While some comparisons were rather informal [6, 8], others involved ranking simulators based on specific evaluation criteria. For example, in [9], programming language support, documentation, user interface and debugging techniques of simulators were evaluated. In [5], the evaluation criteria included simulator physical fidelity, functional fidelity, ease of development and cost.

To the best of our knowledge, no formal comparison between V-REP, ARGoS and Gazebo has been conducted before. Inspired by [5, 7, 9], it is therefore our

aim to provide a ranked evaluation of the simulator characteristics in Section 2. Moreover, similarly as in [9], the simulator performance is evaluated on a set of benchmark experiments in Section 3.

2 Simulator Characteristics

All tests were performed in the 64-bit Ubuntu Linux 16.04 environment running on a computer with 4x Intel Core i7 2.2 Gz processor, 8GB RAM and Intel HD Graphics 6000 graphics card. The built-in capabilities, model library, programming methods and user interface of the simulators are compared in Table 1.

Table 1: Simulator characteristics ranked as rich (green), neutral (white) and poor (red). Ranking was performed by considering characteristics in the same row (i.e., of the same type) relatively to each other.

V-REP	**Gazebo**	**ARGoS**
Available for MacOS, Linux and Windows. Binary packages are available for all platforms.	Available for MacOS, Linux and Windows. A binary package is only available for Linux Debian. Installed via the command line using third-party package managers on other systems.	Available for MacOS and Linux. Binary packages are available for Linux. On MacOS, ARGoS is installed via the command line using a third-party package manager.
Built-in capabilities		
Default **physics engines** include: Bullet 2.78, Bullet 2.83, ODE, Vortex and Newton.	Only the ODE **physics engine** is available by default. It is, however, possible to build Gazebo from source with a different physics engine.	A 2D and a 3D custom-built **physics engines** with very limited capabilities are available by default.
Includes a code and a scene **editor**.	Includes a code and a scene **editor**.	Includes a Lua script editor but no scene **editor**.
Meshes can be **manipulated** (e.g., cut) by robots in real time.	No **mesh manipulation** is available.	No **mesh manipulation** is available.
Scene objects can be fully **interacted** with (e.g., moved or added) by the user during simulation. The world returns to its original state when the simulation is reset.	**Scene objects** can be fully **interacted** with (e.g., moved or added) by the user during simulation. The world does not return to its original state when the simulation is reset.	**Scene objects** can be **moved** by the user during simulation.

Outputs include video, custom data plots and text files.	**Outputs** include simulation log files, video frames as pictures and text files.	**Outputs** include video frames as pictures and text files.
Includes particle systems.	No particle systems are available.	No particle systems are available.
Robot and other models		
Provides a large variety of **robots**, including bipedal, hexapod, wheeled, flying and snake-like robots. Also provides a large number of robot actuators and sensors.	A less diverse library of default **robots**, that mostly includes wheeled and flying robots. Third-party robot models are available, but their documentation is often poor.	A fairly small library of **robots**, only including the e-puck [11], eyebot [13], Kilobot [17], marXbot [12] and Spiri [14] robots.
The default models are very detailed and therefore appropriate for high-precision simulations. It is possible to simplify the models directly in V-REP.	**The default models** are fairly simple and are therefore more appropriate for computationally complex simulations.	**The default models** are fairly simple and are therefore more appropriate for computationally complex simulations.
Meshes are **imported** as collections of sub-components. It is therefore possible manipulate individual parts of an imported model and to change their textures, materials and other properties.	**Meshes** are **imported** as single objects. Models that contain multiple sub-components have to be assembled in Gazebo from multiple DAE files, each corresponding to one sub-component.	**Mesh importing** is not available. Object representations are programmed using OpenGL.
It is possible to **simplify, split and combine meshes**. This makes it possible to optimise the triangle count of imported models and to manipulate meshes (e.g., to cut them) with robot actuators.	Imported **meshes cannot be changed**. A model therefore has to be optimised in third-party 3D modeling software. This may be difficult during iterative development.	N/A
Programming methods		
A scene is saved in a special V-REP format. All scene editing therefore has to be done using the V-REP interface.	**A scene is saved** as an XML file. This makes it possible to e.g. create a bash script that changes the scene and then runs a simulation.	**A scene is saved** as an XML file. This makes it possible to e.g. create a bash script that changes the scene and then runs a simulation.

