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APPLICATIONS OF THE VIRTUAL INTELLIGENT PORTABLE VIPRO PLATFORM FOR 3D CONTACT PROBLEMS WITH FRICTION IN THE HUMANOID ROBOTS CONTROL

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Abstract: *In this paper we investigate the influence of the friction force while the robot is doing different actions. By computing the limit conditions for the robot walking according to the friction force between ground and feet, we have found the maximum safe values for a walking step and other stability conditions, according to the walking slope and type of the support surface. The motion trajectory positions of the robot leg end-effector and joints with reaction forces are analyzed and the virtual projection method is adopted using the Versatile Intelligent Portable Robot Platform VIPRO. The presented simulations demonstrate through a numeric modeling of the 3D contact problems with friction, that we can detect the slip/stick phenomenon for a walking robot motion on a uneven terrain, so it can improve the real time control to predict and avoid robot overthrow. The obtained results lead to the development of new technological capabilities of the control systems.*
Keywords: *mobile robots, stick/slip motion, NAO robot, virtual projection*

1. INTRODUCTION

Humanoid robots use bipedal walking to move from point to point [1]. This means that the dynamic motion control should be planned according to every possible perturbation that can hinder the walking process [2, 3]. One of these is the slipping conditions [4, 5] for each robot feet which can destabilize the walking process. To compensate for this, many walking robots compensate through dynamic control all the forces that are present within the robot joints. But only some robots actually take into account the slip conditions to compensate additional forces [2, 6].

In bipedal walking, robots will often encounter slip conditions [5-7]. These positions must be avoided, and unless their trajectory will keep them outside the dangerous areas of kinematic positions, the slip conditions become active. In these cases, the robot joint control will also have to compensate for the slip forces, so that the slip/stick conditions will fall back to the stick state [4, 5].

For the friction problem, a reference on analysis and numerical approximations of contact problems involving elastic materials with or without friction is given by Kikuchi and Oden [8]. This is concerned by the effects of friction at the interface accurately and of the non-penetration constraints at contact boundary of deformable bodies being in a mutual contact [9-13,19]. The non-smooth friction law and the non-penetration constrains depend on time [4].

The aim of this paper is to obtain a mathematical algorithm and a chart for the slip/stick conditions for a bipedal walking robot according to different center of mass position regarding the robot feet and on different values of the friction coefficient. The robot chosen is the NAO robot, from which we have taken its measurements and added into the testing simulation of our algorithm.

The obtained results are an application of the virtual intelligent portable VIPRO platform [14, 18], which analyzes the problem of friction during robot walking. By using the VIPRO platform, we can improve the stability performances of robot motion in a virtual and real environment on unstructured and uneven terrains. This will lead in building more efficient mobile robots by adding different control methods [15-17, 18, 19] which can benefit from the robot feet friction research [4, 5].

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2. STICK/SLIP CONDITIONS

The three-dimensional frictional model consists of a mass M, with three translational degrees of freedom, u_1, u_2 and u_3, with constrain $u_3 \geq 0$, that can make contact with a rigid plane surface at which the frictional coefficient is μ. The mass M is connected to a generalized linear elastic support with stiffness and damping matrices K, C, respectively, and is subjected to an externally applied forces F. When the mass makes contact with the plane ($u_3=0$), induces a reaction force R (R_1, R_2, R_3) [4].

2.1. States of the system

For any given time there are three states of the contact nodes: separation (open contact), stick or slip. But in 3D case the slip state has two components in the contact plane surface [4]. These states are defined by the conditions:

1) Separation (open contact)
For this case the mass may lose contact with plane and there is no reaction between the mass and plane:

$$u_3 \geq 0 \text{ and } R = 0 \tag{1}$$

and for R = 0 and $u_3=0$ the state is a limiting state of separation.

2) Stick
Stick is the state when the mass makes contact with the plane and is not moving:

$$\begin{gathered} u_3 = 0 \\ \dot{u} = 0 \end{gathered} \tag{2}$$

and the normal reaction be compressive:

$$R_3 > 0 \tag{3}$$

The Coulomb friction law demands that:

$$\sqrt{R_1^2 + R_2^2} < \mu R_3 \tag{4}$$

3) Slip
For slip must have:

$$\begin{gathered} u_3 = 0 \\ R_3 > 0 \end{gathered} \tag{5}$$

and the Coulomb friction law demands that:

$$R_k = -\frac{\mu R_3 \dot{u}_k}{\sqrt{\dot{u}_1^2 + \dot{u}_2^2}}, \qquad k = 1,2 \tag{6}$$

i.e. the result frictional force has the magnitude of and is in a direction opposing the instantaneous motion direction [4].

