Dynamic Simulation of Actively-Coordinated Wheeled Vehicle Systems on Uneven Terrain

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Abstract

In this paper, a graphical dynamic simulator is developed that can simulate actively-coordinated wheeled vehicle systems on uneven faceted terrain. Based on the considerations of model fidelity and computational efficiency, a simple geometric model for wheel-terrain contact is proposed. In addition, a computationally-efficient algorithm for contact detection is developed. We also devise a contact force model based on soil mechanics. Simulation results of a case where the WAAV [1] is traversing a concave edge between facets are used to demonstrate the good performance of our contact model.

1 Introduction

Variably-configured vehicles with active coordination (also called actively-coordinated vehicles) generally possess larger numbers of independently-controlled actuators than those of motion degrees of freedom. The redundancy of actuation can be used to distribute and optimize the contact forces at the vehicle-terrain interface to improve contact conditions, such as reduction of slip and sinkage, and to enhance the system performance, such as minimization of power consumption. Therefore, their mobility and terrain-adaptive properties on unprepared terrain are generally superior to those of conventional vehicles. This type of vehicle has potential in many off-road applications including those in mining, agriculture, forestry, military locomotion, and exploration of planetary surfaces.

During the past decade, several prototypes of actively-coordinated wheeled vehicles have been developed: such as the Attached Scout Concept Rover [2] for Mars exploration by FMC, the Actively Articulated Six Wheeled Vehicle Concept [3] for the same purpose by Martin-Marietta, and the Wheeled Actively Articulated Vehicle (WAAV) [1] at The Ohio State University. However, in much of the work only preliminary research results have been obtained [1, 4, 5]. In order to bring actively-coordinated wheeled vehicles into applications, more advanced methods for coordination and control still need to be developed.

For the test and evaluation of coordination and control methods of vehicles, dynamic simulation is a very useful tool. By using numerical simulation with a reasonable execution speed, vehicle trials may be repeated at no risk. This will expedite the development of a system and save cost. In this work, a dynamic simulator (see Figure 1) with efficient algorithms is developed. It is able to simulate actively-coordinated, off-road wheeled vehicles with multiple modules operating on uneven terrain. In particular, this paper will focus on the development of the vehicle-terrain contact model.

Several issues are involved in the modeling of vehicle-terrain contact. Among them include (1) object modeling in a proper form based on the considerations of model fidelity and computational cost, (2) contact detection together with identification of contact locations, and (3) computation of the corresponding contact force. In the following sections, we propose efficient approaches to these problems.

The remainder of the paper is organized as follows. Section 2 describes the proposed geometric contact model. In Section 3, contact detection is addressed. In Section 4, the contact force model is formulated. Simulation results are given in Section 5. The paper ends with a summary and conclusions in Section 6.

2 Geometric Contact Model

With regard to object modeling, one approach is to model the wheels and terrain with polyhedra. There exists many efficient algorithms, such as the one in [6], to do collision detection for moving polyhedra. However, to model a smooth surface closely, such as for a wheel, a large numbers of faces are needed in the
Figure 1: The dynamic simulator for WAAV, with triangular-facet terrain model.

polyhedron. This will significantly increase the computation time for contact detection.

In a dynamic simulation package, called DynaMechs [7], a polling strategy is used to detect contact. Evenly distributed points on the wheels of the vehicle system can be chosen as the polled points. In each time step, these points are computed relative to the environment to see whether contact occurs or not. Since this approach does not take full profiles of the wheel surface into consideration, a large number of points need to be defined to obtain a contact location close to the actual one. This also increases the computation time.

Based on the consideration of model fidelity, algebraic equations can also be used to represent the profiles of the wheels and terrain. For example, a wheel can be modeled as a cylinder or a torus [8]. Contact is then determined by solving a set of nonlinear equations. Generally, an analytical solution of this set of nonlinear equations is difficult to find, and an iterative algorithm must be applied to obtain the solution, which may not be computationally efficient.