There are various options for **programming** functionality, including scripts attached to robots, plug-ins, ROS nodes [10] or separate programs that connect to V-REP via the RemoteAPI.	Functionality can be **programmed** either as compiled C++ plug-ins or as ROS [10] programs. Lack of scripting makes it difficult to run quick tests with ad-hoc solutions.	Robots can be **programmed** either through Lua scripts or in C++.
Scripts can be included in robot models and are often used to **describe the models** and their capabilities.	It is difficult to recognise how a third-party robot **model works** or what plug-ins it uses. The plug-in list is only available in the Model Editor.	Some **documentation** of the robots is provided in ARGoS, but most of how a robot works needs to be deducted from code examples.
"CustomUI" API, based on QT[15], is used to create **custom interfaces**. Custom UI controllers can be attached to individual robots. For example, it is possible to display a robot's camera output when the robot is clicked on.	**Custom interfaces** can be created as plug-ins by using the default QT API [15]. However, the interfaces can only be attached to the whole scene and not to individual robots.	**Custom interfaces** can be created in C++ by sub-classing an ARGoS API class. The interfaces can be attached to the whole scene or to individual robots.
All scripts and **plug-ins provided with the default robot models** and example scenes worked.	Many **plug-ins provided with the default robot models** did not work. Some on-line examples were difficult to run due to a large number of dependencies and differences in ROS versions.	A few **examples are provided** on the ARGoS website, all of which worked.
Good API **documentation**, a large library of tutorials and code examples and a large user community are available. Regular **updates** have been provided since 2013.	A fairly comprehensive **documentation**, step-by-step tutorials and a large user community are available. Gazebo is likely to be **supported** in the future, since a development road map is available on the website.	Good **documentation**, but a small user community are available. Development has not been regular.
User interface (UI)		

No freezing issues with the interface were experienced.	**The interface froze** a number of times and the program, and sometimes the computer, had to be restarted. This occurred, e.g., when editing robot models, starting or stopping the simulation, and in other instances.	**No freezing issues** with the interface were experienced.
All **functionality is fairly intuitive** and follows general conventions known from similar applications.	**The UI usability** is relatively low. For example, the top application tool bar sometimes disappears, it is not possible to copy and paste multiple objects, or to save a scene into the same file after making changes to it.	The UI is very limited, but all **functionality is fairly intuitive** and follows general conventions known from similar applications.
The model library is distributed with V-REP and it is thus always available regardless of Internet connectivity.	**The model library** is not distributed with Gazebo, and it is instead available on-line. On multiple occasions, the library could not be accessed because Gazebo could not connect to its server, even though the computer was connected to the Internet.	**The robot models** are distributed with ARGoS and it is thus always available regardless of Internet connectivity.
The model library is organised into folders based on model category. User can create their own folders for their own models.	**The model library** is a long list of models and particular model types (e.g., robots) can be difficult to find.	**Different robot types** are natively a part of ARGoS and can be found by querying command-line documentation.

V-REP offers the largest repertoire of features including, most notably, a scene editor, 3D model importing, mesh manipulation, video recording and an API for remotely connecting to a simulation. Also, its model library is relatively large and well-documented. Gazebo also offers a scene editor and 3D model importing, however, no mesh editing is available and the imported models need to be optimised in third-party software. Gazebo relies on ROS [10] when it comes to remote connectivity. Notably, Gazebo crashed a number of times on our computer system and its interface was generally slow during testing (see details in Table 1). Furthermore, and again only tested on our computer system, some of its example code could not be compiled or did not run properly. Finally, ARGoS offers the smallest amount of features compared to the other two simulators. It has no scene editor and 3D models cannot be imported into it. Also, by comparison, its robot library and documentation are limited.