3. MATH MODEL AND SLIP/STICK DETECTION ALGORITHM

Before explaining the mathematic model we need to present the robot structure on which we have made the testing and simulations. The bipedal robot that we have used is the robot NAO (figure 1).

Figure 1: NAO robot

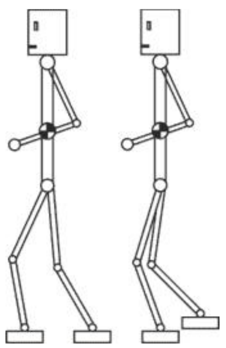


Figure 2: Walking robot summary diagram

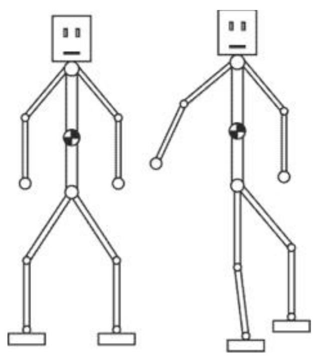


Figure 3: Other robot positions

This robot has become very popular within the scientific community and in the academic area in which students learn to control its behavior for different stimuli. This is why we have chosen this robot which is accurately presented by Goualier et. all [20], from where we have taken the robot technical data. Starting from the original kinematic diagram, we have made figures 2 and 3. These images show the simplified diagram of the robot, removing most of the links and joints to a point that helped us in presenting different positions of the robot while not removing the joints that helped the robot to reach certain positions within its kinematic space.

To test the slip/stick conditions, we didn't have to use the whole system of links and joints. For that we have made a simplified model of the legs and center of gravity to allow us to easily compute and demonstrate the slip/stick conditions.

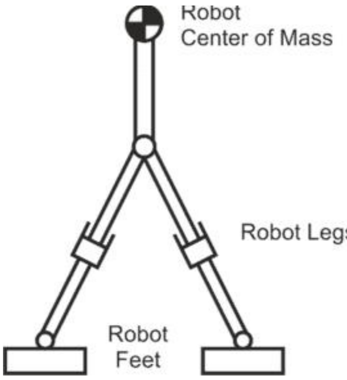


Figure 4: Over simplified robot diagram to show only the points of interest

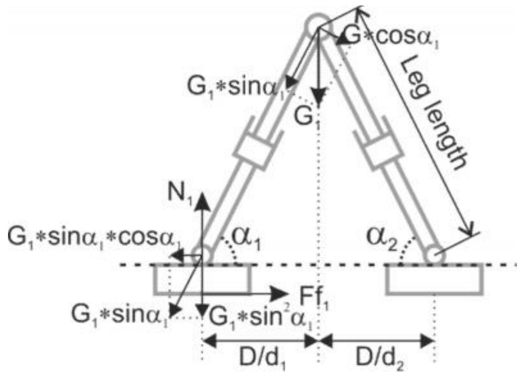


Figure 5: Weight force decomposition for leg 1

Figure 4 presents the walking robot diagram as needed for the slip/stick detection algorithm. The detection algorithm needs the position of the Center of Mass (COM) of the entire robot, which for our simulation we'll take only above the hip and change the hip position to achieve all the possible kinematic positions. For this we have another simplification. The legs have rotation joints within the robot knees but for our simulation we can replace these with translation joints because we'll only need the leg extension which is equal to the distance between the robot feet to its hip.

Taking this into account, we have made the diagram from figure 5, which presents the force decomposition for one leg of the robot, where G is the weight of the entire robot, G_1 and G_2 are the distributed weights of the robot on each foot, α_1 and α_2 are the angles for each leg with the horizontal, D is the distance between the two feet, and d_1 and d_2 are the distances between each foot and the projection of the center of mass on the horizontal plane.

$$d_1 + d_2 = D \tag{7}$$

Before computing the friction force and the force acting on the foot, we need to compute the weight ration which is distributed on each foot.

$$G_{1,2} = G\frac{d_{1,2}}{D} \tag{8}$$

Knowing the weight value for each foot from equation (8), we then compute the force acting on the foot and the one that adds torque to the ankle, which are presented in equations (9) and (10), respectively.

$$G_x = G\sin\left(\sim\right) \tag{9}$$

$$G_y = G\cos\left(\sim\right) \tag{10}$$

Equation (10) will give us the static torque which will act on the robot foot after multiplying it with the distance from the force to the joint. But for our research we'll not use it. What we use is the force that is transmitted along the leg to the foot (G_x). This force will give us the friction force as in equation (11). The other force remaining is the one that pulls on the robot foot which is presented in equation (12).

