Proceedings of the ASME 2012 International Symposium On Flexible Automation
ISFA 2012
June 18-20, 2012, St. Louis, Missouri, USA

ISFA2012-7179

USARSIM/ROS: A COMBINED FRAMEWORK FOR ROBOTIC CONTROL AND SIMULATION

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ABSTRACT

The Robot Operating System (ROS) is steadily gaining popularity among robotics researchers as an open source framework for robot control. Additionally, the Unified System for Automation and Robot Simulation (USARSim) has already been used for many years by robotics researchers and developers as a validated framework for simulation. This paper presents a new ROS node that is designed to seamlessly interface between ROS and USARSim. It provides for automatic configuration of ROS transforms and topics to allow for full utilization of the simulated hardware. The design of the new node, as well as examples of its use for mobile robot and robotic arm control are presented.

INTRODUCTION

Robots have now become a part of many people's everyday lives. Whether as simple toys used by children, floor cleaning robots used in the home, or high precision industrial manipulators used in manufacturing, these systems are quickly changing the ways in which we play and work. One can no longer make the assumption that robots will exist in enclosed areas, or that the programmer or developer of the systems will be highly-skilled robotics experts. Indeed, new open source projects in robotic control systems such as the Robot Operating System (ROS)[1] [1] allow even novice users with a Linux platform to download and run some of the most advanced robotic algorithms. If the users desire a deeper knowledge of how these algorithms work, there is even a free robotics course from Stanford University that may be taken online.

However, one thing that many of these individuals are missing is robotic hardware. Simulators exist to fill this void and allow both experts and novices to experiment with robotic algorithms in a safe, low-cost environment. In order to truly provide valid simulation, the simulator must provide noise models for sensors and must be validated. One modern robotic simulator, known as the Unified System for Automation and Robot Simulation (USARSim) [2], provides such a simulation platform. This simulator has been used by the expert robotics community for several years and has played an important role in developing robotics applications. Its uses include rapid prototyping, debugging, and development of many tasks ranging from legged robots playing soccer [3] to urban search and rescue (USAR) [4, 5]. In fact, a search for the keyword "USARSim" on Google Scholar returns over 700 articles that have referenced the simulation platform.

A simulation environment enables researchers to focus on algorithm development without having to worry about the hardware aspects of the robots. Simulation can be an effective first step in the development and deployment of new algorithms and provides extensive testing opportunities without the risk of harming personnel or equipment. Major components of the robotic architecture (for example, advanced sensors) can be simulated and enable the developers to focus on the algorithms or components

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[1] Certain commercial software and tools are identified in this paper in order to explain our research. Such identification does not imply recommendation or endorsement by the authors, nor does it imply that the software tools identified are necessarily the best available for the purpose.

in which they are interested without the need to purchase expensive hardware. This can be advantageous when development teams are working in parallel or when experimenting with novel technological components that may not be fully implemented or available.

Simulation can also be used to provide access to environments that would normally not be available to the development team. Particular test scenarios can be run repeatedly, with the assurance that conditions are identical for each run. The environmental conditions, such as time of day, lighting, or weather, as well as the position and behavior of other entities in the world can be fully controlled. In terms of performance evaluation, it can truly provide an "apples-to-apples" comparison of different software running on identical hardware platforms in identical environments. Another important feature of a robotic simulator is easy integration of different robotic platforms, different scenarios, different objects in the scene, as well as support for multi-robot applications.