One advantage of Gazebo and ARGoS over V-REP is the ability to define a scene in a XML file. This is convenient, for example, when multiple experiments with varying parameter values need to be generated and run automatically. On the other hand, a V-REP experiment can only be specified in a V-REP scene file via the V-REP graphical interface. It is therefore difficult to vary experimental parameters, especially when running V-REP from the command line. While V-REP offers up to nine optional command-line arguments that can be supplied to a simulation, a more involved parameter specification would have to be handled, for example, by a plug-in that could parse parameter text files. Such a plug-in is currently not distributed with V-REP.

3 Simulator Performance

3.1 Methods

There were two types of benchmark test performed with each simulator:

- **The GUI benchmark** involved running a simulation of robots that moved in a straight line and avoided obstacles in real-time. The simulators were run along with their user interfaces. Each simulation took one minute.
- **The headless benchmark** involved running the same simulation as in the GUI benchmark, that lasted five minutes. The simulators were run from the command line without their user interfaces.

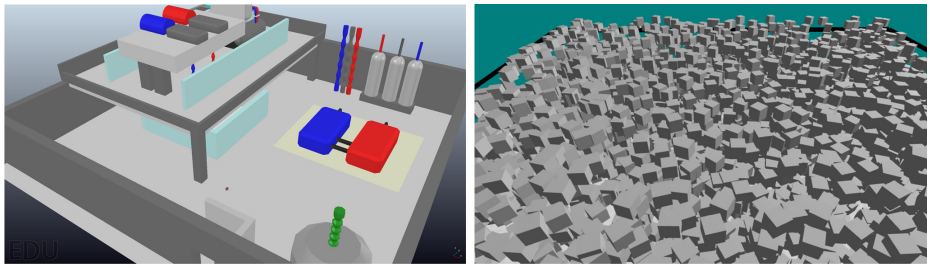
There were two types of simulation environment:

- **Small scene**, where robots were put on a large 2D plane
- **Large scene**, where an industrial building model with approximately 41,6000 vertices was imported into the simulator (Figure 1a). Since it was not possible to import the model into ARGoS, 5,200 boxes, corresponding to 41,6000 vertices, were randomly placed in the environment (Figure 1b).

Robot models were selected from a library of models available in each simulator, so that a sensible similarity, in terms of robot geometry and controller capabilities, was achieved (Figure 2). In ARGoS, a flying instead of a wheeled robot was used, since all wheeled robots in ARGoS are handled by a relatively simple 2D physics engine. In V-REP, the original e-puck model was simplified in order to decrease its vertex count. Each benchmark test was run with 1, 5, 10 and 50 robots in both environments.

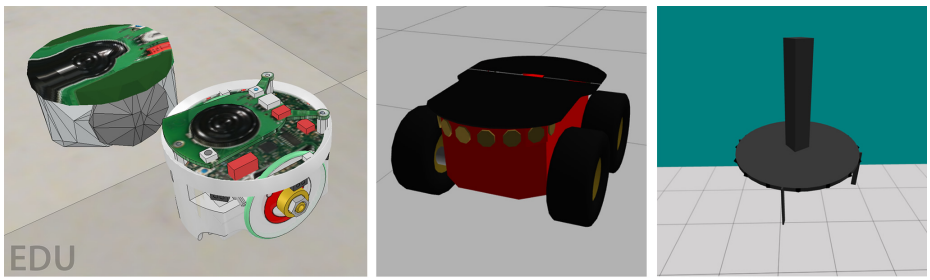
At the beginning of each benchmark experiment, a simulator was restarted. The computer was not running any other applications, apart from those normally required by its operating system, and a simple CPU and memory monitoring application. V-REP was running in "threaded rendering" mode during the GUI benchmarks.

