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PyDSLRep: A Domain-Specific Language for Robotic Simulation in V-Rep

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Abstract

Calculating forward and inverse kinematics for robotic agents is one of the most time-intensive tasks when controlling the robot movement in any environment. This calculation is then encoded to control the motors and validated in a simulator. The feedback produced by the simulation can be used to correct the code or to implement the code can be implemented directly in the robotic agent. However, the simulation process executes instructions that are not native to the robotic agents, extending development time or making it preferable to validate the code directly on the robot, which in some cases might result in severe damage to it. The use of Domain-Specific Languages help reduce development time in simulation tasks. These languages simplify code generation by describing tasks through an easy-to-understand language and free the user to use a framework or programming API directly for testing purposes. This article presents the language PyDSLRep, which is characterized by the connection and manipulation of movement in mobile robotic agents in the V-Rep simulation environment. This language is tested in tree different environments by twenty people, against the framework given by V-Rep, demonstrating that PyDSLRep reduces the average development time by 45.22%, and the lines of code by 76.40% against the Python framework of V-Rep.

Introduction

Robotic agents are widely used for industrial, surveillance, and search and rescue tasks. However, these applications have increased their development complexity in both hardware and software, as they rely on increasingly complex algorithms to perform them. This has moved developers to use techniques and tools that enable robotic agents to have more autonomy, depending on the environment in which they are deployed.

Currently, developers need to calculate and assess the development of a robotic agent, and this has a direct impact in the increase of development time, due the
generation of a simulation model, which in several cases is independent of the software models implemented in physical agents, increasing the designer’s work.

The design of this type of tests is usually done using Domain-General Languages (DGLs) that extend APIs or high-level libraries for robotic applications development. However, these Domain-General Languages lack the required semantics or abstractions needed to develop movement actions, making it necessary to debug the code before the simulation stage.

There are languages capable of increasing the abstraction level and reducing development time by representing clearer semantics and allowing more simplicity in writing code. These languages, which rely on model generation and domain-specific concepts, are known as Domain-Specific Languages (DSLs). Domain-Specific Languages are becoming popular in robotics due to their flexibility, automation, and encapsulation of repetitive tasks, which results in a decrease of common errors in code generation. DSLs can also generate code that can be integrated easily to a GPL to handle API’s or libraries for specific use in platforms for real-world environments.

There are several tools that can be used to generate DSLs. These are divided into internal and external tools. Internal tools are extensions of GPLs like LUA or RUBY by adding new expressions or functionality. One example is the virtual simulation environment V-REP, which uses LUA to describe and control the environment and robotic agents being simulated.

External DSLs define their own syntax and concepts, which must be related to the desired application domain. For this type of DSLs, there are editors like Xtext, which allow the creation of a language grammar by designing its syntax and creating rules through a language called Xtend, which is used to implement grammar definitions, design the interpreter, and generate the DSL code.

Dejanovic et al. create a language based in Xtext called textX, to build a DSL in Python. This DSL allows to create Python code and presents an example of robotics application to simulate movements in a discrete environment. However, it does not demonstrate a direct application or the kinematic modeling of the robotic agent.

Currently, DSLs are oriented to manipulating robotic arms and describing the parts or robotic agents. The goal of DSLs in the control of robotic arms in focused on generating movements to manipulate elements by allowing the modification of kinematic parameters. Conversely, DSLs such as the Universal Robotic Description Format (URDF) by ROS, allow describing all the parts of the robotic agents, specifying dynamic and kinematic parameters and allowing to model robotic agents for displacement in a real environment. However, it does not model the interaction of the robotic agent with obstacles in the environment.

This limitation prompted the development of an internal DSL called , to code movement tasks in robotic agents, and oriented to their validation using the V-REP simulation environment. This language offers a set of rules that abstract the kinematic behavior of the robot, helping reduce complexity in code development and testing by abstracting the functional and software architecture of the robotic agent, avoiding errors in the generation of the kinematic model. As it was developed using Xtext, it can be easily used in any operating system. Its text editor features auto-complete, highlights reserved words, and shows errors. Furthermore, generates the connection to V-REP’s proxy through a Python script, which can be easily modified by the user to embed it directly in a differential robotic platform, ensuring applicability and reusability in physical robotic agents.

To improve code generation, PyDSLRep divides code description into 4 stages. The first stage is modeling the differential robot, taking as a variable the size of the wheels to generate the model for forward and inverse dynamics. The second stage is declaring the robotic agent instances. The third is describing the movements that the robotic agents
can perform, either serialized or concurrent, according to the user’s needs. Finally, the fourth stage groups the robotic agents in the environment and executes the movements.

The rest of the article is structured as follows. Section 2 presents the works performed in the implementation of DSLs oriented to robotic systems. Section 3 describes the kinematic model of the robotic agent modeled in PyDSLRepCode. The creation of the development environment is explained in Section 4. Section 5 presents the evaluation and discussion of the results obtained with compared to the Python framework. Finally, Section 6 presents conclusions.