$$F_f = \text{«}N = \text{«}G_x\sin\left(\sim\right) = \text{«}G\sin^2\left(\sim\right) \tag{11}$$

$$F = G_x\cos\left(\sim\right) = G\sin\left(\sim\right)\cos\left(\sim\right) \tag{12}$$

Using equation 11 and 12, in which μ is the friction coefficient and α is the angle between leg and horizontal, along with the stick condition in (4), we achieve the stick condition for our legs:

$$F < F_f \Leftrightarrow G\sin\left(\sim\right)\cos\left(\sim\right) < \text{«}G\sin^2\left(\sim\right) \tag{13}$$

Which is simplified to:

$$\cos\left(\sim\right) < \text{«} \sin\left(\sim\right) \tag{14}$$

This results in the next equation which we have used in our simulations:

$$\arctan\left(\frac{1}{\text{«}}\right) < \sim \tag{15}$$

So it all reduces to a condition between the angle that the horizontal is making with the line that goes through the robot ankle joint and its hip joint and the friction coefficient between the robot's feet and the walking surface. In addition to this, we can add the angle that the surface has with the ground horizontal, when the robot is walking on a slope and achieve a different result. But for our test cases we have used a horizontal walking surface so we can detect and easily interpret the results.

Algorithm 1: used for determining the stick/slip condition:

Step 1: Generate the distance between the two feet.
Step 2: Generate a new position of COG (center of gravity) of the robot.
Step 3: Validate COG position in respect to each foot.
Step 4: Compute mass distribution for each foot using equation (8).
Step 5: Compute angle between legs and horizontal, while knowing the position of COG and each foot.
Step 6: Check the slip/stick conditions for each leg using Equations (4), (11) and (12).
Step 7: Go Back to Step 2, until no new position can be found.
Step 8: Go Back to Step 1, until no new valid distance can be found.

Algorithm 1 is the actual algorithm we have used in our simulations, and the results are presented in the next section.

5. RESULTS AND CONCLUSIONS

Using the mathematical model and algorithm presented in this paper, we have implemented a Matlab simulation to prove our research. In the conducted simulations the initial conditions which we have used are presented in table 1.

Table 1: Simulation data

Parameter	Value
Minimum leg length	55 [mm]
Maximum leg length	200 [mm]
Robot weight	5,12 [Kg]
Distance between feet	5 [mm] – 140 [mm]

One initial condition we have imposed in the simulation is that the two feet are in constant contact with the support surface. If we'll have only one foot in contact with the ground then we'll have two cases the robot could be in. The first one is the support case in which the robot will support its entire weight on one leg and the center of mass will have to be within the support surface that for now is the footprint. The other case is when the center of mass is outside the support surface, in which case the robot will start falling and at some point slipping. But the slipping condition will not be the main problem at that point.