The simulation in both V-REP and ARGoS was updated 10 times per second, i.e., $dt = 100$ ms. In Gazebo, 10 times more simulation steps per second



(a) (b)

Fig. 1. The "Large scene" environment in (a) V-REP and Gazebo, and (b) ARGoS.



(a) (b) (c)

Fig. 2. (a) The simplified (left) and the original (right) e-puck [11] models in V-REP. (b) The Pioneer 3AT [16] model in Gazebo. (c) The eye-bot [13] model in ARGoS.

were needed (dt = 10 ms), otherwise some robots exhibited strange movement dynamics, such as rocking behaviour on a straight horizontal plane.

Three performance metrics were used to evaluate the simulator performance. *Real-time factor*, R = simulated time / real time, the amount of *CPU usage*, C, and the amount of *memory usage*, M. When $R > 1$, a simulation could run faster than real time and vice versa. When $C > 100\%$, a simulator could utilise multiple processor cores. Two values for C and M were noted for Gazebo GUI experiments, corresponding to the usage of gzclient (visualisation) and gzserver (simulation), respectively.

3.2 Results

ARGoS achieved the highest simulation speed in the GUI experiments with up to 50 robots in the Small scene and with up to 5 robots in the Large scene, while utilising the smallest amount of resources (Table 2). Gazebo outperformed ARGoS in other experiments, especially when the Large scene was used in the

Headless benchmark (Tables 2 and 3). However, Gazebo usually required the largest amount of memory when it was running in the GUI mode, and a median amount in the Headless mode. V-REP combined with ODE usually achieved the lowest simulation speed. Using Bullet 2.78 often significantly increased the performance of V-REP.

Table 2: Simulator performance in the GUI mode. The best (green) and the worst (red) performance are indicated.

	V-REP + Bullet 2.78	**V-REP + ODE**	**Gazebo + ODE**	**ARGoS + Point-Mass3D**
1 robot + Small scene	$R \geq 1$ $C = 180\%$ $M = 235$ MB	$R \geq 1$ $C = 190\%$ $M = 225$ MB	$R \geq 1$ $C = 100 + 9\%$ $M = 225 + 58$ MB	$R \geq 1$ $C = 7\%$ $M = 85$ MB
5 robots + Small scene	$R = 0.52$ $C = 395\%$ $M = 380$ MB	$R = 0.37$ $C = 395\%$ $M = 360$ MB	$R \geq 1$ $C = 100 + 19\%$ $M = 305 + 58$ MB	$R \geq 1$ $C = 10\%$ $M = 88$ MB
10 robots + Small scene	$R = 0.11$ $C = 400\%$ $M = 536$ MB	$R = 0.099$ $C = 400\%$ $M = 530$ MB	$R \geq 1$ $C = 100 + 30\%$ $M = 402 + 58$ MB	$R \geq 1$ $C = 13\%$ $M = 89$ MB
50 robots + Small scene	Not feasible	Not feasible	$R = 0.87$ $C = 100 + 105\%$ $M = 1410 + 358$ MB	$R = 0.9$ $C = 103\%$ $M = 93$ MB
1 robot + Large scene	$R = 0.96$ $C = 205\%$ $M = 235$ MB	$R = 0.53$ $C = 200\%$ $M = 225$ MB	$R \geq 1$ $C = 100 + 10\%$ $M = 264 + 58$ MB	$R \geq 1$ $C = 32\%$ $M = 90$ MB
5 robots + Large scene	$R = 0.18$ $C = 400\%$ $M = 325$ MB	$R = 0.1$ $C = 400\%$ $M = 310$ MB	$R \geq 1$ $C = 100 + 25\%$ $M = 333 + 58$ MB	$R \geq 1$ $C = 60\%$ $M = 97$ MB
10 robots + Large scene	$R = 0.052$ $C = 400\%$ $M = 433$ MB	$R = 0.036$ $C = 400\%$ $M = 460$ MB	$R \geq 1$ $C = 100 + 40\%$ $M = 425 + 58$ MB	$R = 0.86$ $C = 120\%$ $M = 97$ MB
50 robots + Large scene	Not feasible	Not feasible	$R = 0.57$ $C = 100 + 100\%$ $M = 1450 + 426$ MB	$R = 0.052$ $C = 107\%$ $M = 106$ MB

