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Christophe Grand, Faiz Ben Amar, Philippe Bidaud, Guillermo Andrade. A simulation system for behaviour evaluation of off-road mobile robots. 4th International Conference on Climbing and Walking Robots (Clawar'01), Sep 2001, Karlsruhe, Germany. pp.307-314. hal-03178091

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A simulation system for behaviour evaluation of off-road mobile robots

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Abstract: This study deals with optimization of planetary rover traversability over challenging outdoor terrains. In this aim, it is necessary to simulate rover behaviour on soft soil with a high degree of realism. The paper describes a simulation system for mobile robots evolving on natural and unstructured surfaces. This simulator integrates the whole dynamics of the multibody systems and complex interactions with soft ground as well as control schemes.

1 Introduction

To improve exploration capabilities of autonomous planetary rover, complex locomotion devices that allow terrain adaptation have to be developed. The main motivation in the development of this software is to investigate adaptation capabilities of a high-mobility redundantly actuated rover to complex natural surfaces. The class of systems considered can be illustrated by the Marsokhod rover [1], or mobile robots with adaptation capabilities [9],[6].

These robots are supposed to evolve on natural and unstructured surfaces like in planetary or volcanic exploration, where the ground can be characterized by physical and geometrical properties. Soil constitution can be considered as rigid (big heavy rocks or highly compacted soils), or as agglomerated particles of various sizes (sand or small rocks). Its complex geometry is modeled as slopes of various inclines and high slopes represent complex obstacles like steps or rocks. Since the mechanical structure offers different locomotion modes, an investigation of their potentialities in various ground configurations (from physical and geometrical point of view) is needed to be able to optimize the locomotion performances, and then to increase field of accessible rough terrains.

We have developed a simulator that take the whole dynamics of mobile robot and soft soil into account. Interaction models between rover locomotion organs and soils are also integrated [4]. This simulator is composed by three independent modules linked together

(see figure 1). One is dedicated to dynamics simulation of multibody systems (i.e. the robot model), another one deals with complex interaction models, and a third one is used to introduce control schemes. We have added a fourth one for post-computing and results analysis through graphs or movies. Thus, we consider each module of the simulator as a black-box with codified inputs and outputs, and use files based communication between each module. This modularity provides a high flexibility in the simulation implementation.

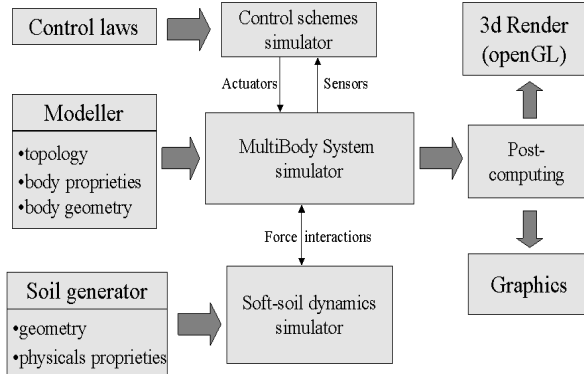


Figure 1: Simulator overview

2 Multibody system simulator

Mobile robots are considered as articulated mechanisms with locomotion organs (feet, wheels or tracks) in contact with the ground. Thus, we can define legged, wheeled, tracked or hybrid rovers. The simulation problem of rover dynamic behaviour on soft soils that has to be solved consists in computing the generalized accelerations of each body when external forces are applied on the mechanism. Forward dynamics is a classical problem in robotics. Featherstone and al.[7] have presented an overview of equations and algorithms for robot dynamics analysis. The most common approaches are known as Newton-Euler and Lagrange formulations. Our simulator is based on the Lagrange formulation for kinematically constrained mechanisms. Lagrange multipliers are used since they are more well adapted to mechanisms with closed-loops [3], [10].

The mechanism is defined by a set of n bodies linked together.

Each body \mathcal{B}_i is defined by three kinds of parameters :

- kinematic: $\mathbf{q}_i = [\mathbf{r}_i, \mathbf{p}_i]^t$ is the generalized body position vector, and $\mathbf{h}_i = [\dot{\mathbf{r}}_i, \boldsymbol{\omega}_i]^t$ the generalized body velocity with respect to the reference frame,
- Inertial: \mathcal{I}_i is the inertia matrix and m_i the mass,
- Geometrical: external shape of the bodies in contact with the ground.