To make a compromise between model fidelity and computational efficiency, we model a wheel as a thin disk that represents the middle cross section of the wheel. In addition, the terrain is modeled as a set of triangular facets; that is, the terrain is uneven and composed of piecewise planes with different slopes (see Figure 1). By increasing the number of facets, a smooth terrain surface can be approximated. We also model the wheel-terrain contact as a point contact. The deepest penetration point into the terrain is assumed to be the contact point on the wheel. For each wheel contacting a facet of the terrain, there is only one contact point although multiple contact points result when traversing an edge or vertex of the terrain.

In our wheel-terrain contact model, we assume that the wheel is nearly rigid, and the terrain is deformable under pressure. This is the case where rigid wheels or wheels with high tire pressure move on soil. Also, the terrain is modeled as a rigid foundation covered with a viscoelastic surface layer of uniform thickness [9]. The surface layer is used to account for the system’s compliance (includes the compliance in the vehicle system, soil deformation, etc.). When a wheel and the terrain are in contact, it is assumed that the wheel will penetrate into the terrain. However, the penetration will never reach the inner rigid foundation. A geometric model for a wheel in contact with a terrain facet is illustrated in Figure 2.

Usually, a wheel contacts the terrain with a small contact area. However, we simulate the contact on the wheel with a net force acting at a single point, called the wheel contact point. For each wheel-terrain contact, a pair of spatial points are located: one on the wheel, \( p_c \), and the other on the terrain, \( p_t \). The relative movement (velocity and position) between \( p_c \) and \( p_t \) is used to model the deformation of the terrain and to develop the contact force model.

In this work, the contact point \( p_c \) on the wheel is assumed to be the deepest penetration point into the terrain. The corresponding closest point on the rigid foundation to the wheel is labeled as \( p_r \). A contact coordinate system, \( \{c\} \), is set at \( p_c \). Its z-axis, \( \hat{z}_c \), points up along the direction from \( p_r \) to \( p_c \). Also, the x-axis, \( \hat{x}_c \), of \( \{c\} \) is directed normal to both the wheel axle and \( \hat{z}_c \), while the y-axis, \( \hat{y}_c \), is set to form a right Cartesian coordinate system. In addition, \( p_t \)
Figure 3: (a) Discontinuity of the contact point with least deepest-penetration approach. (b) Continuity of the contact point with elastic-surface-layer approach.

is initialized as the projection of \( \mathbf{p}_c \) onto the surface of the viscoelastic layer along \( \hat{z}_c \).

When traversing a convex edge, a wheel contacts both of the adjacent facets simultaneously. In [1], the contact point with less penetration into the plane is chosen as the correct one. When the wheel center is at \( \mathbf{p}_w \) (see Figure 3(a)), the wheel has less penetration into facet 1 than into facet 2. Thus, the wheel is regarded as contacting facet 1, and the corresponding contact points are \( \mathbf{p}_c \) and \( \mathbf{p}_i \). Subsequently, the wheel moves forward to the position with the center at \( \mathbf{p}_w \). At this moment, the wheel has less penetration into facet 2 than into facet 1. The wheel is regarded as contacting facet 2, and the corresponding contact points are \( \mathbf{p}_c' \) and \( \mathbf{p}_i' \). It is noted that the contact points are suddenly changed to backward locations while the wheel is moving forward during the edge crossing. This discontinuity does not simulate the edge traversal of the wheel in a realistic manner.

On the other hand, the introduction of the viscoelastic surface layer [9] for the terrain model combined with the assumption that a contact occurs at the deepest penetration point overcomes this problem. When a wheel penetrates into the viscoelastic surface layer, the deepest penetration point on the wheel is the closest point to the rigid foundation. During the edge or vertex traversal, there is always only one closest point to the rigid foundation. Therefore, the contact point on the wheel can be uniquely determined. Also, the contact points \( \mathbf{p}_c \) and \( \mathbf{p}_i \) are continuous (see Figure 3(b)), which is more realistic.