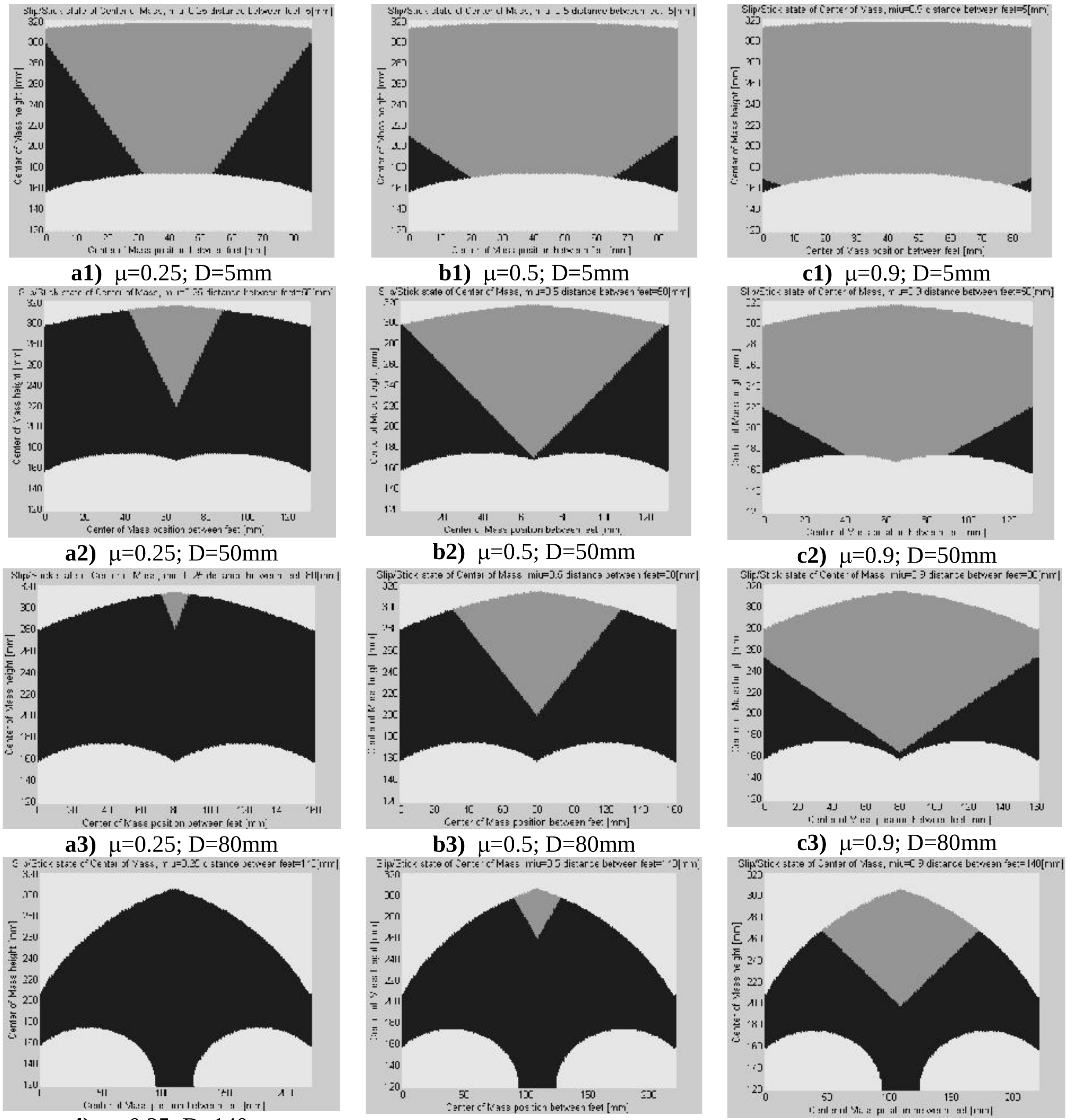
Having our first initial condition so that the feet are in constant contact with the support surface, we then add another one. The second condition is that the center of mass will be within the bounded area of the support surface, which is given by the two feet in contact with the ground. This will allow us to have a stable robot which will not be in critical overthrowing condition that is not related to the stick/slip effect.

Having the initial conditions, we then change the distance between the two feet and test in each case for different friction coefficients, the kinematic area in which the robot hip can be positioned and the stick/slip condition on each foot. If the condition on one of the legs for a certain point in space of the robot hip will meet the slip condition then that point will be considered dangerous and be marked on the diagram appropriately.

In figures 6 we have presented the results after simulation for different inputs, in which:

- The light grey areas are areas in which the center of mass can't be positioned due to the conditions in leg length.
- The darker grey areas are the positions for the center of mass where both feet will not slip and the stick condition is fulfilled.

- The black areas are the position for the center of mass in which the stick condition is not fulfilled and one of the feet can slip.



a1) μ=0.25; D=5mm **b1)** μ=0.5; D=5mm **c1)** μ=0.9; D=5mm

a2) μ=0.25; D=50mm **b2)** μ=0.5; D=50mm **c2)** μ=0.9; D=50mm

a3) μ=0.25; D=80mm **b3)** μ=0.5; D=80mm **c3)** μ=0.9; D=80mm

a4) μ=0.25; D=140mm **b4)** μ=0.5; D=140mm **c4)** μ=0.9; D=140mm

Figures 6: Simulation results for different values of D (distance between feet) and the friction coefficient

For the simulation, we have changed the friction coefficient to vary between 0.25 and 0.9, but we have shown only 3 values of it which are 0.25, 0.5 and 0.9. While varying the friction coefficient we have also change the distance between the two feet from 5mm up to 140mm.

In the conducted simulations for which we have presented figures 6 with the results, we can clearly see as expected that for smaller friction coefficients the robot can enter the slip area faster. Also, while increasing the distance between feet we can see that the stick condition is not fulfilled.

Another important observation is that for the robot to be in the stick area and its legs not slip on the support surface, it must have its center of mass as high as possible while the step length should be shorter, when the friction coefficient is smaller. This means that the control laws for robot trajectory and planning should take into account for the stick/slip conditions. In this way, the control law that acts on the robot joints torque can easily compensate for other dynamic forces and not worry about the slipping effect. It results that the torque needed for each joint to reach its target will not need to compensate for the torque value that can be found using equation (10).

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