Related Works

Robotic agents have been employed for a wide variety of work domains, ranging from planning, mapping, locations, and assistance tasks. Several design architectures have been used for development in these work areas, with the goal of reducing software development time.

Silva et al. [10] establish a metamodel for the requirements analysis and software development for a generic system of robotic agents. This metamodel establishes a methodology based in software engineering, for the study of the agents’ requirements, by implementing different roles for the agents and how they have to share information. However, this metamodel only provides guidelines for roles and information specifications among different levels.

Like Silva, other authors have established frameworks and methodologies for the control [11–15], planning [16–18], and communications [19–21] of robotic agents, but they present the characteristics of DSLs to reduce development time in a flexible and efficient manner, and at the same time, increasing autonomy between hardware and software [8]. This autonomy is dependent on the domain knowledge for which the robotic agents are being used; this is, the problem requirements, proposed objectives, and system restrictions.

Klotzbücher et.al. [22] establishes an internal DSL based on LUA, based on the Model Driven Engineering (MDE) approach, to standardize the representation of Task Frame Formalism (TFF) for industrial robotic arms, by modeling the language through hierarchical definitions and orienting the user intuitively, without direct influence of hardware during program design. This is achieved by implementing the design flow through DSL representation, according to the four levels of standardization of the OMG group, applying the MDE approach. In this case, the level M0 is in charge of manipulating the robotic arm. Although software design in the previous case is not directly related to hardware, it depends on pre-existing frameworks or libraries for manipulating robotic arms [23].

Frigerio et al. [22] present a DSL focused on reducing the calculation of transformation matrices required to control actuators in robotic arms, by generating models to be implemented according to the kinematic parameters of the robotic arm. This DSL develops code generation for implementation in positioning tasks for a robotic arm inside a simulation, emphasizing the use of models to be reused in physical robots. However, this is only possible in agents that have the same kinematics.

The previous works present DSLs oriented to application in robotic arms, which prevents them to be used in other types of mobile platforms such as differential or wheeled robots. Loetzsch et al. [24] propose a DSL called XABSL, for implementation in autonomous agents in complex environments. XABSL minimizes the developer’s role in code creation by using finite state machines to represent the actions to be executed by the robotic agent. The language presented by Loetzsch has been used in RoboCup, showing good results in the team that implemented it. However, robotic platforms must have a framework compatible with the language, which prevents implementation in
proprietary platforms. Furthermore, it cannot model the entire agent, as it only provides selection mechanisms by action, and it does not allow the possibility of performing simulation tests prior to implementation.

Similar to Loetzsch, Campusano et al. design a DSL that represents code functionality by finite state machines, but in this case, they can take four possible states, as chosen by the user. It also allows the programmer to see the solution deployment in real-time by using live programming, which reduces programming time by allowing code debugging without the need for compilation or sending the code to a test unit. Conversely, the language can generate code to create communication nodes with the Robotic Operating System (ROS) and use the implemented algorithms directly. The drawback of this language is that it avoids evaluating proprietary algorithms and, like XABSL, it is not compatible with simulators for testing the generated program.

DSLs have also been oriented to graphical programming. In these cases, the user programs using blocks that contain pre-programmed routines. Pot et al. developed Choregraphe, a development environment that includes the characteristics presented by Campusano by showing the results of the programs developed by users in real-time and inside a virtual environment. Each of the blocks contained in Choregraphe can be modified through a Python script, allowing the user to implement their own algorithms or libraries for remote information processing. However, as this software is dedicated to NAO humanoid robots, it cannot be used for programming other robotic agents.

Another advantage of Choregraphe is the use of Python scripts. Blasco et al. highlight the importance of using this high-level language to control robotic agents in high-complexity tasks. In contrast with the previous works mentioned, PyDSLRepCode is a language oriented to movement control in mobile robotic agents. This language features a simple user syntax, simplifying the connection and direct verification with V-REP before direct implementation in the test agent. Another great advantage of PyDSLRepCode is the generation of organized code in Python, which allows the user to reuse the code to add the robotic agent’s API for direct motor manipulation or to implement navigation algorithms directly.

PyDSLRepCode kinematic description

Every movement of a robotic agent is represented by its kinematic description, which describes the position in which the robot can be according to the speed of its wheels (forward kinematics) or the speed that every wheel should have to achieve the desired orientation and position (inverse kinematics.) In every case in which the developers wish to control the movement of the robotic agent, they must calculate the forward and inverse kinematics of the robotic agents to generate the software code to manipulate the agent’s motors. Errors might be introduced during the execution of this task, resulting in the execution of movements with errors by the robotic agents and preventing the completion of the desired navigational tasks.

PyDSLRepCode simplifies writing code to control the robotic agent’s movements. This language embeds the kinematic description of the differential robotic agent, as this is one of the most commonly used structures for navigational tasks. To achieve this, PyDSLRepCode describes code development in four stages: 1) Describes the robotic agent components to calculate forward kinematics. 2) Instances the robotic agents. 3) Assigns to each agent the movement actions required by the developer (inverse kinematics.) 4) Creates the environment to contain the robotic agents and assigns the execution order of the movements developed in stage 2.