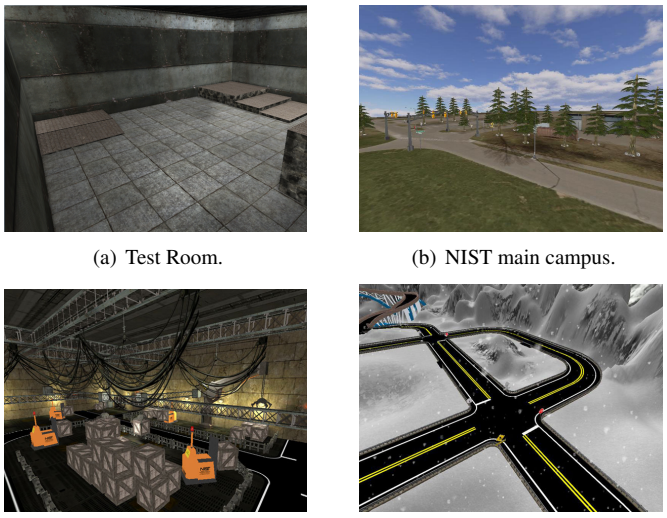
This paper examines a new interface that allows the ROS control framework to communicate directly with USARSim thus opening up sophisticated robot control and development to an entirely new audience. Novice robot developers can now work with world class algorithms from the safety of their computer without the expense of actual robotic hardware. This paper describes a ROS node that acts as an interface connecting the USARSim framework with the ROS framework. The following sections describe, analyze, and illustrate the new interface for the navigation of a mobile robot base, control of a robotic arm, and interface to existing sensors. In addition, a novel sensor interface is presented that allows the simulator to mimic a sensor processing system that produces the 6-degree-of-freedom pose for known objects.

BACKGROUND

In order to experiment with robotic systems, a researcher requires a controllable robotic platform, a control system that interfaces to the robotic system and provides behaviors for the robot to carry out, and an environment to operate in. This paper examines an open source (the game engine is free, but license restrictions do apply), freely available framework capable of fulfilling all of these requirements. This framework is composed of the USARSim framework that provides the robotic platform and environment, and the ROS framework that provides the control system.

The USARSim Framework

USARSim [4, 5] is a high-fidelity physics-based simulation system based on the Unreal Developers Kit (UDK) [6] from Epic Games. USARSim was originally developed under a National Science Foundation grant to study Robot, Agent, Person Teams in Urban Search and Rescue [7]. Since that time, it has been turned into a National Institute of Standards and Technology (NIST)-led, community-supported open source project that provides validated models of robots, sensors, and environments.



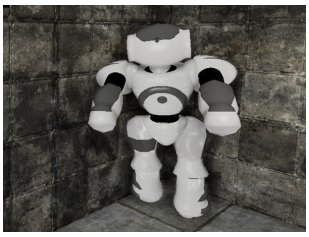
(a) Test Room. (b) NIST main campus.

(c) Factory, (d) Road course.

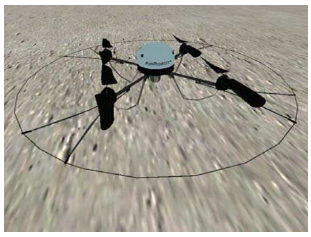
FIGURE 1. Sample of 3D environments in USARSim.

Through its usage of UDK, USARSim utilizes the physX physics engine [8] and high-quality 3D rendering facilities to create a realistic simulation environment that provides the embodiment of, and the environment for a robotic system. The current release of USARSim consists of various model environments, models of commercial and experimental robots, and sensor models. High fidelity at low cost is made possible by building the simulation on top of a game engine. By delegating simulation specific tasks to a high volume commercial platform (available for free to most users) which provides superior visual rendering and physical modeling, full user effort can be devoted to the robotics-specific tasks of modeling platforms, control systems, sensors, interface tools and environments. These tasks are in turn accelerated by the advanced editing and development tools integrated with the game engine. This leads to a virtuous spiral in which a wide range of platforms can be modeled with greater fidelity in a short period of time.

USARSim was originally based upon simulated environments in the USAR domain. Realistic disaster scenarios as well as robot test methods were created (Figure 1(a)). Since then, USARSim has been used worldwide and more environments have been developed for different purposes. Other environments such as the NIST campus (Figure 1(b)) and factories (Figure 1(c)) have been used to test the performance of algorithms in different efforts [9–11]. The simulation is also widely used for the RoboCup Virtual Robot Rescue Competition [12], the IEEE Virtual Manufacturing and Automation Challenge [13], and has been applied to the DARPA Urban Challenge (Figure 1(d)).

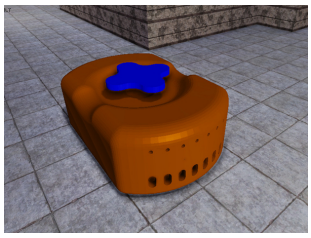


(a) Aldebaran Robotics Nao.



(b) Air Robot AR100B.

(c) Kuka KR60,



(d) Kiva Robot.

FIGURE 2. Sample of vehicles in USARSim.

