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ANALYSIS OF COMPLIANT JOINT FOR PLANAR LEGGED ROBOTS

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Abstract. *In the last years there was a considerable advance on mobile robotics. Wheeled robots found limitations while navigating on uneven or rough terrains. These limitations and the observed movements capacity of legged animals provide good insights for researchers looking for modeling and building bio-inspired legged robots. Bio-inspired robots should have some complacency during the movement of its structure while following the planned trajectory. The purpose of this article is to evaluate the behavior of a planar robot leg with three revolute joints with added compliant elements on its system. There should be external forces to the system, representing the body's weight, in order to verify the system's response regarding torques, keeping the system in static equilibrium, as well as regarding position/speeds. In order to achieve these results a procedure will be followed to couple the kinematics and statics. For the analysis development, screw theory and Davies method is going to be applied. The screw theory allows a simple and essential view of the behavior of bodies and joints, and it is possible to make parallels between instantaneous kinematics by one hand and statics by another. This way, it is possible to work on angular and linear velocities, forces and moments. Davies method is applied to static and kinematics analysis of the mechanism. The use of compliant elements will be made while applying kinematics targeting joints position, and the forces and moments are produced as a result for the compensations that holds the system equilibrium. The analysis of the results for compliant elements on joints will allow the evaluation of compliant actuator, so that it will be possible to add complacent joints on structures that were primarily build with no complacency. Finally, as a work in progress, a systematic could be developed, with generalization for spatial robotic systems.*

Keywords: legged robot, compliance, kinetostatic, Davies Method

1. INTRODUCTION

In order to get a real automation during interventions on remote, restrictive and irregular environments, robots must be capable of movement over irregular ground and provide six degrees of freedom to manipulate tools. Legged robots are good candidates for this purpose, since they arise as an important solution to overcome rough terrains, climb stairs and maneuver thru obstructed passages. There are some different categories of legged robots, including biped, triped, quadruped, hexapod and octopod (Agheli *et al.* (2014)). In general, for legged robots, the environments must be considered unstructured, so the robot is unconfined and must interact with the environment in order to act and accomplish tasks. These contacts the robots do with the environment are still hard to be modeled and perceived, and the forces that emerge from the contacts cannot be absorbed by rigid structures (Hoffmann and Simanek (2017)).

With these characteristics in mind, this study is focused on the integration of kinematics, statics and complacency. This research uses as a study case a planar robotic leg composed by one body simulating a mass of 20 kg (200 N weight) and three revolute joints, and on one of these three, the knee joint, a spring is added, simulating an elastic element. The purpose is to evaluate the kinetostatic behavior of a structure composed with elastic elements, as well as the friction analysis of the foot contact points on the ground.

There are some researches on legged robots related to kinetostatic or composed with elastic elements. Jun *et al.* (2006) and Alamdari and Krovi (2016) explore articulated subsystems combining legs and wheels, looking for kinetostatic optimization. These papers present the project parameters and how these parameters affect the locomotion performance evaluating, for example, the kinematics effects of different link lengths, the static effects due to the spring stiffness. Toscano *et al.* (2018) presents a new kinetostatic model for a humanoid robot based on screw theory, virtual Assur chains and Davies method.

The elastic elements are important to improve the dynamics of robotics systems, and Hutter *et al.* (2012, 2014) developed a quadruped robot with articulated legs for researches including static and dynamics. The elastic serial actuators

are implemented in all joints by using linear compression springs. Portman (2020) developed a new method to define the stiffness values of an elastically supported system defined through the dimensionally inhomogeneous robot stiffness matrix (RSM). The method is applied to serial or parallel robots, and performance index for kinetostatic are presented. Zhong *et al.* (2019) provides a data collection on existing robotic legs for quadruped robots, classifying them into categories evaluating the project methods for the actuators and mechanical structure of the legs, making a proposal for a future development for quadruped robot.

Some of the cited researches (Jun *et al.* (2006); Alamdari and Krovi (2016); Hutter *et al.* (2012, 2014)) presented specific approaches that are applied to particular scenarios, providing no possibilities for methodological generalization. Toscano *et al.* (2018), by the other hand, presents a model based on screw theory and Davies method for biped robots, by using some common tools with this paper, but do not includes compliant joints. Finally, Zhong *et al.* (2019) reviews different designs for robot legs.