Our strategy for modeling the wheels and terrain makes the computation of contact detection relatively simple and fast, which is shown later. Specifically, in the case where a wheel contacts a facet of the terrain, the solution can be found analytically. Even in the case where a wheel traverses an edge or a vertex of the terrain, the computation is still relatively fast compared to other approaches mentioned previously.

### 3 Contact Detection

There are three possible cases for a wheel traversing uneven faceted terrain: traversing a plane, an edge, and a vertex. The computation of the corresponding contact locations for each case is presented in the following. The components of all vectors are referenced to an earth-fixed coordinate system \( \{ E \} \).

#### 3.1 Traversing a Planar Facet

Figure 2 shows the case of a wheel traversing a planar faceted terrain. In the figure, \( \mathbf{p}_c, \mathbf{p}_i, \mathbf{p}_w, \hat{\mathbf{x}}_e, \) and \( \hat{z}_c \) have been defined previously. In addition, \( \mathbf{n}_w \) is the unit normal vector of the wheel plane and is parallel to the wheel axle; \( r \) is the wheel radius; and \( \mathbf{n}_t \) is the unit normal vector to the rigid foundation facet and is parallel to \( \hat{z}_c \) in this case.

Given \( \mathbf{n}_w, \mathbf{p}_w, r, \) and the equation of the rigid foundation plane, \( \mathbf{p}_c \) can be analytically computed as follows. First, \( \mathbf{p}_c \) is in the wheel plane, and the distance between \( \mathbf{p}_c \) and \( \mathbf{p}_w \) is \( r \):

\[
\mathbf{n}_w \cdot (\mathbf{p}_c - \mathbf{p}_w) = 0, \\
\|\mathbf{p}_c - \mathbf{p}_w\|^2 = r^2,
\]

where \( \cdot \) is the inner product operation, and \( \| \| \) represents the 2-norm of a vector.

Next, the vector from \( \mathbf{p}_w \) to \( \mathbf{p}_c \) is perpendicular to the common normal vector of \( \mathbf{n}_w \) and \( \mathbf{n}_t \):

\[
\frac{\mathbf{n}_w \times \mathbf{n}_t}{\|\mathbf{n}_w \times \mathbf{n}_t\|} \cdot (\mathbf{p}_c - \mathbf{p}_w) = 0,
\]

where \( \times \) denotes the cross product.

Combining Eqs. (1) and (3) which are linear, we can express the \( x \) and \( y \) coordinates of \( \mathbf{p}_c \) as a function of its \( z \)-coordinate and substitute them into Eq. (2). Equation (2) then becomes a second-order equation in the \( z \)-coordinate, which possesses two solutions. The correct \( z \)-coordinate is the one with the lower value (deepest penetration). In turn, the \( x \) and \( y \) coordinates of \( \mathbf{p}_c \) can be obtained.
and follows:

\[ \text{traversing an edge} \]

when a wheel traverses an edge \( \text{(see Fig. 4)} \), located on the edge line. It can be expressed as follows:

\[ s = \mathbf{n}_i \cdot (\mathbf{p}_0 - \mathbf{p}_c) \]

In turn, \( \mathbf{p}_c \) is obtained. If the distance between \( \mathbf{p}_r \) and \( \mathbf{p}_c \) is larger than the the uniform thickness \( d_e \) of the viscoelastic surface layer, or \( \mathbf{p}_r \) is outside the rigid foundation facet, then there is no contact. Otherwise, the wheel contacts the terrain, and the penetration depth \( d_p \) of the wheel into the terrain is

\[ d_p = d_e - \| \mathbf{p}_c - \mathbf{p}_r \| \]

Also, \( \mathbf{p}_i \) is the projection of \( \mathbf{p}_c \) onto the surface of the viscoelastic layer along \( \mathbf{n}_i \) and can be computed by

\[ \mathbf{p}_i = \mathbf{p}_c + d_p \mathbf{n}_i \]