USARSim was initially developed with a focus on differential drive wheeled robots. However, USARSim's open source framework has encouraged wide community interest and support that now allows USARSim to offer multiple robots, including humanoid robots (Figure 2(a)), aerial platforms (Figure 2(b)), robotic arms (Figure 2(c)), and commercial vehicles (Figure 2(d)). In USARSim, robots are based on physical computer aided design (CAD) models of the real robots and are implemented by specialization of specific existing classes. This structure allows for easier development of new platforms that model custom designs.

All robots in USARSim have a chassis, and may contain multiple wheels, sensors, and actuators. The robots are configurable (e.g. specify types of sensors/end effectors) through a configuration file that is read at run-time. The properties of the robots can also be configured, such as the battery life and the frequency of data transmission.

The ROS Framework

ROS [1] is an open source framework designed to provide an abstraction layer to complex robotic hardware and software configurations. It provides libraries and tools to help software developers create robot applications and has found wide use in both industry and academia. Examples of ROS applications include Willow Garage's Personal Robots Program [14] and the Stanford University STAIR project [15]. Developers of ROS code are encouraged to contribute their code back to the community and to provide documentation and maintenance of their algorithms.

ROS possesses a large range of tools and services that both users and developers alike can benefit from. The philosophical goals of ROS include an advanced set of criteria and can be summarized as: peer-to-peer, tools-based, multi-lingual, thin, and free and open-source [16]. Furthermore, debugging at all levels of the software is made possible with the full source code of ROS being publicly available. Thus, the main developers of a project can benefit from the community and vice-versa.

Nomenclature ROS uses the concept of nodes, messages, topics, services, stacks, and packages. These terms are used throughout the rest of the paper and are detailed below [16].

- Node: A process that performs computation. Nodes communicate with each other by passing messages.
- Message: A strictly typed data structure. A node sends a message by publishing it to a given topic.
- Topic: A communication channel between two or more nodes. A node that is interested in a certain kind of data will subscribe to the appropriate topic. There may be multiple concurrent publishers and subscribers for a single topic, and a single node may publish and/or subscribe to multiple topics.
- Service: A remote procedure call defined by a string name and a pair of strictly typed messages: one for the request and one for the response.
- Package: A compilation of nodes that can easily be compiled and ported to other computers. Packages are necessary to build a complete ROS-based robot control system.
- Stack: Packages in ROS are organized into ROS stacks which simplifies the process of code sharing.

THE USARSIM/ROS INTERFACE

USARSim is designed to communicate over an American Standard Code for Information Interchange (ASCII) Transmission Control Protocol/Internet Protocol (TCP/IP) socket with a host computer. The host computer initiates the socket interface and creates the desired robot in the simulated world that is currently running on the game server. A robot's configuration is controlled by an initialization file that resides on the simulation system's computer. This file controls such aspects as sensor configuration, battery life, and simulated noise models. Please see the USARSim wiki for more information on robot configuration [2]. One socket connection is established per simulated robot, with both commands and sensor data being transmitted over the socket. An additional separate socket is established for high-volume sensors such as camera systems.

ROS stacks are designed with their lowest-level node at a hardware abstraction layer that provides basic topics to and from the robot. For example, the mobility stack expects to control a platform by writing commands to low-level topics that control items such as platform velocities, and to receive feedback from sensors over other low-level topics. These stacks may also place constraints or naming conventions on the topics. In or-

Parameter	Default	Definition
robotType	P3AT	Type of robot to spawn.
hostname	localhost	Name of host running USARSim.
port	3000	TCP/IP Port on which USARSim listens.
startPosition	Vehicle1	Named location where robot should be spawned. This location is simulated world dependent.
odomSensor	InsTest	Odometry sensor that should be used as the default sensor for feeding the *odom* topic of ROS.

TABLE 1. Parameters for USARSim ROS node.