\mathbf{r}_i is the position of center of mass of body \mathcal{B}_i , p_i is vector of Euler parameters for the body orientation $\mathbf{p} = [e_0, \mathbf{e}^t]^t = [e_0, e_1, e_2, e_3]^t$. These parameters present the advantage to be free of singularity and have low computational cost. Velocity vector \mathbf{h} is a linear function of $\dot{\mathbf{q}}$ and the time-derivative of Euler parameters [10] ($\tilde{\mathbf{e}}$ is the 3x3 skew-symmetric matrix of vector \mathbf{e}):

$$\mathbf{h} = \begin{bmatrix} \mathbf{I}_3 & 0 \\ 0 & 2\mathbf{L} \end{bmatrix} \dot{\mathbf{q}} \quad \text{and} \quad \mathbf{L} = [-\mathbf{e}, -\tilde{\mathbf{e}} + e_0\mathbf{I}_3] \quad (1)$$

Each joint \mathcal{L}_j is defined by the following set of constraint equations between the two bodies \mathcal{B}_i and \mathcal{B}_j

$$\phi_j(\mathbf{q}) = 0 \quad (2)$$

Then, solving the forward dynamic problem consists in writing dynamic equations for each body considering them first as unconstrained. Kinematic constraints are then introduced by applying forces on each body. Forces due to constraints can be defined as a linear function involving the jacobian matrix of joint \mathcal{L}_j and relative to bodies \mathcal{B}_i and \mathcal{B}_j [10] : $\mathbf{F}_c = -\mathbf{J}^t \boldsymbol{\lambda}$, where $\boldsymbol{\lambda}$ is a vector of unknown scalars called Lagrange multipliers.

$$\begin{aligned} \mathbf{M} \dot{\mathbf{h}} + \mathbf{J}^t \boldsymbol{\lambda} &= \mathbf{F} \\ \mathbf{F} &= \mathbf{F}_e + \mathbf{F}_i + \boldsymbol{\tau} \end{aligned} \quad (3)$$

\mathbf{F} is the generalized forces vector applied on mechanism and is composed by :

- external forces (\mathbf{F}_e) due to gravity and gyroscopic effect,
- contact forces (\mathbf{F}_i) due to interactions between the ground and locomotion organs,
- motor torques ($\boldsymbol{\tau}$) taken from control scheme,

\mathbf{M} is the generalized mass-inertia matrix.

The second time-derivative of equation (2) gives an algebraic equation. It is added to equation (3) to form the differential algebraic equations set (DAEs set):

$$\begin{aligned} \mathbf{M} \dot{\mathbf{h}} + \mathbf{J}^t \boldsymbol{\lambda} &= \mathbf{F} \\ \mathbf{J} \dot{\mathbf{h}} - \boldsymbol{\gamma} &= 0 \end{aligned} \quad (4)$$

Where \mathbf{J} is the jacobian matrix relative to velocity vector \mathbf{h} .

$$\mathbf{J} = \frac{\partial \phi}{\partial \mathbf{q}} \begin{bmatrix} \mathbf{I}_3 & 0 \\ 0 & \frac{1}{2} \mathbf{L}^t \end{bmatrix} \quad \text{and} \quad \boldsymbol{\gamma} = \dot{\mathbf{J}} \mathbf{h} \quad (5)$$

Equations (4) can be written in the more compacted matrix form:

$$\widehat{\mathbf{M}} \widehat{\mathbf{q}} = \widehat{\mathbf{F}} \quad \text{and} \quad \widehat{\mathbf{M}} = \begin{bmatrix} \mathbf{M} & \mathbf{J}^t \\ \mathbf{J} & 0 \end{bmatrix} \quad \widehat{\mathbf{q}} = \begin{bmatrix} \dot{\mathbf{h}} \\ \boldsymbol{\lambda} \end{bmatrix} \quad \widehat{\mathbf{F}} = \begin{bmatrix} \mathbf{F} \\ \boldsymbol{\gamma} \end{bmatrix} \quad (6)$$