The innovation here presented is the evaluation of the interaction between kinematic and statics, regarding the presence of the elastic element and its impact on the static stability. This evaluation is made by using a developed method for coupling resolution, in a iterative process, and applies screw theory in both domains (kinematics and statics).

2. FUNDAMENTAL TOOLS

The movement of a rigid body can be evaluated by using screw theory. An historic review about this subject can be seen in Ceccarelli (2000) and Dai (2006). There are registers that in 1763, the Italian mathematician Giulio Mozzi made some references about the instantaneous movement axis and, in 1830, the general movement theorem for rigid bodies was introduced by Michel Chasles. In 1990, Ball presented the formal system based on screw theory for rigid body mechanics. On mechanics, specially on rigid body kinematics and statics, angular and translational speeds of a body combines as a twist on a screw; in the same way that a force and a binary combine as a wrench on a screw.

The development of a kinetostatic model proposed for a planar legged robot was based on the following tools: Screw Theory, Davies method, Virtual Assur Chains and Graph Theory. These subjects are presented on details in several references: Screw Theory (Hunt (2000)), Davies Method (Davies (1981); Cazangi (2008)), Virtual Chains (Campos *et al.* (2005)).
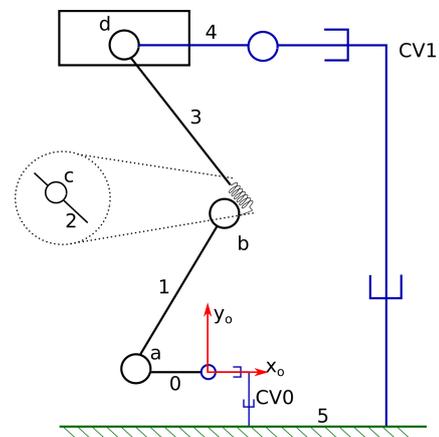
3. KINEMATICS AND STATICS MODELS

On this section details are presented about the models developed, as well as the analysis for some selected cases.

3.1 Planar legged robot

The schematics of the topological structure of a planar legged robot is presented on Fig. 1a. The structure is composed by 4 rigid bodies (body/torso, upper leg, lower leg and foot), these bodies are connected by three revolute joints. For this research the rigid body dimensions are based on the typical human sizes (Contini (1972)), so that the foot dimension is $l_1 = 0.152H$, lower leg is $l_2 = 0.246H$ and upper leg is $l_3 = 0.245H$. The average human height of $H = 1.73$ m was assumed, evaluating the average size of Brazilians from 20 to 29 years (IBGE (2008)). A total weight of 20 kg was considered for the Torso. On the structure, an elastic element (spring) was added on the joint between upper (l_3) and lower leg (l_2), so that the complacency effects on the structure can be evaluated.
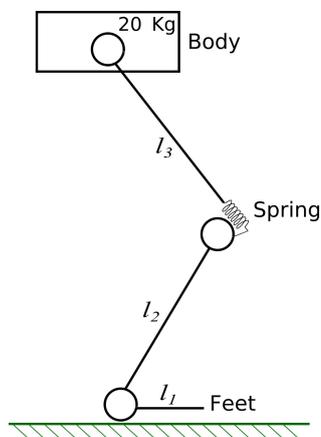
(a) Model of a planar robot.　　　　(b) Labeled planar legged robot model with added virtual chains.

Figure 1: Planar Robotic Leg.

3.2 Kinematic Model

For the leg kinematic model a typical screw theory was applied. The first step is the definition of the geometric data of the screws for the initial configuration. The first joint is related to the heel, and the last one is located on the torso, and the initial pose is regarded as the upright position. On this base the screw parameters listed on Table 1 are found.

Table 1: Screw Parameters

Joint	s	s_o
a	(0;0;1)	$(-l_1;0;0)$
b	(0;0;1)	$(-l_1;l_2;0)$
d	(0;0;1)	$(-l_1;l_2 + l_3;0)$

Since all the structure joints are revolute, the formulation on Eq. (1) are applied in order to define the screws.

$$\hat{\$} = \begin{bmatrix} \mathbf{s} \\ \mathbf{s_o} \times \mathbf{s} \end{bmatrix}; \qquad \$ = \hat{\$}\dot{q} \tag{1}$$

In order to have a closed chain so that the Davies method could be used, virtual chains are added, as in Fig. 1b. For this study analysis, it is assumed that the foot is constantly in contact to the ground, so that, for the kinematics point of view, CV0 is null, while CV1 is going to be defined in order to impose movement to the robot's body.

