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Real-time Simulation of Non-Deformable Continuous Tracks with Explicit Consideration of Friction and Grouser Geometry

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Abstract—**In this study, we developed a real-time simulation method for non-deformable continuous tracks having grousers for rough terrain by explicitly considering the collision and friction between the tracks and the ground. In the proposed simulation method, an arbitrary trajectory of a track is represented with multiple linear and circular segments, each of which is a link connected to a robot body. The proposed method sets velocity constraints between each segment link and the robot body, to simulate the track rotation around the body. To maintain the shape of a track, it also restores the positions of the segment links when required. Experimental comparisons with other existing real-time simulation methods demonstrated that while the proposed method considered the grousers and the friction with the ground, it was comparable to them in terms of the computational speed. Experimental comparison of the simulations based on the proposed method and a physical robot exhibited that the former was comparable to the precise motion of the robot on rough or uneven terrain.**

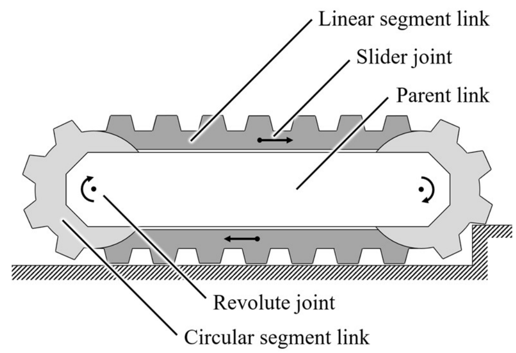

Figure 1. Design of the proposed method.

I. INTRODUCTION

Tracked vehicles have widespread usage and are expected to be employed in search-and-rescue operations, plant inspections, construction activities, and military missions, which require high mobility on rough terrain [1].

Developing a tracked vehicle involves training its operators or populating the motion data for machine learning and conducting extensive trails on rough terrain. However, it is nearly unfeasible to establish physical experimental test environments that cover all the possible scenarios a robot will encounter in practical missions. In addition, a robot developer or trainee has to risk accidental breaking of the robot in its physical tests.

Thus, performing simulation experiments is important because it allows for assessing a robot prior to conducting physical tests or complements the physical tests that can potentially damage the robot. Hence, the motion of a tracked vehicle on rough terrain must be simulated with a high degree of accuracy. In addition, the simulation should be conducted in real time if it is used to train the operators.

Realistic simulation of the movement of a tracked vehicle on rough terrain is based on the interaction between the continuous tracks (including the grousers) and the surface/ground. This interaction is characterized by (1) collision detection based on the precise geometries of the tracks and ground to generate the contact points, (2) constraints, including the friction at the contact points, and (3) the deformation of the tracks, which may be caused by (1) and (2). For non-deformable tracks that are constrained to follow a fixed trajectory with respect to the robot body, (1) and (2) are key to realizing realistic simulations, instead of (3).

In this study, we developed a real-time simulation method for non-deformable tracks with grousers on rough terrain based on the collision and friction between the tracks and the ground. A track for which the proposed method is developed is illustrated in Fig. 1. In the method, an arbitrary trajectory of a track is represented with multiple linear and circular segments, where each trajectory segment is a link consisting of a flat belt and arbitrary-shaped grousers. The proposed method was so designed for the real-time simulation because it required a few links and joints. In the method, velocity constraints were set between the track and the robot body to represent the track rotation around the robot body. However, the constraints between the track and the ground were not modified in the proposed method. Instead, these were deferred to the physics engine in the simulator such that the collisions and the friction between them were explicitly considered by an appropriate model in the physics engine.

The remainder of this paper is organized as follows: Sec. II introduces the related work on the real-time simulation of tracked vehicles. Sec. III provides a detailed description of the proposed method, including its qualitative comparison to other related methods. Sec. IV presents the evaluation of the proposed method by its quantitative comparison to other related methods and to the real-life motion of a physical robot. Sec. V summarizes the conclusions and suggests some applications of the method.