Down below is a description of each of PyDSLRepCode’s coding stages, demonstrating the abstraction capability to describe movement in differential robotic agents.
Direct Kinematic in PyDSLRepCode

Differential robots are characterized by having two wheels, which are placed parallel to each other along the same axis and separated from each other by a distance \( d \). Each of the wheels has an autonomy of movement represented by a velocity vector \( v_w \). This allows controlling the rotational movement of the robot. As both wheels are placed along the same axis, the rotational movement has a common rotation point for both wheels, which is where the agent presents rotation. This point is known as Instantaneous Center of Rotation (ICR).

Fig. 1 shows the action of velocity vectors in each of the wheels, with respect to the ICR. Each of these velocities has a direct effect on the trajectory of the robotic agent, generating the same angular velocity \( \omega(t) \) in both wheels with respect to the ICR. Equation (1) presents the calculation of velocities in the wheels, according to the curvature radius \( R \) with respect to the ICR point.

\[
v_{r,l} = \omega(t) \left( R \pm \frac{d}{2} \right)
\]

From equation (1), we can clear the curvature radius \( R \) and the angular velocity \( \omega(t) \) generated by the rotational movement, obtaining equations (2) and (3).

\[
R = \frac{d (v_l(t) + v_r(t))}{2 (v_r(t) - v_l(t))}
\]

\[
\omega(t) = \frac{v_r(t) - v_l(t)}{d}
\]

Fig 1. Kinematic representation of a two-wheeled differential drive robot.

Using trigonometric properties, and assuming that the point \( d/2 \) is located at the position \((x, y)\) with an angle \( \theta \) respect the x-axis, we obtain the position \( ICR = [x - R\sin(\theta), y + R\cos(\theta)] \). Taking this into account, if the robot moves at a speed \( \omega(t) \) for a time \( t_\alpha \) (Fig. 2), its new position can be calculated with equation (4).

\[
\begin{bmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
\cos(\theta_{t_\alpha}) & -\sin(\theta_{t_\alpha}) & 0 \\
\sin(\theta_{t_\alpha}) & \cos(\theta_{t_\alpha}) & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
R\sin(\theta) \\
-R\cos(\theta) \\
\theta
\end{bmatrix}
+ 
\begin{bmatrix}
x - R\sin(\theta) \\
y + R\cos(\theta) \\
\theta_{t_\alpha}
\end{bmatrix}
\]
As is shown in equation (4), both the angular velocity \( \omega(t) \), the position of the robot in the Cartesian plane, and the reference point in the rotational movement ICR, depend directly on the velocity of each wheel and on the time in which energy is applied to the motors. Using this information, PyDSLRepCode builds a model of the robotic agent by asking the developer the wheels included in the robot model, in which the input of the radius and the port number through which communication will be made are mandatory.

To identify each wheel and the robotic agents using them, PyDSLRepCode requires each wheel to have a unique identifier, which is represented by a string (Fig. 3).

Another important aspect of PyDSLRepCode is that if the user characterizes more than one robotic agent, and these agents share the same wheel type, PyDSLRepCode allows the creation of a single instance of the wheel, which can be assigned to all the agents.

The abstraction power of PyDSLRepCode exempts developers from representing equations (1) – (4), taking the value \( d \) of separation between wheels directly from the references acquired through V-Rep, and effectively reducing the number of variables the user is required to encode.

**Inverse Kinematic in PyDSLRepCode**

By knowing the velocity of a robotic agent, its position can be calculated after a time \( t_\alpha \), as shown in Equation (4). However, to move to a location or configuration in the environment \( (x, y, \theta) \), the velocity and orientation of the robotic agent must be controlled. This problem can be solved by breaking down the velocity vector \( v(t) \) in \( (x, y) \), integrating it with respect to time \( t \) (equation (5).) From this, to simplify the
displacement calculations and avoiding the problem of perpendicular displacement in differential robots, the speeds of the wheels are equalized by generating the movement matrix of equation (6), where $\phi$ is the desired angle of rotation.

$$x(t) = \frac{1}{2} \int_0^t (v_r(t) + v_l(t)) \cos(\theta t) dt$$

$$y(t) = \frac{1}{2} \int_0^t (v_r(t) + v_l(t)) \sin(\theta t) dt$$

$$\theta(t) = \int_0^t \omega(t) dt$$

(5)

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta) & 0 & 0 \\ \sin(\theta) & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} r \\ \theta \end{bmatrix} + \begin{bmatrix} x \\ y \\ \phi \end{bmatrix}$$

(6)

To save the designer from having to calculate the integrals (5) and the calculation of velocities in the matrix (6), PyDSLRep groups the movement actions in a way that the user is only required to input the displacement distance and the velocity for the movement of the robotic agent, separating the movement actions in straight lines and turns, and thus avoiding the displacement problems in horizontal agents (Fig. 4). During the input of information to instantiate a collection of movements, PyDSLRep requests two parameters. The first parameter is the assignment of a unique name, and the second is that the collection is related to a single robotic agent. This is to ensure the execution of actions by the robotic agent at the desired moment.