This way, the Davies formulation for the inverse kinematics is as presented on Eq. (2), that is totally defined, since there are three secondary joints (with positions to be defined, on the robot leg), three primary joints (with positions imposed by CV1: translation on x, y and rotation on z), while the space has $\lambda = 3$.

$$\dot{q}_s = -N_s^{-1} N_p \dot{q}_p \tag{2}$$

It is worth noting that the presence of the elastic element does not modifies the kinematics computation. There are two main reasons for that: Firstly, the deformation isn't still known, since the torques on the joints aren't known. Secondly, as will be shown later on, the deformation is going to be assumed as an alteration of the angular parameters on θ joints, and, as such, aren't considered as an input for the kinematics model. With this formulation, there is no need to adapt the kinematic modeling for complacent elements.

3.3 Static Model

The starting point is the same constructive model from the kinematics, with the structure including two virtual chains. In Fig. 2 all the forces that occurs on the system elements can be seen. From this model, as defined by Cazangi (2008), for the static analysis, the mechanism must be over-constrained in order to prevent any kind of movement. As such, all the external actions must be internalized, being substituted by passive couplings equivalents. The external forces and moments, acting between the external bodies (or environment) and internal bodies through the coupling network, are exchanged for equivalent actions between bodies on the evaluated network (Cazangi (2008)).

Regarding the external forces, it is assumed that the foot has two contact points to the ground: the heel and the toe. As such, the reactions from the floor are modeled as additional external forces. On the heel there is a normal force $^{N}f_y$ and a friction force $^{af}f_x$, while these two forces on the toe are modeled directly by using CV0, as well as the necessary moment for the stability of the foot (as a rigid body).

The analysis is made by using Davies method applied to twists. The spatial position of each joint is important in this step, since the localization where the forces are applied changes the static equilibrium of the system.

The action graph over bodies is depicted in the Fig. 3, in which every edge is expanded if the constraint degree of the evaluated coupling is greater than 1. Each edge of the graph is substituted by the action screw, that is, by the twist that represents the constraints applied to each joint of the mechanism.

From the fundamental cuts k_i on the graph, the f-cuts expanded matrix $[Q_A]_{k \times C}$ is build (Eq. (3)), as well as the unitary actions matrix $[\hat{A}_D]_{\lambda \times C}$ (Eq. (4)), in which k is the number of cuts, C is the gross constraint degree, λ is the space dimension.

$$Q_A = \begin{array}{c} \\ k_a \\ k_b \\ k_c \\ k_d \\ k_e \end{array} \begin{bmatrix} ^{a}f_x & ^{a}f_y & ^{a}m_z & ^{af}f_x & ^{af}f_y & ^{af}m_z & ^{b}f_x & ^{b}f_y & ^{b}m_z & ^{c}f_x & ^{c}f_y & ^{c}m_z & ^{d}f_x & ^{d}f_y & ^{d}m_z & ^{V0}f_x & ^{V0}f_y & ^{V0}m_z & ^{V1}f_x & ^{V1}f_y & ^{V1}m_z \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & -1 & -1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{3}$$
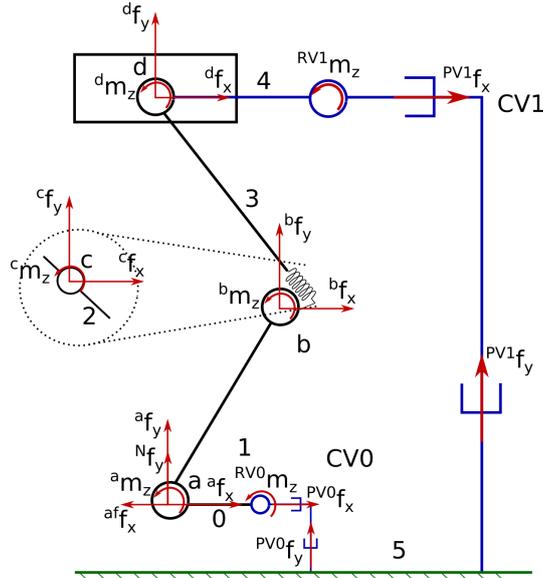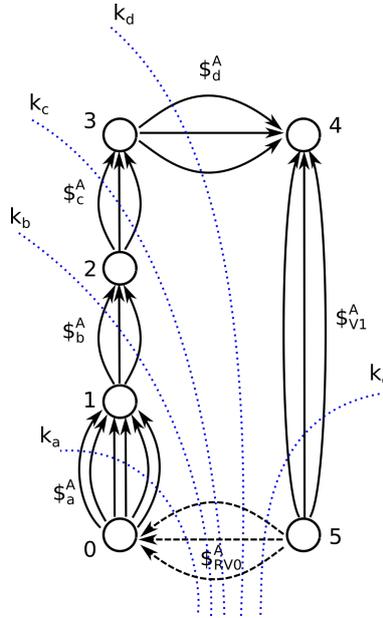
Figure 2: External forces on the structure.