This DAEs set could be solved by computing pseudo-inverse matrix $\widehat{\mathbf{M}}$ but it is well know that this method is not the most efficient one (the computational cost is in $O(n^3)$). Though, as each constraint involves only two bodies (binary link), \mathbf{J} is a sparse matrix. The proposed algorithm, is based on ABA's one [7] and includes the sparse character of $\widehat{\mathbf{M}}$ matrix. Taking the tree-structure topology into account allows the complexity to be linear to the number of bodies $O(n)$. This algorithm is described in [2] and can be summarized as follows. The following notation is used in order to simplify the description of the tree-structure topology: Body \mathcal{B}_j have one or more children \mathcal{B}_k with $k \in \{\text{children}(j)\}$, and \mathcal{B}_i is the parent body of \mathcal{B}_j (with $i < j < k$). A link between two bodies is identified by the number of his child body. (ie. link between \mathcal{B}_j and \mathcal{B}_k is \mathcal{L}_k) This recursive algorithm is divided in two steps. First, we go up through the tree (from terminal bodies to the root) recursively to compute \mathbf{M}_j^e and \mathbf{F}_j^e (respectively the equivalent mass-matrix and force-vector) equations (7). They include dynamic effects of all children sub-tree on this body.

Secondly, starting from the root of the tree and go down, each local sub-system (equations 8) is solved in equations (9).

$$\begin{aligned}\mathbf{M}_j^e &= \mathbf{M}_j + \sum (\mathbf{J}_k^j)^t \mathbf{K}_k^{-1} \mathbf{J}_k^j \\ \mathbf{F}_j^e &= \mathbf{F}_j + \sum_k (\mathbf{J}_k^j)^t \mathbf{K}_k^{-1} \{\gamma_k - \mathbf{J}_k^k (\mathbf{M}_k^e)^{-1} \mathbf{F}_k^e\} \\ \mathbf{K}_k &= \mathbf{J}_k^k (\mathbf{M}_k^e)^{-1} (\mathbf{J}_k^k)^t\end{aligned}\quad (7)$$

This system provides a more simple equations set, local to body \mathcal{B}_i

$$\begin{aligned}\mathbf{M}_j^e \dot{\mathbf{h}}_j + (\mathbf{J}_j^j)^t \boldsymbol{\lambda}_j &= \mathbf{F}_j^e \\ \mathbf{J}_j^i \dot{\mathbf{h}}_i + \mathbf{J}_j^j \dot{\mathbf{h}}_j &= \gamma_j\end{aligned}\quad (8)$$

This local system (8) is solved as follows ($\dot{\mathbf{h}}_i$ is supposed to be known) :

$$\begin{aligned}\boldsymbol{\lambda}_j &= (\mathbf{J}_j^j (\mathbf{M}_j^e)^{-1} (\mathbf{J}_j^j)^t)^{-1} \left(\mathbf{J}_j^j (\mathbf{M}_j^e)^{-1} \mathbf{F}_j^e + \mathbf{J}_j^i \dot{\mathbf{h}}_i - \gamma_j \right) \\ \dot{\mathbf{h}}_j &= (\mathbf{M}_j^e)^{-1} (\mathbf{F}_j^e - (\mathbf{J}_j^j)^t \boldsymbol{\lambda}_j)\end{aligned}\quad (9)$$

Systems with closed kinematic loops are more complicate to solve than tree-structured systems. Joint variables introduced are not independent. As it is hard to determine an independent set of variables, resolution of such systems is difficult. A classical approach [7] considers such system as tree-structured by cutting all closed-loops and introducing constraint equations

$$\boldsymbol{\Phi}_c(\mathbf{q}) = 0 \quad (10)$$

that introduce constraints forces expressed by $\mathbf{J}_c^t \boldsymbol{\lambda}_c$. Added to the previous dynamics equation (6):

$$\begin{bmatrix} \widehat{\mathbf{M}} & \mathbf{J}_c^t \\ \mathbf{J}_c & 0 \end{bmatrix} \begin{bmatrix} \widehat{\mathbf{q}} \\ \boldsymbol{\lambda}_c \end{bmatrix} = \begin{bmatrix} \widehat{\mathbf{F}} \\ \boldsymbol{\gamma}_c \end{bmatrix} \quad (11)$$

A classical method consists in solving equation (11) for $\boldsymbol{\lambda}_c$ in the first place. This is particularly well adapted when ($n \gg m_c$), as computational cost is in $O(n m_c + m_c^3)$. (m_c is the number of closed-loops.)

