Validation of Simulated Robots with Realistically Modeled Dimensions and Mass in USARSim

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Abstract — In the case of simulators of mobile robots, it is necessary to clarify the similarity between actual and simulated robots in order to improve the efficiency and transparency of simulators as research tools. Because of its real-time performance, USARSim [1] has been popularly used in studies involving human-robot interactions. However, since USARSim uses approximations and abbreviations in its physical computations, there are some doubts over its computational accuracy.

The objective of this study is to compare the actual and simulated robots in order to investigate whether the simulated environments can be used as a training tool. The authors modeled two types of response robots -IRS Soryu [2] and Kenaf [3]- and compared the abilities of the simulated robots and the actual robots in navigating obstacles such as steps and trenches. The dimensions such as heights, widths and lengths and total mass of the real robots were accurately modeled in the simulation and the other physical parameters were assigned default values. It was observed that the maximum error in the sizes of the traversable objects was 18% of the body length of the robot. It was also found out that the angular velocities of the robots were significantly different for the real and simulated robots.

The conclusion is that a training system can be built based on USARSim when the simulated environments involve simple obstacles because there are not significant discrepancies between the basic traversing abilities of the actual robots and those of the simulated robots. However, in terms of the dynamic motions of the robots the operators need further trainings using the real robots.

Keywords: USARSim, IRS Soryu, Kenaf, Response Robot, Rescue Robot

I. INTRODUCTION

3D simulators play an important role in the development and training of mobile robots. In particular, simulators serve as good tools for training first responders in the teleoperation of response robots used in disaster management. First responders can practice maneuvering the robots in various virtual disaster environments rather than in actual environments, which reduces the risk as well as the cost of testing.

The authors have employed the USARSim, which is a 3D simulator, for training operators who conduct search and rescue tasks in confined spaces such as underground cities during NBC terrorism activities or during natural disasters.

A. Research Objectives

This study investigates the performance of USARSim in simulating response robots in order to test its efficiency and transparency as a research and training tool. We compare the traversing abilities of real robots and simulated robots that have the same dimensions and mass as the actual robots. With regard to the traversing abilities, the sizes of the obstacles that are traversed rather than the dynamics of the robots are compared.

There are three major reasons why the dimensions and total mass of the simulated robots are accurately modeled and the physical parameters are not. First, the authors have assumed that the ability of the response robots to traverse around simple obstacles significantly depends on the dimensions and mass of the robots. Hence, by using the simulated robots with accurately modeled dimensions and mass, we can determine the capabilities of the actual robots. Second, measuring the physical parameters of the real robots takes time and also is high in cost. Finally, the approximations and abbreviations of the physical computations in USARSim are significant. Some physical parameters such as kinetic friction and static friction coefficients are not configurable. Even if the configurable parameters are accurately reproduced in the simulator, the dynamic interactions between the robots and the virtual environments are not expected to match those of the real robots in an actual environment.

B. USARSim and Related Studies about Validation

USARSim is used as a 3D simulator in this study. A 3D simulator was chosen on the basis of its applications. The simulators with high physical fidelity and small time steps of computation are qualitatively different from real-time simulators, which can handle multiple robots and large areas simultaneously. Real-time simulators are suitable for the training tools. There exist several 3D simulators for robots such as Open Dynamics Engine and Microsoft Robotic Studio [4]. In order to impart effective training in the teleoperation of the response robots it is necessary for the simulator to have real-time abilities, high-quality images, easy handling of multiple robots, easily developable large environments, and extended connections to other software, if required. USARSim satisfies all these conditions. In addition, USARSim has also been utilized in the RoboCup Rescue Virtual Robots Competition [5] and it has been used in several studies on mobile robots.

The biggest concern about USARSim is its computation accuracy. This is because it uses approximations of the physical computations to maintain real-time performance and because of its nondisclosure of proprietary parts of the physics engine. It is necessary to validate both the simulated robot models and
the physical accuracy of the simulator in order to ensure its reliability as a training and research tool.