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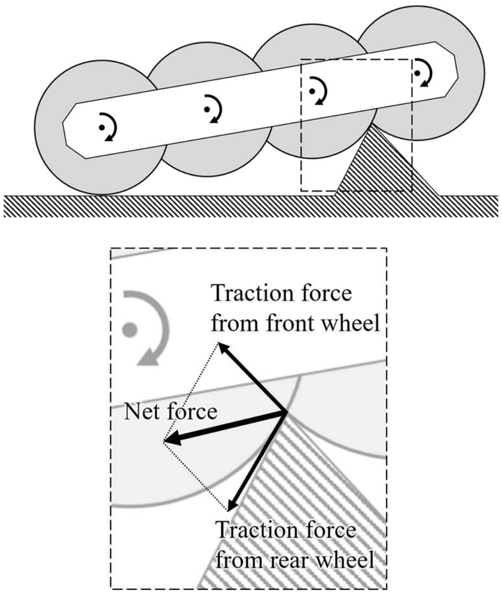


Figure 2. Multiple-wheel simulation

II. Related Work

A. Multiple-Wheel Simulations

Simulation methods in which multiple wheels are aligned along a track trajectory, as depicted in the upper part of Fig. 2, are widely used because they only require cylindrical links and revolute joints, which all robot simulators support by default [2]. Because a track is assumed to be comparable to a set of wheels, the simulation of the collision and friction between a track and the ground in physics engines is similar to that of general wheels.

The drawback of a multiple-wheel method is that real-time simulations have to be conducted using fewer wheels (e.g., links and joints) than required to ensure a low computational cost. This impacts the accuracy, because the trajectory of the simulated track is altered along straight segments and may yield erroneous results for rough terrain. For example, when both the adjacent wheels contact a bump on the ground, the traction forces from these wheels act on the bump in the upper and lower directions, respectively, as displayed in the lower part of Fig. 2. This generates a low driving net force, propelling the robot forward, so that it cannot climb over the bump, which is not the case with real tracks.

Another drawback is consideration of grousers. An inaccurate trajectory of a track can also result in an incorrect geometry of the grousers. Using relatively larger number of wheels improves these drawbacks and increases the simulation accuracy but also makes the simulation more expensive.

B. Multiple-Plate Simulations

Simulation methods involving a closed loop consisting of thin short plate links and hinge joints connecting adjacent links are also known [3–5]. Such methods precisely model tracks with grousers and consider the effect of the friction and collision with the ground as well as the deformation of the tracks.

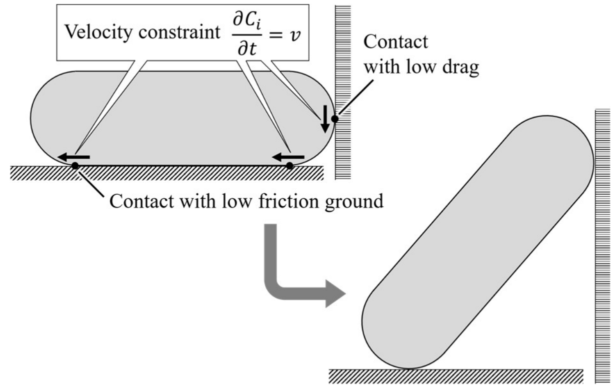


Figure 3. Constraint-to-ground simulation

However, realizing the accurate behavior of a track using this method in real time is challenging, as reported in [6], because of the high computational cost required to handle the numerous plate links and hinge joints in the simulated track. Moreover, the parameter tuning is also complex, including that of the inertial parameter of the links, dynamic parameters (e.g., rotational friction and damping coefficient) of the hinge joints, and horizontal tension that acts on the simulated track, as reported in [4–6].

C. Simulation with Velocity Constraints Applied to the Ground

This simulation method is for non-deformable tracks without grousers involving modification of the velocity constraints applied to the ground [6]. Simulations can be conducted over a shorter time than those of other methods, because this method represents an entire track as a single link. The effect of track rotation around the robot body is achieved by changing the velocity constraints on the contact points between the track and the ground according to the desired rotational velocity of the track. This is performed instead of rotating the track with respect to the robot body.