Fig 4. Class diagram inverse kinematic behaviour PyDSLRep.

In addition to the differential model presented above, PyDSLRep also includes two additional models. The first one is a four-wheel robot, in which the calculations for
inverse and direct kinematics are based on the article by Maulana et.al. [29]. While the second model is also four-wheeled, the motion of its wheels is omnidirectional or holonomic, which is possible when using mecanum wheels [31]. The inverse and direct kinematics of this second model are based on the work of Zimmermann et.al. [30].

Fig 5. Four wheeled robots implemented in PyDSLRep (a) non holonomic (b) holonomic using mecanum wheels.

Creation of the development Environment

The work environment in PyDSLRep contains the robotic agents’ instances and the collection of movements they will perform. This is possible by starting the development of each of the components of the robotic system. The creation process of the environment is done in four steps, which are described as follows. The steps follow the bottom-up architecture pattern, as shown in Fig. 6:

1. Instantiating the components of the wheels. This requires the creation of at least two of these components. If necessary, as is the case if the robotic agent will connect to a remote host, an additional IP component is created, containing its respective IPv4 address.

2. Declaring and instantiating the robotic agents, which must contain the wheels, to generate their kinematic model.

3. Creating the collection of movements for each of the robotic agents that were instantiated.

4. Finally, creating the environment component, which contains the robotic agents and the movements desired, which were instantiated in previous stages.

Fig 6. Code architecture of an environment.

The grammar created in PyDSLRep is shown in Table 1. This is used to instantiate components and declare instructions to complement the usability for each of them.
Table 1. Grammar implemented in PyDSLRep.

<table>
<thead>
<tr>
<th>Keyword</th>
<th>Feature</th>
<th>Grammar rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>wheel</td>
<td>Creates a wheel component</td>
<td>wheel wheel_name with radius (float in cm)</td>
</tr>
<tr>
<td>wheelH</td>
<td>Creates an holonomic wheel component</td>
<td>wheelH wheel_name with radius (float in cm)</td>
</tr>
<tr>
<td>robot</td>
<td>Creates a robot component</td>
<td>robot type_declaration</td>
</tr>
<tr>
<td>type two_wheels</td>
<td>Creates a two wheels differential robot component</td>
<td>type tw</td>
</tr>
<tr>
<td>type four_wheels</td>
<td>Creates a four wheels robot component</td>
<td>type fw</td>
</tr>
<tr>
<td>type four_wheelsH</td>
<td>Creates a four wheels holonomic robot component</td>
<td>type fwh</td>
</tr>
<tr>
<td>sensor movement</td>
<td>Declares a distance sensor</td>
<td>sensor senor_name</td>
</tr>
<tr>
<td>parallel movement</td>
<td>Creates a collection of movements that are concurrent</td>
<td>parallel movement mov_name of robot_name { move (float) meters at (float) turn right (int) }</td>
</tr>
<tr>
<td>slam</td>
<td>Declares a movement to create a map</td>
<td>slam</td>
</tr>
<tr>
<td>environment</td>
<td>Creates a collection of movements with a specific collection of movements</td>
<td>environment area_name has { robot_name _1 ... robot_name _n } robots with { mov_name _1 ... mov_name _n } moves</td>
</tr>
<tr>
<td>ip</td>
<td>Creates an IP component as IPv4</td>
<td>ip ip_name (int), (int), (int), (int)</td>
</tr>
<tr>
<td>move</td>
<td>Creates a linear movement component with a specific velocity</td>
<td>move (float) distance_declaration at (float)</td>
</tr>
<tr>
<td>turn</td>
<td>Creates a rotatory movement component</td>
<td>turn rotatory_declaration</td>
</tr>
<tr>
<td>left</td>
<td>Declares the orientation of the turn component 90 degrees to its left if there is not an angle_declaration</td>
<td>turn left (int)</td>
</tr>
<tr>
<td>right</td>
<td>Declares the orientation of the turn component 90 degrees to its right if there is not an angle_declaration</td>
<td>turn left (int)</td>
</tr>
<tr>
<td>turn until</td>
<td>Creates a rotatory movement component</td>
<td>turn rotatory_declaration until {sensor_name}</td>
</tr>
<tr>
<td>port</td>
<td>Declares the port number of each robotic agent</td>
<td>port (int)</td>
</tr>
<tr>
<td>meters</td>
<td>Declares the linear distance traveled in meters</td>
<td>move (float) meters at (float)</td>
</tr>
<tr>
<td>centimeters</td>
<td>Declares the linear distance traveled in centimeters.</td>
<td>move (float) centimeters at (float)</td>
</tr>
</tbody>
</table>

Fig. 7 shows a differential robotic two-wheel agent that must travel a total distance
of 12 meters to reach its final objective. To model this task in PyDSLRep, the grammar rules of Table 1 are applied, with the bottom-up design architecture, as shown in Table 2.