$$\mathbf{J}_c \widehat{\mathbf{M}}^{-1} \mathbf{J}_c^t \boldsymbol{\lambda}_c = \mathbf{J}_c \widehat{\mathbf{M}}^{-1} \widehat{\mathbf{F}} - \boldsymbol{\gamma}_c \quad (12)$$

The algorithm used in our simulator is based on the Augmented Lagrangian method. It is a penalty method that reduces complexity to $O(n m_c + m_c^2)$. $\boldsymbol{\lambda}_c$ is computed iteratively (methodology and convergence condition are described by Andrade in [4]). c is the penalty coefficient.

$$\begin{aligned}\widehat{\mathbf{q}}^k &= \widehat{\mathbf{M}}^{-1} \widehat{\mathbf{F}} - \mathbf{J}_c^t \boldsymbol{\lambda}_c^k \\ \boldsymbol{\delta}^k &= \mathbf{J}_c \widehat{\mathbf{q}}^k - \boldsymbol{\gamma}_c \\ \boldsymbol{\lambda}_c^{k+1} &= \boldsymbol{\lambda}_c^k + c \boldsymbol{\delta}^k\end{aligned}\quad (13)$$

The choice of this method is motivated by its efficiency in terms of computation time. Furthermore, Lagrange multipliers approach offers the possibility to integrate dynamically new bodies and simplifies the integration of ground interactions. It is also well adapted for the description of various topologies. The simulation diagram in figure 2 summarizes all the simulation process and shows data flow between each module.

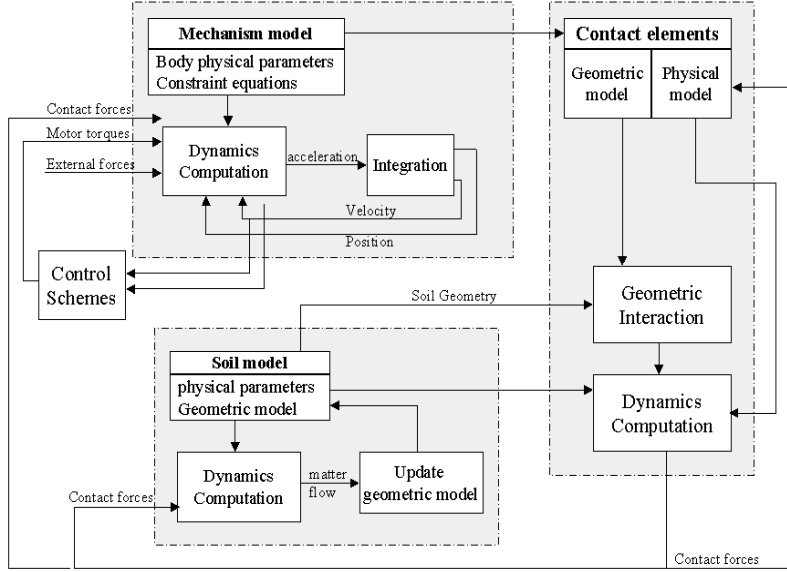


Figure 2: Simulation diagram

3 Robot-ground interaction model

The main motivation in development of this simulator relies on the integration of interactions between robot and ground. The interaction model is divided in two parts : one for the soil dynamic behaviour, another for the contact model between the locomotion organs and the ground.

3.1 Contact model

Locomotion organs are considered as objects, flexible or not, defined by their shape. Ground geometry is defined by elevation map. Then, considering interactions between an object and the ground, the model is divided in three part :

- Collision detection that provides normal force F_n
- Friction model that gives tangential force F_t
- soil and object deformation due to contact force

Collision detection is based on an elastic model of solid penetration known as compliant contact model [12]. Solid shape is divided in elements of a basic shape like triangles. The distance between each element and the ground is computed. If the distance is negative, a normal force due to the deformation of soil and solid results. This force determination is explained in the next section.

The friction model derives from Coulomb law which gives the relation between force ratio $\frac{F_t}{F_n}$ and slipping velocity g (figure 3). Because of a discontinuity around $g = 0$, this model is not adapted for slow slipping velocity. Therefore, we consider another model which concerns evolution of the force ratio for a relative displacement X between the locomotion organ and the ground ($\frac{F_t}{F_n} = f(X)$). It is a semi-empirical model based on a precise description of friction phenomena [4]. This model allows to compute F_t for a given F_n and g .