The above-mentioned method is an innovative approach for real-time simulation; however, it does not consider the friction with the ground because the original velocity constraints set using the friction model of the physics engine are modified. This may also result in the model presenting scenarios that are impossible in reality, such as those shown in Fig. 3. The above method presents a scenario where a track can start climbing a vertical wall even if the track contacts the wall with low drag and the ground with low friction. Further, it does not consider the effect of a grouser because a track link does not move with respect to the robot body.

III. Proposed Method

A. Representation of a Trajectory

In the proposed method, an arbitrary trajectory of a track with respect to the robot body is a closed loop of multiple

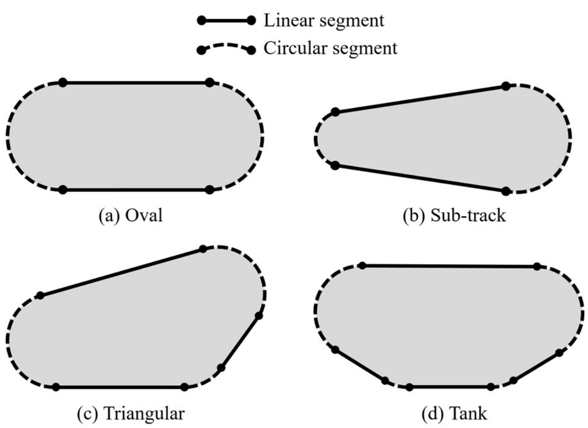


Figure 4. Examples of the tracks represented by the proposed method.

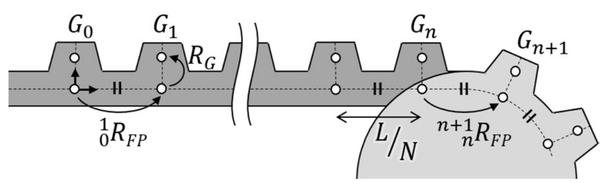


Figure 5. Distribution of the grousers between the segment links.

segments that are either a linear or circular-shaped, as presented in Fig. 4. It can represent oval tracks, which are used for numerous tracked vehicles [7–9] (Fig. 4(a)); tracks with different radii of the front and rear pulleys, which are frequently employed in sub-tracks [7, 8] (Fig. 4(b)); triangular tracks, which can enhance mobility [9] (Fig. 4(c)); and trapezoidal tracks, which are used for tanks (Fig. 4(d)).

Each linear segment is parameterized by the start position and the direction of the end position with respect to the robot body as well as the length of the segment. The base shape of this segment without grousers can be implemented in a robotic simulator as a cuboid link, whose pose and dimension are based on the above parameters. Each segment link is constrained with respect to the body by a slider joint. Sec. III-B explains the manner in which to represent the grousers on a segment link.

The circular segments are parameterized by the start position and the rotational axis with respect to the robot body as well as the angle of rotation. The base shape of such a segment without grousers can be implemented in a robotic simulator as a cylindrical link whose pose and dimension are based on the above parameters. Each segment link is constrained with respect to the robot body using a revolute joint.

B. Representation of the Grousers

Grousers can be parameterized by their pose (with respect to the trajectory), shape, and total number. Any shape of a grouser is acceptable, provided it is supported by the employed robotic simulator.