![First basic environment created in V-Rep.](image)

**Fig 7.** First basic environment created in V-Rep.

<table>
<thead>
<tr>
<th>Step</th>
<th>Code</th>
</tr>
</thead>
</table>
| 1    | wheel wheelR with radius 4.5  
      | wheel wheelL with radius 4.5  
      | robot robot_1 type tw with port  
      | 19999 has {  
      | wheelL  
      | wheelR }wheels  
      | movement mov_1 of robot_1 {  
      | move 4.0 meters  
      | turn right  
      | move 4.0 meters  
      | turn right  
      | move 400.0 centimeters }  
| 2    | environment area_1 has {  
      | robot_1 } robots with {  
      | mov_1 }moves  

Table 3 shows the bottom-up architecture for a four wheeled robotic agent, meanwhile, Table 4 shows the implementation using an holonomic four wheeled robotic agent in the same environment Fig. 7.
Table 3. Bottom-Up architecture design in PyDSLRep four wheeled robot.

<table>
<thead>
<tr>
<th>Step</th>
<th>Code</th>
</tr>
</thead>
</table>
| 1    | wheel wheelR0 with radius 4.5  
|      | wheel wheelR1 with radius 4.5  
|      | wheel wheelL0 with radius 4.5  
|      | wheel wheelL1 with radius 4.5  
|      | robot robot_1 type fw with port 19999 has { wheelL0 wheelL1 wheelR0 wheelR1 } wheels |
| 2    | movement mov_1 of robot_1 { move 4.0 meters turn right |
|      | move 4.0 meters turn right |
|      | move 400.0 centimeters } |
| 3    | environment area_1 has { robot_1 } robots with { mov_1 } moves |

Table 4. Bottom-Up architecture design in PyDSLRep holonomic four wheeled robot.

<table>
<thead>
<tr>
<th>Step</th>
<th>Code</th>
</tr>
</thead>
</table>
| 1    | wheelH wheelR0 with radius 4.5  
|      | wheelH wheelR1 with radius 4.5  
|      | wheelH wheelL0 with radius 4.5  
|      | wheelH wheelL1 with radius 4.5  
|      | robot robot_1 type fw with port 19999 has { wheelL0 wheelL1 wheelR0 wheelR1 } wheels |
| 2    | movement mov_1 of robot_1 { move 4.0 meters turn right |
|      | move 4.0 meters turn right |
|      | move 4.0 meters turn right } |
| 3    | environment area_1 has { robot_1 } robots with { mov_1 } moves |

In case the robotic agent needs to make turns at angles different than 90 degrees, as shown in turn commands must be implemented, specifying the direction and angle of rotation. Table 5 shows the development of the path using a two-wheel differential
robotic agent. Four-wheel robotic agents are also capable of executing these motions.

Fig 8. Second basic environment created in V-Rep.

Table 5. Bottom-Up architecture design in PyDSLRep two wheel differential robot third environment.

<table>
<thead>
<tr>
<th>Step</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><code>wheel wheelR with radius 4.5</code>&lt;br&gt;<code>wheel wheelL with radius 4.5</code>&lt;br&gt;<code>robot robot_1 type fw with port 19999 has { wheelL0 wheelL1 wheelR0 wheelR1} wheels</code></td>
</tr>
<tr>
<td>2</td>
<td><code>movement mov_1 of robot_1 { turn right 45 move 4.0 meters turn left move 0.5 meters turn left 45 move 4.0 meters }</code></td>
</tr>
<tr>
<td>3</td>
<td><code>environment area_1 has { robot_1 } robots with { mov_1 } moves</code></td>
</tr>
</tbody>
</table>

PyDSLRep supports distance sensors, which can be used directly by robotic agents to generate motion autonomously. Table 6 shows the results of using a robotic agent with three frontal distance sensors, which are used to determine how much of the path should the agent rotate autonomously to continue with the following motion instruction.
Table 6. Bottom-Up architecture design in PyDSLRep two wheel differential robot with sensors.

<table>
<thead>
<tr>
<th>Step</th>
<th>Code</th>
</tr>
</thead>
</table>
| 1    | `wheel wheelR with radius 4.5`  
|      | `wheel wheelL with radius 4.5`  
|      | `sensor fSensor` |
| 2    | `sensor lSensor`  
|      | `sensor rSensor` |
|      | `robot robot_1 type tw with port 19999 has` |
|      | `{wheelL wheelR } wheels with sensors`  
|      | `{fSensor, lSensor, rSensor}` |
| 3    | `movement mov_1 of robot_1`  
|      | `{move 4.0 meters turn right until {fSensor, rSensor}}`  
|      | `{move 4.0 meters turn right until {fSensor, rSensor}}`  
|      | `{move 400.0 centimeters}` |
| 4    | `environment area_1 has`  
|      | `{robot_1 robots with Greek}`  
| 5    | `{mov_1 moves}` |

Finally, PyDSLRep contains an instruction for generating a topological SLAM, as demonstrated in et.al [31]. For its use, the robotic agent needs to be equipped with at least five distance sensors, as shown in Fig. 7. The generation of the map requires that the environment be closed. Table 7 shows the bottom-up architecture implemented for map generation. The generated map result is shown in Fig. 9.
Table 7. Bottom-Up SLAM architecture design in PyDSLRep.