Finally, \( \mathbf{z}_c \) is set to \( \mathbf{n}_i \), and \( \hat{\mathbf{x}}_c \) is set to the common normal vector of \( \mathbf{n}_w \) and \( \mathbf{n}_i \):

\[ \hat{\mathbf{x}}_c = \frac{\mathbf{n}_w \times \mathbf{n}_i}{\| \mathbf{n}_w \times \mathbf{n}_i \|} \]

### 3.2 Traversing an Edge Between Facets

When a wheel traverses an edge (see Fig. 4), \( \mathbf{p}_r \) is located on the edge line. It can be expressed as follows:

\[ \mathbf{p}_r = \mathbf{p}_1 + t \mathbf{u} \]

where \( \mathbf{p}_1 \) is a point on the edge line, \( t \) is a scalar, and \( \mathbf{u} \) is the unit directional vector of the edge line. Also, the vector from \( \mathbf{p}_c \) to \( \mathbf{p}_e \) must be perpendicular to \( \mathbf{u} \):

\[ \mathbf{u} \cdot (\mathbf{p}_c - \mathbf{p}_e) = 0 \]

By combining Eqs. (10) and (11) and using the fact that \( \| \mathbf{u} \| = 1 \), the scalar \( t \) is:

\[ t = \mathbf{u} \cdot (\mathbf{p}_c - \mathbf{p}_1) \]

To find the closest points between the wheel and the edge line, we must find the smallest distance between \( \mathbf{p}_r \) and \( \mathbf{p}_c \) under the constraint that \( \mathbf{p}_c \) is located on the circumference of the wheel (expressed in Eqs. (1) and (2)). Thus, the problem can be described as

\[
\begin{align*}
\text{minimize} & \quad \| \mathbf{p}_r - \mathbf{p}_c \|^2 \\
\text{subject to} & \quad \mathbf{n}_w \cdot (\mathbf{p}_c - \mathbf{p}_r) = 0 \\
& \quad \| \mathbf{p}_c - \mathbf{p}_w \|^2 = r^2
\end{align*}
\]

By replacing \( \mathbf{p}_r \) with Eqs. (10) and (12), Eq. (13) becomes a nonlinear optimization problem of three variables, the coordinates of \( \mathbf{p}_c \), subject to one linear and one nonlinear constraint. This nonlinear-constraint minimization problem can be solved by an algorithm that uses a successive quadratic programming method to solve the general nonlinear programming problem, such as the “NCONG” routine in the IMSL library. After \( \mathbf{p}_c \) is computed, \( \mathbf{p}_r \) can be obtained. If the distance between \( \mathbf{p}_r \) and \( \mathbf{p}_c \) is larger than the the uniform thickness \( d_e \) of the viscoelastic surface layer, or \( \mathbf{p}_r \) is outside the edge-line segment of the adjacent facets, then there is no contact. Otherwise, the wheel contacts the terrain, and the penetration depth \( d_p \) of the wheel into the terrain is computed using Eq. (7).

For the edge contact, \( \mathbf{n}_i \) is assigned to be the vector from \( \mathbf{p}_r \) to \( \mathbf{p}_c \), and \( \mathbf{z}_c \) is set along this normal vector:

\[ \hat{\mathbf{x}}_c = \frac{\mathbf{p}_c - \mathbf{p}_r}{\| \mathbf{p}_c - \mathbf{p}_r \|} \]

The unit vector \( \hat{\mathbf{x}}_c \) is set to be the common normal vector of \( \mathbf{n}_w \) and \( \mathbf{n}_i \) (Eq. (9)). Finally, \( \mathbf{p}_i \) is initialized as the projection of \( \mathbf{p}_c \) along \( \hat{\mathbf{x}}_c \) onto the surface of the viscoelastic layer, which can be computed with Eq. (8).
surface layer, then there is no contact. Otherwise, except that \( p_r \) in Eq. (13) is a known vertex. After \( p_r \)
is computed, if the distance between \( p_r \) and \( p_v \) is larger than the the uniform thickness \( d_v \) of the viscoelastic surface layer, then there is no contact. Otherwise, the wheel contacts the terrain, and the penetration depth \( d_p \) of the wheel into the terrain is computed using Eq. (7). Finally, \( p_r \) is initialized as the projection of \( p_v \) along \( n_r \) (\( z_r \)) onto the surface of the viscoelastic layer, which can be computed with Eq. (8).