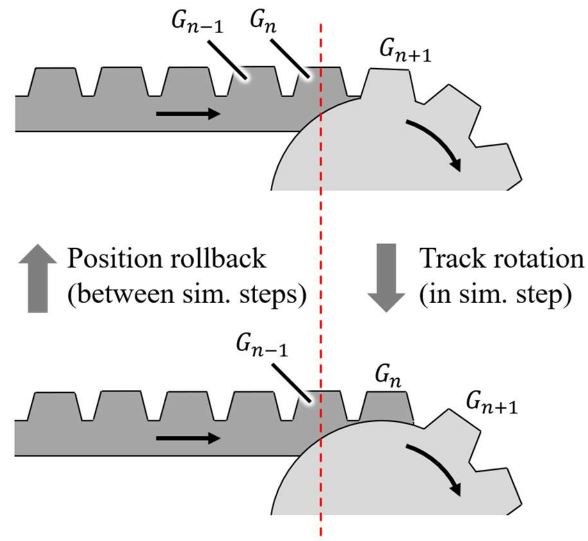


Figure 6. Representation of a rotating track.

The grousers are distributed along the trajectory such that the distance between the footprints of the adjacent grousers is equal to L/N, as presented in Fig. 5, where L and N are the total length of the trajectory and the total number of grousers, respectively. The pose of the n-th grouser with respect to the footprint of the 0-th grouser can be expressed by the following equation:

$$ {}^{n}_{0}R = \left(\sum_{i=0}^{n-1} {}^{i+1}_{i}R_{FP} \right) R_G, $$

where ${}^{j}_{i}R$, ${}^{j}_{i}R_{FP}$, and R_G are the transforms from the footprint of the i-th grouser to the center of the j-th grouser, from the footprint of the i-th grouser to that of the j-th grouser, and from the footprint to the center of a grouser, respectively.

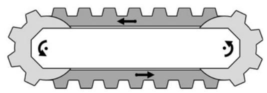
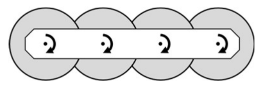
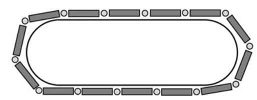
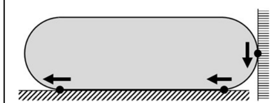
In a robotic simulator, this can be implemented by embedding the shapes of the distributed grousers in the link representing the trajectory segment of the grouser.

C. Representation of a Rotating Track Along a Trajectory

To represent the motion of a track, each link moves along the corresponding trajectory segment. Specifically, the links that are cuboidal (with the shapes of the grousers) move along the linear trajectory segments, whereas those that are cylindrical move along the circular trajectory segments. This can be realized in a robotic simulator by setting the position and velocity constraints on the slider or revolute joints, which connect each segment link and the robot body, based on the angular position and velocity of the sprocket driving the track.

Continuous movement of the segment links alters the shape of the entire track. This problem is overcome in the proposed method because the segment links roll back to their previous positions when the position of the (n-1)-th grouser in the link reaches the original position of the n-th grouser, as

TABLE I. QUALITATIVE COMPARISON OF THE DESIGN OF THE PROPOSED METHOD AND THE EXISTING METHODS

	Proposed	**Multiple-wheel**	**Multiple-plate**	**Constraint to ground**
				
Real-time	+	+	-	++
Grousers	+	-	+	-
Friction	+	+	+	-
Deformation	-	-	+	-
Rough terrain	++	-	++	+

+: good / supported, -: inferior / not supported / out of scope

TABLE II. COMPARISON BASED ON THE REAL-TIME FACTOR (GREATER THAN 1.0 INDICATES THE METHOD WORKS FASTER THAN REAL TIME)

Proposed	**Proposed (no grousers)**	**4 wheels**	**13 wheels**	**Constraint to ground***
2.79 ± 0.03	3.96 ± 0.02	4.86 ± 0.05	1.79 ± 0.00	5.93 ± 0.21

* Estimated based on the comparison with the multiple-wheel method (4 wheels) results in [6]

depicted in Fig. 6. The segment link position is restored between simulation steps, i.e., when the time is paused in the simulation. The change in the grouser position equals the separation between the adjacent grousers, i.e., L/N, to match the positions of the (n-1)-th and n-th grousers before and after the restoration, respectively. This allows the shape of the entire track to remain consistent before and after the positions of the segment links are restored. By these procedures, the proposed method mimics continuous track movement along a trajectory. This is implemented in a robotic simulator by changing the position of each joint between each segment link and the robot body.