In general, $R \geq 1$ could be achieved by all simulators until all available CPU power was used. The cut-off point, in terms of the number of robots, was always the lowest for V-REP, i.e. the simulation in V-REP slowed down in smaller experiments, compared to the other simulators. Furthermore, the simulation speed decrease due to insufficient CPU power was generally less severe for Gazebo than for V-REP and ARGoS.

Running Gazebo and ARGoS in the Headless mode (Table 3) increased R in environments where maximum CPU power was utilised by the GUI mode. On

Table 3: Simulator performance in the Headless mode. The best (green) and the worst (red) performance are indicated.

	V-REP + Bullet 2.78	**V-REP + ODE**	**Gazebo + ODE**	**ARGoS + Point-Mass3D**
1 robot + Small scene	$R = 4.1$ $C = 200\%$ $M = 165$ MB	$R = 3.12$ $C = 200\%$ $M = 160$ MB	$R = 42.85$ $C = 100\%$ $M = 107$ MB	$R = 300$ $C = 6.3\%$ $M = 18$ MB
5 robots + Small scene	$R = 0.38$ $C = 400\%$ $M = 320$ MB	$R = 0.32$ $C = 400\%$ $M = 320$ MB	$R = 10$ $C = 100\%$ $M = 130$ MB	$R = 150$ $C = 100\%$ $M = 20$ MB
10 robots + Small scene	$R = 0.09$ $C = 400\%$ $M = 470$ MB	$R = 0.08$ $C = 400\%$ $M = 480$ MB	$R = 5.26$ $C = 100\%$ $M = 150$ MB	$R = 21.42$ $C = 144\%$ $M = 20$ MB
50 robots + Small scene	Not feasible	Not feasible	$R = 1.06$ $C = 100\%$ $M = 356$ MB	$R = 0.52$ $C = 103\%$ $M = 25$ MB
1 robot + Large scene	$R = 1.91$ $C = 200\%$ $M = 165$ MB	$R = 0.58$ $C = 200\%$ $M = 160$ MB	$R = 18.75$ $C = 100\%$ $M = 174$ MB	$R = 15.78$ $C = 139\%$ $M = 31$ MB
5 robots + Large scene	$R = 0.2$ $C = 400\%$ $M = 270$ MB	$R = 0.11$ $C = 400\%$ $M = 250$ MB	$R = 5.88$ $C = 100\%$ $M = 192$ MB	$R = 5.45$ $C = 157\%$ $M = 45$ MB
10 robots + Large scene	Not feasible	Not feasible	$R = 3.09$ $C = 100\%$ $M = 211$ MB	$R = 1.59$ $C = 130\%$ $M = 47$ MB
50 robots + Large scene	Not feasible	Not feasible	$R = 0.60$ $C = 100\%$ $M = 423$ MB	$R = 0.03$ $C = 105\%$ $M = 55$ MB

the other hand, R was often smaller in the Headless mode of V-REP, compared to its GUI mode. There were two factors that contributed to this result. Firstly, R of the Headless mode was calculated over a longer period of time (simulated five rather than one minute) and its average, rather than its maximum, value was reported. Secondly, R of the Headless mode took into account not only the actual simulation time, but also the time needed to initialise and close the simulation. This in some cases took a significant amount of time, especially when ODE physics engine was used with V-REP.