### 3.4 Contact Detection Algorithm

The contact detection algorithm can be described in the following steps:

**Step 1** Create set \( L \) of possible contacting terrain facets: From the forward dynamics of the vehicle system [7], the position of the wheel center \( p_w \) is given. We then create a circular area \( A \) on the \( x-y \) plane of \( \{ E \} \) with center at \( p_w^{xy} \) and \( \text{rad} \) where \( p_w^{xy} \) is the projection of \( p_w \) on the \( x-y \) plane of \( \{ E \} \). Set \( L \) consists of facets whose projections on the \( x-y \) plane of \( \{ E \} \) intersects \( A \). For facets outside set \( L \), it is impossible to \( \epsilon \) the wheel, and these facets can be ignored to computation time.

**Step 2** Do plane-contact computation as in Section 3.1 for each facet in \( L \): The contact status variable \( C_{status} \) for each facet is set as follows: \( C_{status} = 1 \) when plane contact occurs; \( C_{status} = 2 \) when the wheel penetrates a facet plane, but \( p_r \) is outside the edges of the associated rigid foundation facet; and \( C_{status} = 3 \) when the wheel is off the terrain (\( d_p > d_v \)). If plane contact occurs (\( C_{status} = 1 \)), the corresponding contact data, \( p_v \), \( \{ c \} \), \( p_r \), and \( p_p \), are recorded.

**Step 3** Do edge-contact computation as in Section 3.2 for each pair of adjacent facets in \( L \) if they are convex, and both of their values of

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**Figure 5:** A wheel traverses a vertex.  
**Figure 6:** (a) A pair of adjacent facets. (b) A pair of facets that intersect at a vertex.

\( C_{status} \) are 1: For a pair of adjacent facets, the edge can be flat, concave, or convex. In Figure 6(a), points \((p_0,p_1,p_2)\) compose facet 1, while points \((p_0,p_2,p_3)\) compose facet 2. If we assume that the normal vector to each facet is upward, then the normal vector \( n_1 \) to facet 1 is

\[
 n_1 = \frac{(p_2 - p_0) \times (p_1 - p_0)}{\| (p_2 - p_0) \times (p_1 - p_0) \|}.
\]

and the equation for facet 1 is

\[
 n_1 \cdot (p - p_0) = 0.
\]

The relationship of the adjacent facets can be defined as follows: They are flat if \( p_3 \) is on the same of facet 1, i.e. \( n_1 \cdot (p_3 - p_0) = 0 \); concave if the direction of the plane \( p_3 \) is the same as that of \( n_1 \), i.e. \( n_1 \cdot (p_3 - p_0) > 0 \); otherwise, they are convex, i.e. \( n_1 \cdot (p_3 - p_0) < 0 \). Edge contact can happen only on the edge between convex adjacent facets. When edge contact occurs, both of their values of \( C_{status} \) are updated to 4, and the corresponding contact data, \( p_r \), \( \{ c \} \), \( p_p \), and \( p_c \), are recorded.

**Step 4** Do vertex-contact computation as in Section 3.3 for each pair of adjacent facets in \( L \), which intersect at a vertex if they are convex, and both of their values of \( C_{status} \) are 1. Vertex contact may occur only when two facets intersecting at a vertex are convex. Figure 6(b) shows a pair of facets that intersect at a vertex. The normal
vector and the plane equation of facet 1 can be computed using Eqs. (15) and (16), respectively. If both of the directions from facet 1 to \( p_3 \) and \( p_4 \) are opposite to that of \( n_1 \), facets 1 and 2 are convex. When vertex contact occurs, both of the values of \( C_{status} \) are updated to 5, and the associated contact data, \( p_{c,v} \), \( p_v \), and \( p_t \), are recorded.

From the variable \( C_{status} \), the contact status is known.