<table>
<thead>
<tr>
<th>Step</th>
<th>Code</th>
</tr>
</thead>
</table>
| 1    | wheel wheelR with radius 4.5  
      | wheel wheelL with radius 4.5  |
|      | sensor fSensor0  
      | sensor fSensor1  
      | sensor fSensor2  
      | sensor lSensor  
      | sensor rSensor  |
| 2    | robot robot_1 type tw with port  
      | 19999 has {  
      | wheelL } wheels with sensors  
      | {fSensor0,fSensor1,fSensor2,  
      | lSensor, rSensor}  
| 3    | movement mov_1 of robot_1 { slam }  
| 4    | environment area_1 has {  
| 5    | robot_1 } robots with {  
|      | mov_1 } moves  

Fig 9. Topological map of the first test environment.

Evaluation and Discussion

It is necessary to propose testing environments to assess PyDSLRep’s usability as compared to the native framework used for the simulation of robotic agents in V-Rep. To this end, this section presents two stages for the testing process. The first stage presents the methodology for conducting experiments using PyDSLRep and the Python framework. The second presents the results obtained and a discussion of the results. The PyDSLRep repository can be found in [32].
Methodology

To validate the usability of PyDSLRep and the Python framework in the V-Rep simulator, three scenarios are introduced. The first two scenarios contain obstacles with robotic agents and two groups of users with knowledge of the Python programming language. The differentiating factor of the first group against the second group is the lack of knowledge about the Python framework for V-Rep. The third scenario is a non-uniform environment, with obstacles with different shapes.

The first testing scenario is shown in Fig. 10. This is a simple scenario, as it contains a single robotic agent. The second scenario contains 4 robotic agents that must be controlled concurrently to complete the objectives (Fig. 11). As this DSL is designed as a script, both scenarios will measure lines of code (LOC), the time to complete the tasks and the ability to create connections to remote hosts to manipulate agents. The third scenario is presented in Fig. 12; it has an area of $7m \times 7.7m$
Fig 12. Third test environment created in V-Rep.

Results

This section will discuss all the test environments. For this, it presents three subsections to analyze the results of each test environment independently. For the first two test and group of people presented, they were presented with the V-Rep work environment already initialized, a tutorial of the Python framework for the group that had not used it before. Each group was also presented with a PyDSLRep manual. For the third test, only the result map is presented.

First Environment

Table 8 presents the results of both groups using the Python framework for robotic agent manipulation in V-Rep. The results show that the first group took an average of 26.94 minutes to solve the problem, with a standard deviation of 5.21 minutes, and the second group showed a shorter average time of 16.53 minutes, with a standard deviation of 6.12 minutes (Fig. 13a.)

In the task of connecting with a remote host to conduct the test, 40% of the first group were able to create a successful connection. This result reached 80% in the second group.

Finally, the first group showed an average of 178.9 lines of code, and the second group generated fewer lines of code, with an average of 164.1 (Fig. 13b.)

Table 8. Results from the first environment using the python framework.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group 1 LOC</th>
<th>Time (hh:mm:ss)</th>
<th>Remote host</th>
<th>Group 2 LOC</th>
<th>Time (hh:mm:ss)</th>
<th>Remote host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>163</td>
<td>00:25:32</td>
<td>yes</td>
<td>162</td>
<td>00:10:48</td>
<td>yes</td>
</tr>
<tr>
<td>2</td>
<td>210</td>
<td>00:23:51</td>
<td>no</td>
<td>158</td>
<td>00:27:53</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>161</td>
<td>00:21:43</td>
<td>no</td>
<td>162</td>
<td>00:22:47</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>143</td>
<td>00:33:56</td>
<td>no</td>
<td>168</td>
<td>00:13:43</td>
<td>yes</td>
</tr>
<tr>
<td>5</td>
<td>207</td>
<td>00:32:51</td>
<td>no</td>
<td>163</td>
<td>00:24:38</td>
<td>yes</td>
</tr>
<tr>
<td>6</td>
<td>155</td>
<td>00:33:50</td>
<td>no</td>
<td>172</td>
<td>00:11:69</td>
<td>no</td>
</tr>
<tr>
<td>7</td>
<td>175</td>
<td>00:18:39</td>
<td>no</td>
<td>161</td>
<td>00:11:62</td>
<td>yes</td>
</tr>
<tr>
<td>8</td>
<td>194</td>
<td>00:30:39</td>
<td>no</td>
<td>162</td>
<td>00:11:51</td>
<td>yes</td>
</tr>
<tr>
<td>9</td>
<td>201</td>
<td>00:25:48</td>
<td>yes</td>
<td>165</td>
<td>00:18:52</td>
<td>yes</td>
</tr>
<tr>
<td>10</td>
<td>180</td>
<td>00:22:40</td>
<td>yes</td>
<td>168</td>
<td>00:10:40</td>
<td>yes</td>
</tr>
</tbody>
</table>
Fig 13. Results from the first environment using the framework in Python (a) Time of completion (b) Lines of code to fulfill the experiment.