Several researches have validated the computation accuracy of USARSim. Carpin et al. evaluated the images provided by the simulator by taking into account the distance of the robot from the target objects and the lighting conditions [6]. Wang et al. compared the consistency in the performances of real and simulated range finders [7].

USARSim has also been validated in HRI (human-robot interaction) researches. For example, it was experimentally confirmed that the metrics of HRI such as the task duration and the number of command inputs were almost identical in tasks performed by operators with real and those performed with simulated robots in similar environments built in the simulator [6–8]. Thus, these studies validated the use of USARSim for HRI researches as well as the accuracy of the simulated sensors.

Simulated robots have been tested in some previous studies. Greggio et al. modeled a humanoid in USARSim and compared its performance with that of a real robot with respect to some features such as walking trajectories [9]. One of the methods to ensure that the behavior of simulated robots resembles that of the real robots, is tuning of the physical parameters of the simulated robots by repeated tests and constant observation of the behaviors of the robots [10][11].

In the above mentioned studies, the researchers designed the simulated robots by tuning the parameters, and they also presented discussion on the similarities between the real and simulated robots.

This study focuses on how similar the traversing abilities of simulated robots are to those of real robots when the simulated robots have been modeled by ignoring the physical parameters but ensuring that both of the dimensions and the total mass are equal to those of the actual robots. Hence, this study is different from the other related studies, although the authors have the same motivation as in the previous studies in validating USARSim and utilizing it for HRI studies and in teleoperation training.

Currently most robots realized in USARSim are modeled with the correct dimensions; however, the other physical parameters are likely to have some default values. This may be because many researchers have utilized USARSim for HRI studies and not for studying the dynamics of robots. In the case of these robots, it is helpful to clarify the similarities and discrepancies between the real robots and simulated robots that have the same dimensions and total mass as the real robots.

C. Evaluation Methods

Common metrics for mobile robots include the performance measurements for navigation tasks, perception of environments and the states of robots, managements of multiple robots, and so on [12]. The test arenas of NIST evaluate the integrated abilities of the operators along with those of the robots based on the number of the searched victims and the accuracy of the reported positions of the victims and so on [5][13]. However, the aim of this study is to evaluate the traversing abilities of the robots. The metrics from the Response Robots Pocket Guide [14] are suitable for this study. The guide proposes for instance, random step fields, stairs, slopes, and steps as metrics of traversing abilities of the robots.

The authors evaluate the traversing abilities for possible obstacles in underground cities. In the event of an NBC terrorism attack on an underground city, stairs and sign boards are considered to be step-like obstacles, while drains behave as trench-like obstacles. Therefore, the authors measure the traversing abilities of the robots for steps and trenches. It is difficult to simulate piles of rubble or fragile ground in USARSim and hence the authors have assumed that the environment does not include them.

II. ROBOT MODELS IN USARSim

The authors have simulated two types of response robots, IRS Soryu[2] and Kenai[3], and compared them with the actual robots. Both robots are highly adaptable and can transform their mechanisms to surmount obstacles that have a greater height than them. It is necessary for operators to undergo training in overcoming obstacles while manually operating these robots as they possess many actuated joints.

A. Physics Engine of USARSim

A physics engine called Karma is installed on USARSim. In the simulator, physical computations are performed for objects designated as Karma objects. The other objects are referred to as static objects, i.e., objects which do not move. Physical phenomena such as collisions, inertia, and rotation are computed for Karma objects. Mechanical impedances between the Karma objects are also taken into consideration during the computations. The configurable physical parameters are mass, the spring coefficient, the viscosity between two connected objects, the restitution coefficient, the inertia tensor, the center of mass, etc. In USARSim, mass is treated as a concentrated load. Details on how the parameters are computed in the engine are not provided. However, according to the experienced model creators, the friction parameter known as KFriction needs to be carefully tuned [10][11]. KFriction is a kind of the friction coefficients and considered to serve as the static and kinetic friction coefficients. Two types of friction parameters are applied to tires in USARSim. They are named TireRollFriction and TireLateralFriction and they are friction parameters for rolling direction and lateral direction of the tires respectively.