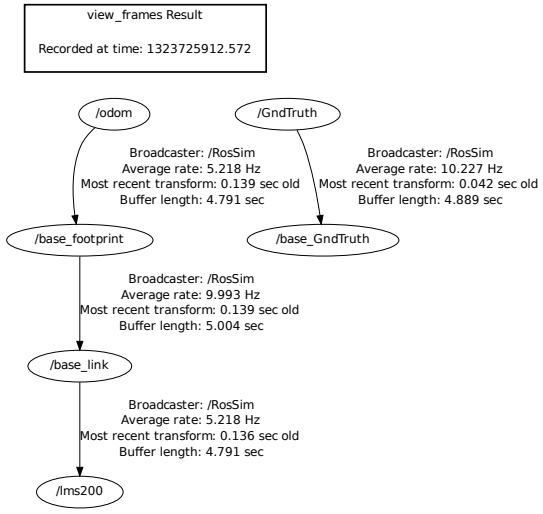


FIGURE 3. Auto-generated tf Transform tree for P3AT robot.

der to close this low-level loop between ROS and USARSim, a USARSim package was created. This package contains a node called *RosSim* that publishes a ROS transform tree (from the ROS *tf* package) and sensor messages, and also accepts platform and actuator motion commands. When run, it provides a mechanism for spawning a robot in USARSim, and then auto-discovering the robot's sensors, actuators, and drive configuration in order to provide the necessary ROS topics.

The *RosSim* node relies on several parameters for its configuration. These are detailed in Table 1, and provide information necessary for the creation of a robot in USARSim and a transform tree in ROS. A transform tree for the P3AT robot is shown in Figure 3. This transform tree is built automatically from data obtained from the USARSim geometry *geo* and configuration *conf* messages. Since USARSim supports more than one localization sensor on a robot, the *odomSensor* parameter is consulted to determine which sensor should be built into the tree. That sensor's name is automatically changed to *odom*. The *base_footprint*, representing the robot platform and the *base_link*, representing robot sensor mounting points, are also automatically generated. Additional localization sensors (e.g., the ground truth sensor for the P3AT robot) are provided with their own transform tree.

Vehicle movement commands into USARSim vary depending on the robot type. For example, skid-steered vehicles require left and right wheel velocities while Ackerman steered vehicles required steering angle and linear velocity. ROS provides a *cmd_vel* topic that includes both linear and angular velocities. The *RosSim* node automatically converts these velocities into the appropriate commands and values for the USARSim simulator based on the robots steering type, wheelbase, and wheel separation. Vehicle speeds are also clamped to not exceed maximum velocities that are set in the simulation.

Sensor Interface

ROS provides a rich vocabulary of sensor interface messages. The *RosSim* node strives to automatically match simulated sensors to the appropriate ROS topic. Currently, USARSim's inertial navigation, ground truth, and LADAR sensors are supported. These sensors automatically join the robot transform tree and publish their sensor messages at the rate that the *RosSim* node receives the sensor output. It is the intent of the authors to implement the full array of USARSim's sensors as time and resources permit.

The USARSim/ROS interface allows one to utilize known, published algorithms with simulated sensors and environments. However, the computational expense of the sensor processing must still be carried by the target hardware. One benefit of simulation is that one can not only simulate raw sensor output, but also the results from complex sensor processing tasks. One such example is the USARSim object recognition sensor. This sensor is simulated in much the same manner as a laser scanner. However, instead of reporting the range that each beam travels, the sensor accumulates the number of beam hits that occur on each detected object. The number of hits, along with the percentage of the object that is visible may then be used to determine the amount of noise to add to the objects position and recognized type. This information may then be sent over standard ROS topics, without incurring the overhead burden of running the actual object and pose recognition algorithms.

FIGURE 4. Pioneer 3-AT (P3AT) in USARSim.

Mobile Robot Control with the ROS Navigation Stack

Control of mobile robots through the USARSim/ROS interface is performed with the ROS navigation stack [17]. The navigation stack provides for 2D navigation and takes in information from odometry, sensor streams, and a goal pose while outputting safe velocity commands that are sent to a mobile base. The velocity commands are sent in the form of: x velocity, y velocity, and theta velocity. Better performance of the navigation stack can be achieved by meeting the following requirements:

- The robot has to use either differential drive or holonomic drive.
- A planar laser has to be mounted on the mobile base. This laser is used for map building and localization.
- The performance of the navigation stack will be best on robots that are nearly square or circular. It does work on robots of arbitrary shapes and sizes, but it may have difficulty with large rectangular robots in narrow spaces like doorways.