Figure 3: Graph representation.

$$
\hat{A}_D = \begin{bmatrix} -a_y & a_x & 1 & -a_y & a_x & 1- & b_y & b_x & 1 & -c_y & c_x & 1 & -d_y & d_x & 1 & -v0_y & v0_x & 1 & -v1_y & v1_x & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (4)
$$

The unitary action network matrix $\hat{A}_N$ is then defined (Eq. (5)), by multiplication of the unitary actions matrix ($\hat{A}_D$) by the resulting matrix of the diagonalization of each line of the f-cuts matrix (Q_A).

$$
\hat{A}_N = \begin{bmatrix} \hat{A}_D \cdot diag(Q_A(1,:)) \\ \hat{A}_D \cdot diag(Q_A(2,:)) \\ \hat{A}_D \cdot diag(Q_A(3,:)) \\ \hat{A}_D \cdot diag(Q_A(4,:)) \\ \hat{A}_D \cdot diag(Q_A(5,:)) \end{bmatrix} \quad (5)
$$

The same way that occurs in kinematics, the action network matrix is splitted into primary and secondary, so that for

primary elements where chosen 6 elements: forces and external torque on heel (3 elements), torque on toe (1 element), horizontal and vertical forces on the torso (2 elements).

By this procedure, it was possible to compute all the remaining elements for the static condition by using Eq . (6).

$$\Psi_s = (-A_{N_s}^{-1} \cdot A_{N_p}) \cdot \Psi_p \tag{6}$$

3.4 Ground-foot contact points

The foot was modeled with two contact point with the ground: one on the heel and one on the toe. In order to define the acting forces on these points, an movement equation system is constructed for the whole system. In this system, the external forces are those applied horizontally and vertically by CV1 on the torso; the normal forces over both points of contact; and the friction forces on both points.

From the rigid body equilibrium equations the normal forces and friction forces can be computed, as well as the required moment on the toe (that will be provided as primary elements on Davies static computation), as a function of the external defined forces (horizontal an vertical forces on the torso). This way, it is possible to define all the primary elements for the static computation.

Regarding the non-equilibrium conditions, they can be observed when at least one of the normal forces on the contact points is less or equal to 0, meaning that one of these points lost the contact to the ground. On the same way, the maximum allowable friction, modeled by $f_{at,max} = \mu \cdot {}^N f$, becomes 0, ensuring the loss of contact. For the friction, it was assumed $\mu = 0.3$, which is the typical friction between steel and concrete.

Summarizing, two stability failure modes were evaluated:

- Normal force on at least one point of contact < 0, characterizing loss of contact to the ground;

- Required friction (computed from the system external forces) higher than the maximum friction ($f_{at,max}$), characterizing the body slippage.

3.5 Flexible element model

The flexible element was added to the knee joint (joint b in Fig. 1a), as a complacent coupling that allows a deformation on the same axis that the actuator applies torque. The complacent element is revolute, and the assumed model for this element is presented in Eq. (7).

$$\tau_c = k \cdot \delta \tag{7}$$

The element is subject to the same torque that occurs on the knee joint, τ_c is the reaction to torque τ_b, being possible to directly compute the deformation from Eq. (8).

$$\delta = -\tau_b/k \tag{8}$$

The resulting deformation, by the nature of the complacent element, is an angular displacement and, this way, induces a total angle on the knee joint that is different from the direct definition of θ_b from the original kinematics.

It is important to notice that, by changing the total angle on the knee, all the kinematics analysis is invalidated and, as a consequence, the static that was used as the starting point for this same displacement is invalidated as well. Further on it will be presented the computation method applied in order to solve this recursive problem.