## 4 Contact Force Model

Broadly, two approaches can be used to estimate the contact forces: the hard contact approach that estimates forces by assuming that the contacting bodies are infinitely rigid and do not penetrate each other, and the soft contact approach that computes forces by modeling the localized deformation in the vicinity of the contact. The hard contact approach usually has problems with the existence and uniqueness of the solutions when friction is present [10]. In addition, compliance normally exists for an off-road vehicle-terrain system. Thus, the soft contact approach is taken in this work. It is worth noting that with a soft contact model, kinematics loops are broken, and the dynamics computation is simplified.

In [4], the author models tractive, lateral, normal, and motion resistance forces for driving wheels on soil, based on vehicle-soil mechanics. In this work, we will extend the development in [4] to also simulate impact forces when wheels first contact the terrain, and retain static forces when the vehicle stands still on a sloped terrain.

### 4.1 Normal Contact Force

The normal contact force based on soil mechanics has been empirically estimated as follows [11]:

\[
N = \frac{3 - n}{3} (K_x + b K_\phi) \sqrt{D z_t^{2n+1}},
\]

where \( N \) is the normal force, \( (N) \); \( n \) the dimensionless exponent of soil deformation, \( z_t \) the depth of sinkage solely due to the normal load, \( (m) \); \( D \) the diameter of the wheel, \( (m) \); \( b \) the width of the wheel’s ground contact area, \( (m) \); \( K_x \) the cohesive modulus of terrain deformation, \( (N/m^{n+1}) \); and \( K_\phi \) the frictional modulus of terrain deformation, \( (N/m^{n+2}) \).

To model the impact force, a nonlinear damping compliant model [12] is involved, and the proposed normal contact force \( f_c^z \) is computed as follows:

\[
f_c^z = \sigma (N - \lambda_n s_z v_c^z),
\]

where \( N \) is computed by Eq. (17); \( \sigma \) is equal to 1 if the wheel contacts the terrain; otherwise it is equal to 0; \( \lambda_n \) is the damping constant along the contact normal direction; \( s_z \) is the penetrating displacement along the contact normal; and \( v_c^z \) is the penetrating velocity along the contact normal.

### 4.2 Tangential Contact Force

The tangential tractive force of a driving wheel can be computed as follows [13]:

\[
H = (c b l + f_c^\phi \tan(\phi)) \left[ 1 - \frac{K}{s l} \left( 1 - \exp \left( -\frac{s l}{K} \right) \right) \right],
\]

where \( H \) is the tangential tractive force, \( (N) \); \( f_c^\phi \) the normal force, \( (N) \); \( b \) the width of the wheel’s ground contact area, \( (m) \); \( l \) the length of the wheel’s ground contact area, \( (m) \); \( c \) the cohesion of the soil, \( (N/m^2) \); \( \phi \) the soil friction angle, \( (deg.) \); \( K \) the soil deformation modulus, \( (m) \); and \( s \) the slip.

When a wheel stops on an inclined terrain, its slip is zero. In this case, the tractive force according to Eq. (19) is zero. This does not simulate the tractive force correctly. To add static-force effects, we involve spring and damper terms in the equation [9]:

\[
f_c^t = H - k_x s^t - B_x v_c^t,
\]

where \( k_x \) is the spring coefficient along the tangential direction, \( (N/m) \); \( s^t \) the contact displacement along the tangential direction, \( (m) \); \( B_x \) the damping coefficient along the tangential direction, \( (N\cdot s/m) \); and \( v_c^t \) the contact velocity along the tangential direction, \( (m/s) \). Finally, the tangential force is the tractive force minus the motion resistance:

\[
f_c^t = f_c^t - f_r
\]

### 4.3 Lateral Contact Force

A similar formulation for the lateral contact force of a driving wheel, based on empirical results, has been developed as follows [13]:

\[
L = (c b l + f_c^\phi \tan(\phi)) (1 - \exp^{-B a}),
\]

where \( L \) is the lateral cornering force, \( (N) \); \( B \) the constant coefficient dependent on the wheel parameters and the soil conditions, \( (1/deg.) \); \( a \) the slip angle, \( (deg.) \); and other definitions of parameters were given previously.