Although different models of mobile robot are developed in USARSim, the Pioneer 3-AT (P3AT) (Figure 4) appears to be a suitable candidate to use the navigation stack. The P3AT is a small square-shaped differential drive wheeled robot. As configured in our experiments, it includes a SICK Laser Measurement Sensor (LMS) 200 mounted on his base. The P3AT is also widely employed for research and prototyping applications involving mapping, navigation, monitoring, reconnaissance, vision, manipulation, cooperation, and other behaviors.

Low-level Navigation The USARSim/ROS interface allows the start-up and the control of the default P3AT base controllers by directly sending velocity commands to the base. This task was performed using the following commands:

1. Bring up an environment in USARSim.
2. $roscore
3. $roslaunch usarsim usarsim.launch
4. $rosrun teleop_twist_keyboard teleop_twist_keyboard.py
5. $rosrun gmapping slam_gmapping scan:=lms200 _odom_frame:=odom

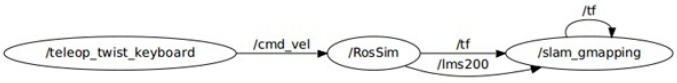
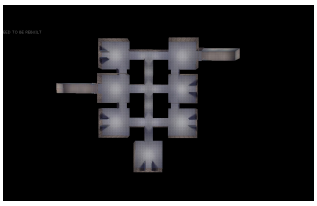
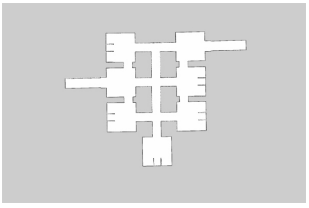


FIGURE 5. Mobile robot control using *teleop*



(a) USARSim environment.



(b) Map of the environment.

FIGURE 6. Environment in USARSim and the corresponding map.

In step 1, an environment is started on the server side (USARSim). If an environment is not up and running, passing messages between ROS and USARSim will fail. Step 2 starts *roscore*, a collection of nodes and programs that are a prerequisites of a ROS-based system for ROS nodes to communicate. Step 3 launches the *usarsim.launch* file. This launch file contains the parameters specified in Table 1 and starts the *RosSim* node that provides a connection between ROS and USARSim. Step 4 starts the *teleop_twist_keyboard* node which sends velocity commands to the *RosSim* node through the computer keyboard. At this point, the P3AT can be controlled by keyboard teleop in the USARSim environment. Step 5 starts the node *slam_gmapping* which transforms each incoming scan from the laser into the odometry tf frame to build a map. Here, the topic *scan* is used to create the map with the parameter *_odom_frame*, the frame attached to the odometry system.

Figure 5 is a graph generated by rxgraph with the option "quiet". The graph illustrates the communication between the nodes *RosSim*, *teleop_twist_keyboard*, and *slam_gmapping*. The keyboard inputs are converted in velocity commands and then communicated to the *RosSim* node on the topic *cmd_vel*. *slam_gmapping* uses the topics (*lms200*) and (*tf*) as inputs to build the map. To save the generated map, the following command is used:

$rosrun map_server map_saver

The generated map is stored in pair of files: a YAML file (YAML is recursively defined as "YAML Ain't Markup Language") which describes the map meta-data and the image file that encodes the occupancy data. Figure 6(a) is a bird's eye view of the environment used to run the teleop command on the P3AT and Figure 6(b) is the map generated by the *map_saver* utility-command.