In the real robots used in this study, in order to increase the traction between the tracks and the ground, tread lugs are crafted on to the belts of the two robots as shown in figs. 1 and 4. The authors have used a sufficiently high value of KFriction in order to ensure that the tires of the robots do not slip. The other physical parameters are not specifically designed and use default values. It should be noted that the most practical method to design other physical parameters is to tune the parameters by repeated tests and constant observation of the behaviors of the robots in USARSim [9][11].
B. IRS Soryu and Simulated IRS Soryu

1) IRS Soryu: IRS Soryu is a serpentine robot that is used for search and rescue at narrow spaces, as shown in fig. 1. The robot consists of three cars. Each car has a motor and two tracks, one each on its left and right side. The cars are connected by two axially connected actuated joints. By controlling the positions of the three cars, the robot can surmount the objects that are higher than it.

The dimensions of the IRS Soryu are 1210 mm × 122 mm (height) × 145 mm (width), and its weight is 10 kg. It is battery-powered. The robot has a tether for communicating with the operator and providing high-quality camera images. Its maximum speed is 370 mm/s, the maximum step height that it can ascend is 483 mm, the maximal trench width of crossing is 590 mm, and the minimum turning radius is 410 mm.

2) Simulated IRS Soryu: Fig. 2 shows an IRS Soryu simulated in USARSim. It has the same dimensions and total mass as the actual robot. The front and rear cars are 3 kg each and the center car is 4 kg. The centers of mass are located in the center of each car. The joints between the cars are modeled as two axial hinges. Their maximal angles are ±π/4. The maximal speed is 370 mm/s, which is the same as that of the real robot.

USARSim does not have a virtual equivalent of the rubber belt. Therefore, in USARSim, instead of the belt, a tire array is employed as a belt. Hence, the simulated IRS Soryu also has tracks comprising an array of two large tires and eight small tires, as shown in fig. 3. The small tires in the array do not interfere with each other. The angular velocities of the large and small tires are adjusted so that the equation

\[ d_1 \theta_1 = d_2 \theta_2 \]

is equalized. In (1), \( d_1, d_2 \) are the diameters, and \( \theta_1, \theta_2 \) are the angular velocities of the large and small tires, respectively. These belt-like arrays of tires are implemented by creating track objects from a Track class, which is a built-in class of USARSim. The friction parameters of the tires are \((\text{TireRollFriction}, \text{TireLateralFriction}) = (1.3, 1.0)\) for enhancing the traction. These parameters are much smaller than those of the simulated IRS Soryu. This is because in case of the simulated Kenaf with friction parameters higher than those set above, apparently unreal behaviors are observed.

C. Kenaf and Simulated Kenaf

1) Kenaf: Kenaf is a response robot, shown in fig. 4, which is designed to function in confined spaces such as underground cities. Its entire torso is covered with two independently driven tracks that prevents it from being stuck on obstacles. Four independent flipper arms are installed on it, and rolling them enables it to overcome the obstacles. Kenaf won the mobility challenge in the Rescue Robots 2007 league. It is battery powered and does not have tethers.

Kenaf is 20 kg and the dimensions are 570 mm × 180 mm (height) × 430 mm (width). The traversing abilities of Kenaf are tested in the next section.

2) Simulated Kenaf: Fig. 5 illustrates Kenaf as simulated in USARSim. The tracks are emulated as tire arrays. The flipper arms are implemented using the Track class used in the case of the simulated IRS Soryu. In order to emulate the tracks of Kenaf, which cover the entire body, the tires are arranged on the body, as depicted in fig. 6. The spaces between the large tires are filled with small tires for imitating the mechanism of the tracks that exert distributed driving forces. The dimensions and the total mass of the simulated Kenaf are the same as those of the real Kenaf. Fig. 6 shows the dimensions of each part. The center of mass was located 15 mm behind the center of the torso, similar to the real Kenaf. The friction parameters of the tires are configured as \((\text{TireRollFriction}, \text{TireLateralFriction}) = (1.3, 1.0)\) for enhancing the traction. These parameters are much smaller than those of the simulated IRS Soryu. This is because in case of the simulated Kenaf with friction parameters higher than those set above, apparently unreal behaviors are observed.