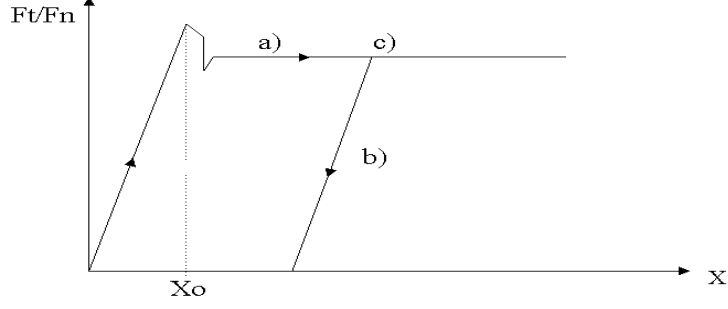


Figure 3: Friction model of sandy soil

3.2 Soft soil model

As said in section 1, there are different dynamic models of soil that depend on its nature. In this paper, we focus on a model of granular soil composed by agglomerated particles, like a sandy soil. Granular soil has a complex behaviour. Nature of such material is not easy to define, it can be considered as a solid or as a fluid, depending on its stress state. Studies on granular soil have been done from a microscopic point of view. Each particle is seen as a solid of complex shape. The application of the Newton's law and interaction laws between grains makes it possible to express the equation of motion of each particle. This provides a realistic model but requires high computational resources, so it is not adapted for this simulation. Our approach is macroscopic and interests global behaviour of granular soil [8]. We propose a planar model that can be extend to 3D. This model is based on finite elements approach where soil is divided in column cells. Each column interacts with its two neighbours. The model description is divided in two separated parts: the first one is dedicated to the soil behaviour without external solicitations, the second one concentrates on soil behaviour under external forces due to robot interactions.

Surface-free behaviour. In this case, the soil behaviour only submitted to gravitation field is studied. When soil slope angle α is higher than critical slope angle, an avalanche can result from a small perturbation. Avalanche is a surface flow of the matter and could be described using fluid dynamics equation. The computing of critical slope angle β_0 is given in [11]. Let's consider in figure 4, a volumic element edx which weight is W_i and sliding along a slope α . γ is its unit mass, ν its kinematic viscosity factor and g the gravity. Friction forces between particles are considered as viscous forces. The dynamic equation along \vec{x} axis gives:

$$\ddot{x} \gamma e dx = -\nu \dot{x} \gamma e dx + g \sin(\alpha) \gamma e dx \quad (14)$$

where x is of a volumic element (fig 4). Flow velocity \dot{x} is extracted from the dynamic equation:

$$\ddot{x} = -\nu \dot{x} + g \sin(\alpha) \quad (15)$$

then matter flow Φ_i across segment i can be computed:

$$\Phi_i = \gamma \dot{x} \cos(\alpha) e = \frac{\Delta W_i}{\Delta t} \quad (16)$$

The relation between mass variation ΔW_i and height variation ΔH_i due to matter flow

across segment i can be expressed as follow:

$$\Delta W_i = (\Delta H_i + \Delta H_{i-1})\gamma \frac{l}{2} \quad (17)$$

And considering volume conservation and boundary constraints:

$$\Delta W_i = \Delta H_i \gamma \frac{l}{2} + \Delta W_{i-1} \quad (18)$$

$$\Delta H_i = \frac{2\Delta t}{\gamma l} (\Phi_i - \Phi_{i-1}) \quad (19)$$

Soil behaviour under robot action. Rover action on soil is mainly vertical and results from the gravity. Vertical interaction studies are based on a triaxial test [5] which gives the soil behaviour under vertical solicitation. This test consists in applying a vertical force F to a soil sample laterally surrounded by an elastic and impermeable membrane submitted to an hydrostatic pressure P_0 (fig 5). Triaxial test provides a curve of soil deformation under vertical force as show in fig 5. The mathematical model of this curve allow to compute the normal force F_n due to robot action. The friction model defined previously, allows to compute the tangential force F_t . The second curve of fig 5 represents volume variation under vertical deformation. It allows to define the column matter flows toward the adjacent columns ($i - 1, i + 1$) and to compute column height variation ΔH_i .