On the other hand, Table 9 shows the results for both groups using PyDSLRep, in which the first group took an average of 13.39 minutes to solve the problem, with a standard deviation of 5.21 minutes, which is a reduction of 50.29% of the time. Group 2 was also able to reduce the average time to 12.76 minutes with a standard deviation of 6.32 minutes, which is 22.82% as compared to using the Python framework (Fig. 14a).

In the task of connecting with a remote host, the first group increased their connection success to 70%, while the second group decreased by 10%. When the second group was asked about their perception of ease to connect to remote hosts, they replied that they were used to using the Python framework, which made it more difficult to understand the connection with an IP address other than localhost.

Finally, both groups showed a reduction in lines of code used to solve the problem. The first and second group used an average of 22.40 lines of code. For the first group, this represents a reduction of 87.47%, and for the second, it is a reduction of 86.34%, on average (Fig. 14b).

Table 9. Results from the first environment using PyDSLRep.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group 1</th>
<th></th>
<th>Group 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOC</td>
<td>Time (hh:mm:ss)</td>
<td>Remote host</td>
<td>LOC</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>00:12:9</td>
<td>yes</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>00:11:12</td>
<td>yes</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>00:15:14</td>
<td>no</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>00:19:21</td>
<td>yes</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>00:21:16</td>
<td>yes</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>00:1:20</td>
<td>no</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>24</td>
<td>00:16:15</td>
<td>yes</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>22</td>
<td>00:10:22</td>
<td>no</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>19</td>
<td>00:14:19</td>
<td>yes</td>
<td>22</td>
</tr>
<tr>
<td>10</td>
<td>23</td>
<td>00:12:27</td>
<td>yes</td>
<td>22</td>
</tr>
</tbody>
</table>
To tell if the differences are significant between the results in the first environment, we apply the t-test. This test is calculated measuring the \( t\)-score using (7) and the critical value by (8). If the \( t\)-score is greater than the critical value, the non null hypotheses is approved, that in this case is that PyDSLRep has better results.

\[
t_{\text{score}} = \frac{M_x - M_y}{\sqrt{\frac{S_x^2}{N_x} + \frac{S_y^2}{N_y}}}
\]  
(7)

\[
cv = \frac{\gamma \left( \frac{df+1}{2} \right)}{\sqrt{\pi \cdot df \cdot \gamma \left( \frac{df}{2} \right) \cdot (1 + (1 - \alpha)^2) \left( \frac{df}{2} \right)}}
\]  
(8)

Using the t-test, shows that the first group has a significant variation when they develop the task using PyDSLRep with a \( t\)-score = 5.815493492345903 > cv = 1.7340636066175354. While the second group doesn’t show a great improvement with a \( t\) = 1.3774471037866356 < cv = 1.7340636066175354

**Second Environment**

The second testing scenario presented to both groups has three differentiating factors as compared to the first scenario. First, they must manage 4 agents, which requires more planning. Second, the movement actions must be executed in parallel. Finally, the distances traveled by the agents vary, which prevents the use of recursive functions.

Table 10 presents the results of both groups using the Python framework for manipulating robotic agents in V-REP. The results show that the first group took an average of 49.82 minutes to solve the problem, with a standard deviation of 5.00 minutes. Group 2 required a shorter average time to solve the problem of 40.08 minutes, with a standard deviation of 5.31 minutes (Fig. 15a.)

In the task of connecting with a remote host, for the first group, 30% were capable of establishing a successful connection. For the second group, this percentage rose to 70%.

Finally, the first group used an average of 342 lines of code, and group 2 generated fewer lines of code, with an average of 303.5 lines (Fig. 15b.)
Table 10. Results from the second environment using the python framework.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOC</td>
<td>Time (hh:mm:ss)</td>
</tr>
<tr>
<td>1</td>
<td>333</td>
<td>00:50:54</td>
</tr>
<tr>
<td>2</td>
<td>353</td>
<td>00:55:34</td>
</tr>
<tr>
<td>3</td>
<td>337</td>
<td>00:49:55</td>
</tr>
<tr>
<td>4</td>
<td>334</td>
<td>00:51:51</td>
</tr>
<tr>
<td>5</td>
<td>347</td>
<td>00:47:52</td>
</tr>
<tr>
<td>6</td>
<td>336</td>
<td>00:49:50</td>
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<tr>
<td>7</td>
<td>362</td>
<td>00:54:53</td>
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<td>8</td>
<td>366</td>
<td>00:43:56</td>
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<td>00:39:44</td>
</tr>
<tr>
<td>10</td>
<td>308</td>
<td>00:54:48</td>
</tr>
</tbody>
</table>

Fig 15. Results from the second environment using the framework in Python (a) Time of completion (b) Lines of code to fulfill the experiment.