Finally, V-REP demonstrated the most optimal CPU utilisation. It automatically spawned new threads when it was necessary and it could thus fully utilise all available CPU cores. Gazebo only utilised a single CPU core per process. In the GUI mode, Gazebo ran two processes, gzclient and gzserver, that could each utilise a maximum of 100% of CPU power. In the Headless mode, only a single core was utilised, as only the gzserver process was running. The multi-threaded core utilisation by ARGoS worked in general but problems were experienced in larger experiments. The CPU usage was notably smaller when more robots were added to the environment. Furthermore, unlike V-REP, ARGoS requires the user to specify the desired number of threads, rather than automatically spawning new threads when it is necessary.

It is notable that the 3D models used in ARGoS and Gazebo were fairly simple compared to those used in V-REP, even though effort was made to simplify the V-REP robot model (Figure 2). Moreover, the ARGoS physics engine was much simpler than those used by V-REP and Gazebo. It is therefore expected that using third-party libraries to cope with various aspects of the simulation that are currently not covered in ARGoS, such as calculating more complex physics dynamics, or working with imported 3D meshes, would decrease the simulator's performance. Similarly, it is expected that more complex 3D models would decrease the performance of Gazebo compared to V-REP.

In order to confirm that the mesh complexity played a major role in V-REP, we ran experiments with the Kilobot robots [17], that could only move forward and did not have the sensing or controller capabilities of e-pucks, but consisted of very simple 3D meshes. In the Kilobot experiments, up to six times higher R could be achieved, using only about an eighth of the computer's resources. In another experiment, the building model in the Large scene was simplified from around 41,600 to around 2,000 vertices. This increased R by up to 66%. Another kind of optimisation involved decreasing the number of simulation update loops per second from ten to two (i.e., $dt = 500$ ms). This increased R by up to 150%, while decreasing memory usage by up to 15%. These results suggest that it is possible to significantly increase the performance of V-REP by carefully setting simulation parameters and by optimising 3D models used in the simulation.

4 Conclusion

V-REP is the most complex and the most resource-hungry of the three simulators. However, it offers a number of useful features, such as multiple physics

engines, a comprehensive model library, the ability of a user to interact with the world during simulation and, most importantly, mesh manipulation and optimisation. Moreover, V-REP automatically spawns new threads on multiple CPU cores and therefore utilises the full amount of CPU power when it is necessary. It is therefore suitable for high-precision modelling of robotic applications such as object transportation or area surveillance, as well as of various industrial applications, where only a few robots are required to operate at the same time.

ARGoS, on the other hand, is a suitable choice for simulations of swarm robotics tasks, such as collective foraging, flocking, or area coverage. Compared to V-REP, ARGoS trades-off robot, environment and physics complexity for superior performance. An XML-based simulation settings file is also very convenient, especially when a large variety of simulations need to be generated automatically. However, there are multiple important features missing from ARGoS, most notably the ability to import 3D meshes into the simulator. Currently, users that are not willing to spend time and effort on programming new robot models in OpenGL, have fairly limited choices.

Gazebo occupies the space between V-REP and ARGoS. While it is much closer to V-REP in terms of features, its interface and default robot models are much simpler and resemble those found in ARGoS. It is notable that Gazebo outperformed ARGoS in the larger simulation environments studied here, which suggests that it is a more suitable choice for large swarm robotics experiments. However, our experiments showed that the usability of Gazebo is relatively poor. Firstly, while it can import 3D meshes, there are no editing options, making it difficult to alter and optimise models. Another problem is the interface that has a number of issues and fails to follow established conventions. Finally, difficulties were noted when installing dependencies for Gazebo and for many of its third-party models. While not necessarily severe by themselves, these issues together could have a negative impact on a research project.

In the future, it would be interesting to conduct a user survey regarding the features and simulator usability in order to obtain a more robust comparison. It would also be interesting to evaluate the extent of the reality gap in the default simulator robot models.

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