III. EVALUATION EXPERIMENT

In this section, the authors compare the traversing abilities of the actual robots with those of the simulated robots. The metrics of the abilities are the maximal step heights and trench widths that can be overcome by the robots. Figs. 7 and 8 schematically illustrate the robot traversing a step and a trench, respectively. In addition, in the case of IRS Soryu,
the minimum turning radii of the simulated and real robots are also compared. In the case of Kenaf, the positions and postures of the real robot are sensed by a motion capture camera and they are compared with those of the simulated robot.

A. Evaluation of Simulated IRS Soryu

In order to investigate the performance of the simulated IRS Soryu, three experienced participants were asked to take part in the experiments. They were asked to operate the robot and make it ascend steps with heights ranging from 425–500 mm and cross trenches with widths ranging from 550–625 mm. Trials for each obstacle were repeated five times. The simulated robot was placed to face the obstacles. The operators operated the robots using a bird’s-eye view and were allowed to change their viewpoints during the experiment.

Table I shows the success rates of the experiments. In the case of the simulated IRS Soryu, the maximal height of the ascendable step was 475 mm. In the experiments that required navigation of steps, all the participants showed similar success rates. This was attributed to the fact that the obstacle was simple and the differences in operating skills had no impact on the results. Also, there was no time limit set for the trials, and the participants could keep on making attempts until the robot successfully climbed the steps. Therefore, no disparity was observed in the success rates.

On the other hand, in the experiments that involved trenches, there was a disparity in the success rates with respect to the trenches that were 600 mm in width. Participant C was not able to complete the crossing. After all the trials were complete, the authors trained him to cross the trenches, and he succeeded in clearing the 600-mm wide trench. The disparity in the success rates was expected to have occurred because of the differences in the abilities of the operators. The authors consider that the simulated IRS Soryu is fully capable of crossing a 600-mm wide trench.

The turning radius of the simulated robot was measured by the following method. When the pitch angles and yaw angles of the two joints between the three cars were maximally bent, only one of the two tracks of each of the cars was in contact with the ground. With this stance, the simulated robot was able to turn in a very tight circle. The smallest radius of the circle drawn from the center of mass was 409 mm. This value was not affected by the speed of turning when the speed was between 46–137.5 mm/s. However, for the speeds above 150 mm/s, the trajectories were shaky and not smooth and it was difficult to regard them as circles.

Table II summarizes the navigation performances of the real and simulated IRS Soryu robots. The maximal heights of the steps ascended by the real and simulated robots were 483 and 475 mm, respectively. The difference between these two values was 8 mm, which was smaller than the interval of the tested steps, which was 25 mm. The maximal trench widths crossed by the real and simulated robots were 590 and 600 mm, respectively. These two values were also within the interval of the tested trenches, which was also 25 mm. The minimal turning radius of the simulated IRS Soryu was 409 mm. The value was close to 410 mm which was the minimal turning radius of the actual robot.

B. Evaluation of Simulated Kenaf

In order to analyze the abilities of the real and simulated Kenaf robot, an experienced operator manually operated the robots and surmounted the obstacles. The heights of the tested steps were 50–350 mm, and the widths of the trenches were 100–400 mm. Two different conditions were used during the ascension of the steps. The first was the condition in which the operator did not activate the flipper arms and the robot traveled forward at a speed of 100 mm/s. The other was the condition in which the operator activated the flipper arms to climb steps. In the case where the operator did not use the flippers, they were kept perpendicular along the Yaw axis. Both conditions are illustrated in figs. 9 and 10. In crossing the trenches, the flipper arms were not utilized and the robot was driven at 100 mm/s. Each experimental condition was attempted only once. The participant had a bird’s-eye view during the operation of the real and simulated robots.
The experimental results are summarized in Table III. The table shows the success or failure of each trial. Both the real and simulated Kenaf robots could ascend steps with a maximum height of 100 mm when their flipper arms were not utilized. On the other hand, when the arms were activated, the maximum height of the steps ascended by the two Kenaf robots was 300 mm. In the experiment with the trenches, the simulated Kenaf was able to cross a trench with width of 350 mm, while the real Kenaf was unable to do so. This caused a disparity in the results. The authors now explain the reason for this disparity.