If there are no grousers on the track, the segment links can be restored to their original positions with respect to the robot body before each simulation step.

D. Representation of the Collision and Friction between a Track and the Ground

Using the aforementioned procedures, a track with grousers moving along the trajectory with respect to the robot body was represented using only links, joints, and the constraints supported by a general robotic simulator (by default). In the proposed method, because a track actually rotates around the robot body, the simulation of the interaction between the moving track and the ground surface is deferred to the built-in physics engine of the robotic simulator. Specifically, the detection of the contact points between the track and the ground and the calculation of the driving forces acting on the contact points are realized using the default collision detection and friction model (e.g., [10]) of the physics engine, without any modifications.

E. Qualitative Comparison with Existing Methods

The proposed method and the existing methods described in Sec. II were qualitatively compared. The comparison was based on the computational costs and the collision and friction between a track (including the grousers) and the ground, as summarized in Table 1.

The computational cost is highly dependent on the number of links and joints in the simulation. In the proposed method, the number of links and joints required to simulate a track were equal to that of the segments that represented the trajectory. In the case of an oval trajectory, which is the most common (and consists of two linear and two circular segments), four pairs of links and joints are required, as depicted in Fig. 4(a). The upper linear link and joint can be omitted, and three pairs of links and joints are adequate if the upper linear link does not come into contact with the ground during operation. The number of links and joints required in the proposed method is thus comparable to that in the multiple-wheel method and less than that in the multiple-plate method; hence, the proposed method is expected to be more effective than these methods in terms of the computational cost.

The effect of the grousers, i.e., the collision between the grousers and the ground, is considered in the proposed method because a track rotates around the robot body along an accurate trajectory, similar to in the multiple-plate method. In terms of the grouser consideration, the proposed method is expected to be better than the multiple-wheel method (owing to the trajectory accuracy) and the constraint-to-ground method, which does not move a track against the robot body.

In the proposed method, the friction between a track and the ground is considered utilizing the default friction model of the simulator, because the proposed method does not modify the constraints on the points that contact the ground. This could be an advantage over the constraint-to-ground method,

TABLE III. SPECIFICATIONS OF THE TRACKED VEHICLE, QUINCE TABLE TYPE STYLES

Total weight		33 [kg]
Size of main body (w/o sub-tracks)		L685 × H150 × W370 [mm]
Shape of tracks		Oval
Main tracks	Number of tracks	2
	Size (w/o grousers)	L685 × H150 × W170 [mm]
	Number of grousers	40
	Shape of grouser	Trapezoidal (Upper base 5 × Lower base 18 × H 16 [mm])
Sub-tracks	Number of tracks	4
	Size (w/o grousers)	L345 × H150 × W25 [mm]
	Number of grousers	22
	Shape of grouser	Same as main tracks

TABLE IV. STEP CLIMBING TEST RESULTS TABLE TYPE STYLES

Front sub-track angle	Step height	Reality	Simulation
0 [°]	40 [mm]	S	S
	120 [mm]	S	S
	190 [mm]	F	F
45 [°]	120 [mm]	S	S
	240 [mm]	S	S
	380 [mm]	F	F

S: Succeeded, F: Failed

which modifies the original constraints established by the friction model.

The proposed method is expected to simulate the motion of a track on rough terrain precisely because it considers grousers and friction.

IV. EVALUATION

A. Quantitative Comparison with Existing Methods

The computational speeds of the proposed method and the considered exiting methods were compared. The tracked vehicle modeled for this evaluation was PackBot 510 [7], the most distributed mobile robot with non-deformable tracks worldwide (more than 2000 copies), to the best of the authors' knowledge. The trajectories of its left and right main tracks are oval in shape. The dimensions of a single main track are L690 × W75 × H180 mm, including grousers. In the proposed method, each grouser was modeled as a cuboid with dimensions of L5 × H8 mm. Forty grousers were distributed on each main track. The sub-tracks were not modeled.