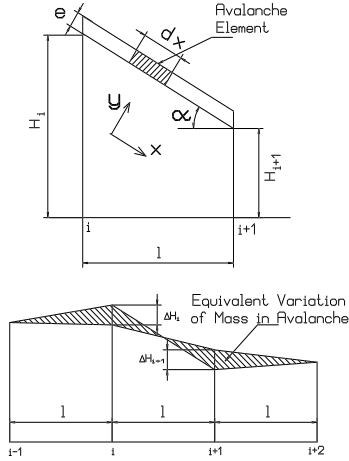


Figure 4: Soil element in avalanche flow

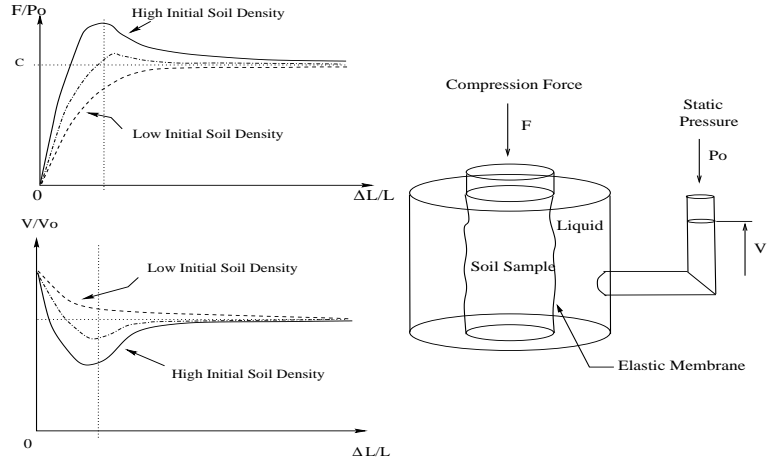


Figure 5: Triaxial test

4 Conclusion

We proposed a simulator that allows to evaluate the dynamic behaviour of mobile robot evolving on granular soil. The main objective is to study optimization of locomotion modes of a mobile robot with hybrid locomotion device [6] on unstructured sandy soil. We have investigated several locomotion modes like purely wheeled or peristalsis ones by evaluating the power consumption to achieve slope climbing task. These studies are to be extend to any kind of mobile robot due to the generic model of contact. The fig 6 shows the simulation of a wheeled vehicle climbing over a slope, and the fig 7 illustrates the

integration of closed loops with a system representing a leg in contact with the ground. In the future, this simulator will integrate flexible bodies like tires, tracks or any locomotion organs and passive suspension. Other type of soil will also be added like ones composed by agglomerated rocks, encountered in planetary or volcanic exploration.

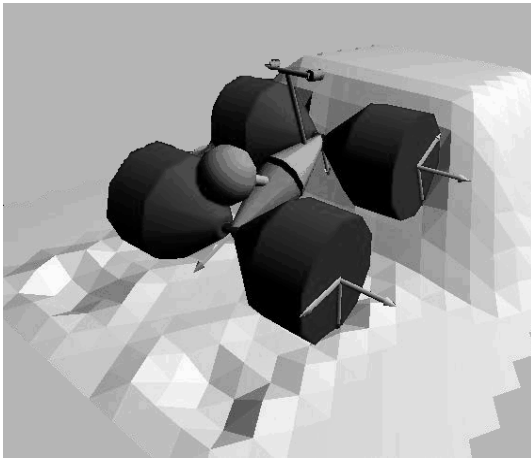


Figure 6: A wheeled vehicle on a slope

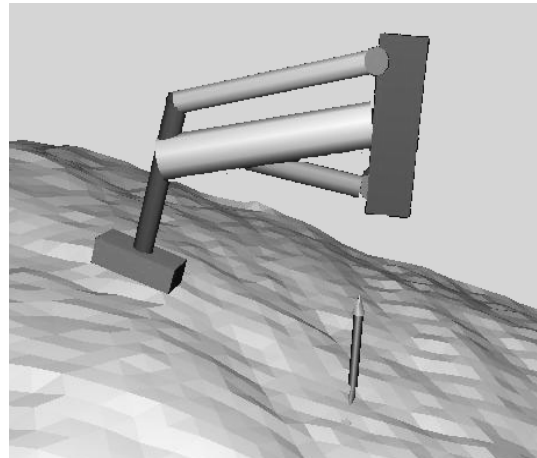


Figure 7: Simulation of a leg on a slope

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