Table 11 shows the results of both groups using PyDSLRep, in which the first group took an average time to solve the problem of 24.47 minutes, with a standard deviation of 4.73 minutes, which is a 50.89% reduction of time. Group 2 was also able to reduce the average time to 17.30 minutes, with a standard deviation of 3.66 minutes, which is 56.85% of the time required using the Python framework (Fig. 16a.)

In the task of connecting with a remote host, both groups increased the percentage of cases in which they were able to establish a successful connection with the remote host. The first group increased the successful connections to 80%, and the second to 90%.

Finally, both groups showed a reduction in the number of lines of code used to solve the problem. The first group used an average of 107.6 lines of code, which is a reduction of 68.54%. The second group used an average of 110.6 lines of code, which is 63.26% less than using the Python framework (Fig. 16b.)

Table 11. Results from the second experiment using PyDSLRep.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOC</td>
<td>Time (hh:mm:ss)</td>
</tr>
<tr>
<td>1</td>
<td>106</td>
<td>00:19:21</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>00:23:20</td>
</tr>
<tr>
<td>3</td>
<td>109</td>
<td>00:25:21</td>
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<tr>
<td>4</td>
<td>108</td>
<td>00:30:21</td>
</tr>
<tr>
<td>5</td>
<td>106</td>
<td>00:31:32</td>
</tr>
<tr>
<td>6</td>
<td>106</td>
<td>00:26:11</td>
</tr>
<tr>
<td>7</td>
<td>106</td>
<td>00:28:25</td>
</tr>
<tr>
<td>8</td>
<td>106</td>
<td>00:21:20</td>
</tr>
<tr>
<td>9</td>
<td>109</td>
<td>00:15:25</td>
</tr>
<tr>
<td>10</td>
<td>110</td>
<td>00:23:25</td>
</tr>
</tbody>
</table>
Using the ttest, shows that the first group has a significant variation when they develop the task using PyDSLRep with a $t$ score = 11.336864645923933 > $cv = 1.330390943569909$. While the second shows a great improvement with a $t = 9.59277373982149 > cv = 8.434164477932882 \times 0.09$

**Third Environment**

The third testing scenario was not presented to the testing groups, this is because PyDSLRep only uses one line of code in the movements declaration to create the map, as it was explained in the Table. The map generated by PyDSLRep is presented in the Fig.

**Conclusions**

DSLs increase the level of abstraction and reduce development time by allowing to generate models and specific domain concepts, enabling developers to use clearer and simpler semantics to write code. This article presents the development and usage of a DSL called PyDSLRep, which enables semantic abstraction for navigation of robotic agents, saving the user from having to generate the dynamic and kinematic models of the robotic agent by applying clear grammar rules used in the specific domain of robotics and applying them to the integrated simulation development environment V-Rep.
Unlike other DSLs, PyDSLRep is not oriented to controlling a specific robotic platform. It also generates plain Python code that can be applied easily to a physical model.

The test performed in this article to validate the usability and effectiveness of PyDSLRep in navigational tasks were done with a total of 20 people who had prior knowledge of the Python programming language. However, only 10 users of this population had the knowledge to use the Python framework to establish communication with robotic agents in V-Rep, allowing the comparison of two groups.

The testing process had three stages. The first stage configured two testing environments with multiple robotic agents, which had to be controlled by using V-Rep’s Python framework. The second stage included the same two development environments, but the control of the agents was done using PyDSLRep. And the last stage was used to perform SLAM in a closed environment.

The results of the first two tests demonstrated that PyDSLRep simplifies the development of navigational routine generation for multiple agents, regardless of having prior experience with the V-REP platform. It reduced the average of generated lines of code by 76.40% and reduced the average development time by 45.22%. And the last test, shows that PyDSLRep could be used for SLAM task, only with a two wheeled differential robot.

Users were also required to connect with a remote host to emulate connection with a physical robotic agent. In this task, PyDSLRep enabled 80% of the users to connect successfully with the remote host, as compared to just 40% of users being able to connect successfully when using the Python framework.

For future work, PyDSLRep’s grammar will be expanded to control different mobile robots and actuators, such as robot arms or Ackerman style robots, and to be capable of reading LIDAR sensors, which would make it capable of generating 3D maps, expanding the language for direct controller generation in physical platforms.

Supporting information

S1 Dataset. Results from the two test groups. https://doi.org/10.6084/m9.figshare.11678085 (xlsx).

S1 Fig. Figures used in the paper. https://doi.org/10.6084/m9.figshare.11959308 (zip).


References

   URL http://dx.doi.org/10.1016/j.knosys.2015.12.004

   URL http://portal.acm.org/citation.cfm?doid=1118890.1118892


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