The multiple-wheel methods used for comparative purposes had four wheels, which was the minimum number of wheels that can be aligned lengthwise without any spacing between adjacent wheels, and 13 wheels, which were comparable to the grousers on the linear segments.

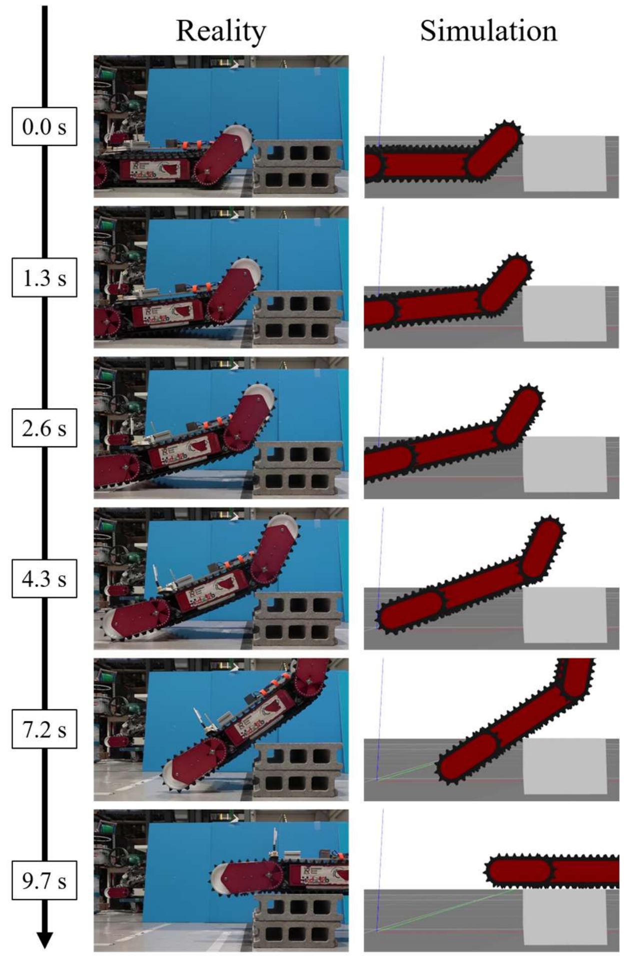


Figure 7. Snapshots of the step climbing test and the simulation by the proposed method.

Both the proposed and existing methods were implemented on Gazebo simulator 7.16 [11] on Ubuntu 16.04 LTS 64 bit. The Open Dynamics Engine [12] was used as the physics engine. The simulation step was set as 1 ms, i.e., the simulation world advanced 1 ms each step. All the test cases were implemented on a laptop with an Intel Core i7-6500U processor (2.50 GHz × 4) with 8 GB RAM.

The test case involved a forward drive at 0.3 m/s on a flat ground. The metric was the real-time factor, a ratio of the time advanced in the simulation world to the time that would have passed in the real world, averaged for 10 s based on a real-world clock. A real-time factor equal to or greater than 1.0 implies that the simulation can run in real time.

The test results are summarized in Table 2. They demonstrate that the proposed method runs beyond the real time at a comparative speed, similar to the multiple-wheel methods. Table 2 also provides the real-time factor of the constraint-to-ground method estimated from the CPU time required for a 110-s drive in the simulation reported in [6]. The evaluation in [6] was based on increased test cases and implemented in the V-REP simulator [13]. The processing of the constraint-to-ground approach is expected to require the shortest time among all the methods; however, it does not support grousers.

B. Comparison with an Actual Robot on Rough Terrain

The accuracy of the proposed method to simulate movement on rough terrain was evaluated by a comparative analysis using an actual robot. The six-degree-of-freedom (6-DoF) tracked vehicle, Quince [8], with two main tracks and four sub-tracks, was used for the evaluation. The detailed specifications of Quince are summarized in Table 3.