Successive pictures of the real and simulated Kenaf robots in motion when they were crossing a trench with a width of 350 mm at a velocity of 100 mm/s are shown in Fig. 11. From the second and the last two pictures, it can be observed that the real Kenaf could not cross the trench and fell down. In contrast, the simulated Kenaf did not fall down and successfully crossed the trench. The pitching motion of the simulated Kenaf was observed to be less than that of the real Kenaf. In particular, the angular velocity of the simulated Kenaf along its pitch axis was much less than that of the real robot when the front part of the simulated robot fell to the ground.

Fig. 12 shows the change in the pitch angles of the real and simulated robots when both the robots climbed 100-mm-high steps with the flipper arms in a perpendicular position. In the figure, the pitch angles increased as the robots came in contact with the step and then climbed over it. The transition of the pitch angle of the real Kenaf was relatively smooth whereas that of the simulated Kenaf showed a zigzag motion. The authors observed the videos and assumed that this behavior of the pitch angles was because the lugs among the tires forming the tracks of the simulated robot got stuck on the edge of the steps. As a result, the pitch angle of the simulated Kenaf took longer to reach its maximum value than the actual Kenaf. After reaching the maximum value, the pitch angle of the actual Kenaf dropped sharply to 0° because the torso of the car that was inclined in the air landed on the ground. The pitch angle of the simulated Kenaf also reduced to 0° after reaching its maximal value. However, the inclination of the simulated Kenaf took 3.95 s to return to 0°. This was much longer than the 0.44 s taken by the actual Kenaf. Therefore, during the free-fall of the robots, the transitions in the pitch angles were significantly different for the real and simulated Kenaf robots. The same trend was observed in the case of a step with a height of 50 mm. Table IV shows the comparison between the real and simulated Kenaf robots about the periods when the inclined torso was in free fall and the difference between
the maximal pitch angles during the ascension of the steps.

The trajectories of the robots on the x-z plane when the robots climbed a 100-mm-high step are shown in Fig. 13. It was observed that the trajectory of the real Kenaf was smooth, while that of the simulated Kenaf was in a zigzag form because of the same reason described above. The maximal disparity between the two trajectories along the z axis was 29.0 mm.

C. Conclusion of Experiments

The authors compared the maximal heights of the steps that could be ascended and the maximal widths of the trenches that could be crossed by real and simulated IRIS Soryu and Kenaf. The difference in the sizes of the obstacles that could be navigated by the real and simulated robots was maximally 100 mm, which was 18% of the dimensions of the Kenaf. The authors also observed that with respect to the pitch angle of the robots, the time taken for the inclination to return to $0^\circ$ included an relative error of 800%.

The authors suggest that the ability of the robots to traverse simple obstacles depended on the dimensions and structures of the robots. Hence, the sizes of the mountable obstacles were similar for both the real and simulated robots. However, a comparison of the behaviors of the real and simulated robots along the temporal axis revealed significant diversities. Therefore, as expected, the dynamics of the actual and simulated robots were not similar. This situation can be improved by adjusting the inertia tensors or the locations of the distributed mass.

IV. CONCLUSION

The authors developed two types of robots in USARSim and compared their traversing abilities with those of the actual robots. The simulated robots were developed with dimensions and total masses that were equivalent to those of the actual robots. Their performances were tested in traversing obstacles such as steps and trenches. As a result of test, the simulated robots with realistically modeled dimensions and total mass in USARSim exhibited a performance similar to that of the real robots. The results indicate that the simulated robots can be used for training for the environments with simple obstacles.

ACKNOWLEDGEMENT

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REFERENCES


TABLE III
RESULTS OF THE EXPERIMENTS IN NAVIGATION OF OBSTACLES BY REAL AND SIMULATED KENAF: S AND F STAND FOR SUCCESS AND FAILURE, RESPECTIVELY.

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<td>50 100 150</td>
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TABLE IV

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