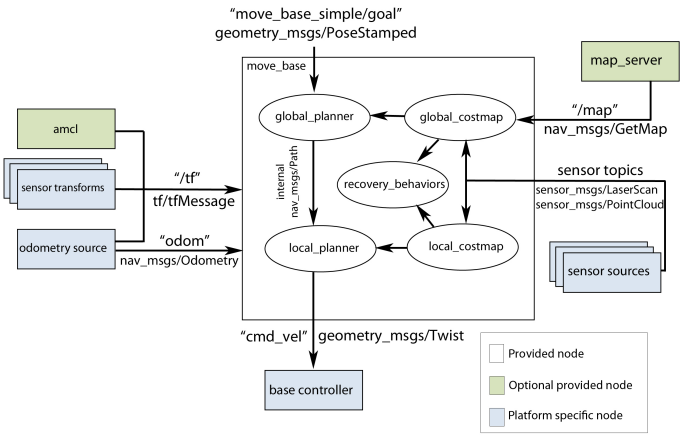


FIGURE 7. Navigation stack setup using *move_base*

High-level Navigation The USARSim/ROS interface also provides high-level navigation through the navigation stack. At this level, goals are sent to the P3AT to move to a particular location in the environment. High-level navigation is possible with the action specification for *move_base*. This package provides an implementation of an action (*actionlib*) that, given a goal in the world, will attempt to reach it with a mobile base. The *move_base* node provides a ROS interface for configuring, running, and interacting with the navigation stack on a robot. The *move_base* node links together a global and local planner to accomplish its global navigation task.

Figure 7 (taken from [18]) depicts a high-level view of the *move_base* node and its interaction with other components of the navigation stack. The white components are required components, the green components are optional components, and the blue components must be created for each robot platform. The white and green components are already implemented. For the navigation stack to work properly for the P3AT, the nodes and topics generated should match the configuration of the *move_base* node with the navigation stack.

Before running the *move_base* node on the P3AT, localization, mapping, and navigation information are filled in the *move_base.launch* file:

- Localization uses map, laser data, and odometry to situate the robot in relation to the environment. The *amcl* and the *map_server* nodes are necessary for robot localization. *amcl* is a probabilistic localization system for a robot moving in 2D and implements the KLD-sampling [19]. The *amcl* node is launched from the examples directory of the amcl package.
- The *map_server* node uses an *a priori* map generated by the *map_saver* command-line utility. The example described in this paper uses the map depicted in Figure 6(b) and its corresponding YAML file.

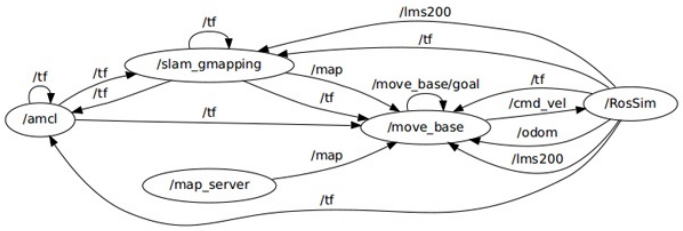


FIGURE 8. Mobile robot control with *move_base*.

- The navigation stack uses cost-maps files (YAML files) to store information about obstacles in the world:
  - A global cost-map for creating long-term plans.
  - A local cost-map for local planning and obstacle avoidance.
  - A common cost-map file which stores configuration options used by the global and local cost-maps.
- The navigation stack uses a base local planner to compute velocity commands to send to the robot. Information on the base local planner is stored in a YAML file which sets configuration options based on the specs of the robot.

Once the *move_base.launch* file is set up with the appropriate configuration options, the *move_base* node is run with the following command:

```
$roslaunch move_base.launch
```

To send commands to the P3AT, the package *simple_navigation_goals* was created (based on [20]). The new package mainly includes the action specification for *move_base*, an action client used to communicate with the action named *move_base* that adheres to the MoveBaseAction interface, and a goal to send to *move_base*. Sending commands through the code to the P3AT is performed by starting the executable for the *simple_navigation_goals* package:

```
$./bin/simple_navigation_goals
```

Figure 8 is a graph generated by rxgraph with the option "quiet". The graph depicts the nodes and topics involved while sending a goal to the navigation stack to move the P3AT. A parallel comparison of this graph with the navigation stack setup diagram (Figure 7) reveals that the blue components have been implemented and the grey components were properly used. The node *move_base* receives messages on the topic *tf* from the nodes *amcl*, *RosSim*, and *slam_mapping*. *RosSim* publishes Odometry (*odom*) and sensor information (*lms200*) to *move_base*. The optional node *map_server* publishes the topic *map* to *move_base*. Incoming messages are interpreted by *move_base* which outputs

velocity commands on the topic *cmd_vel* to be sent to the node *RosSim*.

Robotic Arm Interface

Although not as complete as the navigation interface, an interface has also been developed to allow for the use of the ROS arm_navigation [21] stack. The *RosSim* node once again strives to allow for auto-discovery of the robot and thus eliminate the need for hand-generated configuration files. In the case of the arm_navigation stack, a Unified Robot Description Format (URDF) file that describes the arm must be created as well as various launch files.