To add the static-force effects, we involve spring and damper terms in the equation:

\[
f_c^\phi = L - k_y s^\phi - B_y v^\phi
\]
where $k_y$ is the spring coefficient along the lateral direction, (N/m); $s_y$ the contact displacement along the lateral direction, (m); $B_y$ the damper coefficient along the lateral direction, (N-s/m); and $v_y$ the contact velocity along the lateral direction, (m/s). A variety of soil parameters can be found in [14].

5 Simulation Results

A graphical dynamic simulator used to test our algorithm is shown in Figure 1. The simulator broadly consists of four parts: the forward dynamics of the vehicle, which simulates the vehicle system; the contact model that estimates the contact forces; the set of triangular facets that represents the terrain; and the graphic viewer that shows the animated motion of the vehicle system contacting the uneven faceted terrain.

The forward dynamics of the vehicle system is implemented using the simulation package, DynaMechs [7], a general-purpose dynamic simulation tool, which is able to simulate general tree-structured vehicles, such as the WAAV. The three dimensional (3D) graphical viewer that displays the animated motion of the simulation is implemented with a graphical package, called GLAnimate, based on XAnimate which was developed in [15].

To demonstrate the good performance of the proposed contact model, the results of the case where the WAAV crosses concave facets are shown as follows. The WAAV is crossing concave facets at a constant speed along the $x$ direction, shown in Figure 7 (a). The trace of the resultant contact points $p_r$ and $p_c$ of the right front wheel is shown in Figure 7(b). In this case, the edge line is located at $x = 8.0$ m. As we can see in the figure, the wheel contacts only one facet before $time = 2.84$ sec. At $time = 2.84$ sec, contact with the second facet occurs. During the period of $time = 2.84$ sec to $time = 2.90$ sec, the wheel contacts both facets, simultaneously. At $time = 2.90$ sec, contact with the first facet is released, and the wheel contacts only the second facet afterward. Note in all cases that the movement of the contact point is continuous.

Next, we test the WAAV at different constant speeds along the $x$ direction: 1 m/s, 0.7 m/s, 0.4 m/s, and 0.1 m/s, respectively. The vertical contact forces of the right front wheel are shown in Figure 7(c). As we can see, the vertical contact force is constant before the second contact occurs. During the period of dual contact, the wheel impacts the second facet such that the vertical force increases. When the wheel releases the first contact and moves steadily on the second facet, the vertical contact force decreases. This is because the front module goes up a hill, and the cen-
ter of gravity of the whole vehicle system shifts from the original position to the end of the rear module. It is also noted that the higher the forward speed of the vehicle, the larger the amount of increase in vertical contact force. This is because the wheel has a greater impact with the terrain with a higher forward speed.

6 Summary and Conclusions

In this paper, a dynamic simulator is developed that can simulate actively-coordinated wheeled vehicle systems on uneven faceted terrain. Based on the considerations of model fidelity and computational efficiency, a simple geometric model for wheel-terrain contact is proposed. Also, a computationally-efficient algorithm for contact detection is developed. The introduction of the viscoelastic surface layer for the terrain model, combined with the assumption that a contact occurs at the deepest penetration point, enables the contact point to be uniquely determined when the wheel traverses a convex edge or crosses a vertex. Furthermore, the contact point is guaranteed to be continuous during the traversal of a convex edge.

A contact force model is also developed based on soil mechanics. Three forces at the contact interface are modeled: the normal force which supports the normal load, the tractive force which is generated from the forward friction force, and the lateral (cornering) force which exists when the vehicle makes a turn. In addition, impact forces are modeled.

Simulation results of a case where the WAAV is traversing a concave edge are used to demonstrate the good performance of the contact model. It is believed that the proposed contact model and dynamic simulator can contribute to the development of a variety of actively-coordinated wheeled vehicles in the future.

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8 References