The test case scenario was of a track having to climb over steps at 0.1 m/s. The steps were 40, 120, and 190 mm in height with 0° sub-track angles so that the lower linear segments of the sub-tracks contacted the ground, and they were 120, 240, and 380 mm in height of the steps with 45° sub-track angles. The frictional coefficients of the ground and steps were set as 0.6 each in the simulation, based on a preliminary experiment using the real robot and the ground surface.

The results of all the test cases obtained from the simulation and using Quince were comparable, as can be seen from Table 4. In all the successful tests, the grousers collided with the edge of the steps, and this allowed both the robot in the simulation and Quince in the practical case to climb over the step. This effect was more pronounced for the 120-mm step with 0° sub-tracks and the 240-mm step with 45° sub-tracks. In these cases, the grousers were key for the robot to climb over the step because the step was slightly higher than the center of the front pulley of the sub-track, i.e., the robot might not have been able to climb over the step without grousers. Snapshots of the test with the 240-mm step with 45° sub-tracks are presented in Fig. 7.

In all the failed tests, the sub-tracks and main tracks of the simulation and Quince slipped on the vertical surface of the step and horizontal surface of the floor, respectively. The proposed method successfully simulated this behavior, owing to the explicit consideration of the friction between the tracks and the environment.

V. Conclusion

In this study, we developed a real-time simulation method for non-deformable continuous tracks with grousers on rough terrain with explicit consideration of the collision and friction with the environment. It represented an arbitrary trajectory of a track with multiple linear and circular segments, each of which was a link connected to the robot body, in the employed robotic simulator. The method applied velocity constraints between each segment link and the robot body to represent a track rotating around the body. It could restore the positions of the segment links when needed to maintain the shape of a track consistently. Experimental comparison of the proposed method to other simulation methods demonstrated that it worked faster than real time with a real-time factor of 2.79. Experimental comparison of the simulations and a physical robot showed that the former was comparable to the precise motion of a real robot over multiple test terrains.

Our developed method can simulate continuous tracks and also arbitrary objects moving on an arbitrary trajectory. For

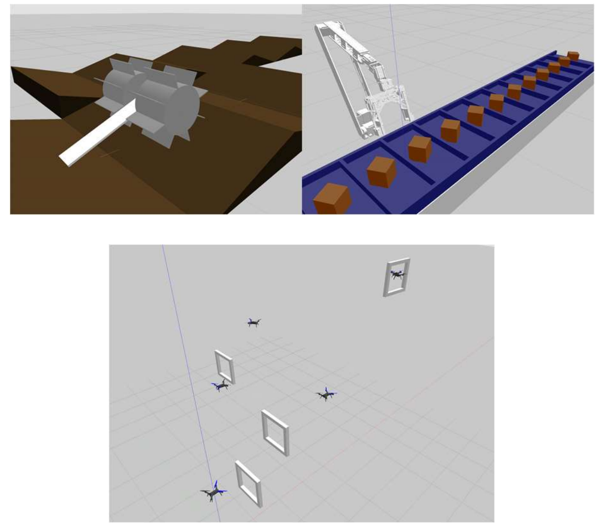


Figure 8. Alternative applications of the proposed method; lugged wheel (left), conveyer (right), and air traffic (bottom).

instance, by setting a circular trajectory and replacing the grousers by thin plates, lugged wheels can be simulated. Using a three-dimensional trajectory and a geometry model of an aerial vehicle, for developing an aerial robot, the air traffic can be simulated. Examples of possible applications of the proposed method are displayed in Fig. 8.

Future studies can be conducted on supporting the deformation of a track; however, a large-scale deformation of the track belt may be challenging using the proposed method. Hence, a small-scale deformation of the grousers could be considered by modeling them as soft objects. With the Open Dynamics Engine, which was used in this research, constraint force mixing (CFM), which is based on a similar concept, can be utilized for this purpose. Future research can also include the evaluation of analytic models of tracked vehicles in comparatively more complex scenarios (e.g., [14]) using the proposed method.

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