Under USARSim, a robotic arm is composed of individual static meshes that are attached to one another via links known as *actuators*. Each actuator has its own coordinate frame. Figure 9 depicts a Kuka KR60 robot that has been modeled in USARSim. The position and orientation of each actuator's coordinate frame is controlled by convention. Actuators must rotate (rotatory joints) or expand/contract (prismatic joints) about the z-axis. The x-axis must point towards the next joint in the kinematic chain. The location of the axis origin is constrained such that rotation/expansion occurs around $z = 0$ and the x-axis passes through the origin of the next frame in the kinematic chain. The *RosSim* node automatically builds the transform tree for the various actuator coordinate frames by reading the USARSim *Conf* and *Geo* messages. The transform tree for the KR60 robot is depicted in Figure 10. This transform is published and made available to any other ROS node.

When a new robotic arm is used for the first time, the *usar_urdf* node of the *USARSim* ROS package must be run. This node accepts the same parameters shown in Table 1 in order to determine the robot to be created and then performs the following actions:

1. The node creates the robot model inside the simulated world in order to be able to read the USARSim *Conf* and *Geo* messages.
2. From these messages, the node composes the transform tree with a transform for each joint in the robotic arm. Information on maximum and minimum rotations of joints and maximum joint velocities and torques is also maintained.
3. The node auto-generates an URDF file that contains all of the joint and link information that defines the robot arm. Rather than exact depictions of the robot's visual form, the URDF file contains simple cylinders to represent each link.

This URDF file may now be utilized by the arm_naviation's *Planning Description Configuration Wizard* in order to generate a stack that contains specific launch files that will be used in arm planning.

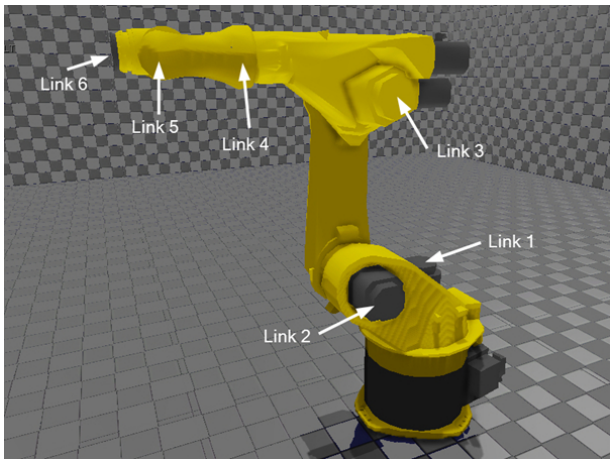


FIGURE 9. Location of joint axes in USARSim model of Kuka KR60 6 degree-of-freedom robot arm as depicted in USARSim.

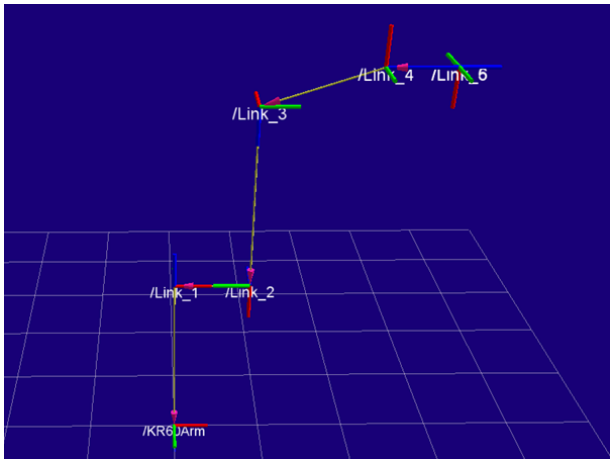


FIGURE 10. Depiction of joint axes from TF topic in ROS for 6 degree-of-freedom Kuka KR60 robot arm.

CONCLUSION AND FUTURE WORK

This paper has presented a new ROS package that allows for the seamless interface of USARSim with ROS. The package provides for auto-discovery of robots and sensors, and produces the standard ROS topics that one would expect from a physical platform. Further work is still required to auto-generate ROS launch files for running standard motion control algorithms for both platform and arm control. In addition, additional sensors must have their USARSim interfaces wrapped to be supported in the ROS environment.

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