3.6 Kinetostatic Model

The procedure presented by Toscano *et al.* (2018) allows the computation of the kinetostatic model variables. The computation is made first for the kinematics and, afterwards, for the statics. The order is important, since the position of every joint is an input for the statics.

The point with complacent elements is that they provide displacement as a function of the stress over them. This means that, with complacent elements, the kinematics is statics-dependent, since the statics defines the stress over the elements of the system.

Because of that, there is a coupling that requires simultaneous resolution in order to find the state of the system. For the presented results the procedure was adapted from Toscano *et al.* (2018), computing multiple times the kinematics and statics until a set of parameters is found for the system equilibrium including the complacent element.

As for the number of required iterations of this procedure, the initial position requires a greater number of iterations, since the first guess of the displacement is null. After the initial equilibrium is achieved, the quasi-static movement is

computed (with speed or displacement small enough in order to disregard dynamic elements), and the iterations for this new configuration uses as first guess the previously computed displacement. This way, less iterations are needed in order to achieve the defined tolerance.

4. NUMERICAL RESULTS

In order to evaluate the behavior of the system including a complacent element, the first kinematic task assigned is a small vertical displacement of the body (50 mm), so that the torso makes the downward movement and upwards, returning to the initial position. Small displacement and speeds were selected, being characterized as a possible subject to kinetostatic analysis, in dynamic effects neglected.

Two different scenarios were evaluated regarding external forces. In the first scenario, the movements are accomplished with an acting force in the negative vertical direction on torso, representing the body's weight over the leg. On the second scenario, results are presented for two different magnitudes of horizontal forces. The results for the system with and without complacency are evaluated for each case, including stability analysis regarding maximum and required friction.

4.1 Vertical Force

For the first scenario, a vertical force of 200 N is applied over the torso, as a representation of the body's weight over the leg. It is expected that, by the act of this force, there is some deformation on the complacent joint. With this external force condition, the static is computed for every point of the movement trajectory, in order to get the desired movement of the torso (vertical displacement of 50 mm downward and return to initial position).

The maximum point of deformation of the complacent joint is exactly the lower position of the torso, which is expected, since this is the position of maximum torque on the knee. For this configuration, the comparison of the leg pose can be observed in the Fig. 4.
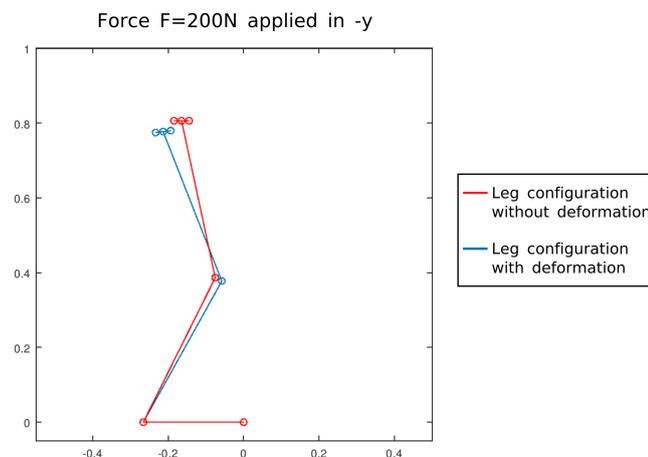

Figure 4: Leg configurations for a vertical force of 200 N.

4.2 Composition with vertical and horizontal forces

Two scenarios are applied to evaluate the proposed movement. The first scenario is made by the applied force of 5 N on the -x direction, over the torso. The second scenario increases this applied force to 10 N on the same direction. In Fig. 5 the joints torques are presented for these two scenarios.

In Fig 5 a) the torque over time is presented for every joint, considering the leg with and without complacent element. It is possible to observe significant differences on the behavior on the knee and heel when comparing both cases. On the knee, considering the use of a complacent element, the torque was presented between -8 Nm and -34 Nm. Without the complacent element, the torque lies between -4 Nm and -20 Nm. The added complacent element can result in increased efforts regarding the maintenance of static position when subject to external forces. An explanation for this effect is that the deformation induced by the external forces displaces the body further away from the equilibrium and this situation must be compensated with more power on the joints motors.

There is no doubt that the added complacency add some advantages to the properties of the system, above all in the dynamic front (better tolerance to perturbations, rough terrains, collisions), but it is inescapable the fact that, by addind these elements, it is expected greater efforts in some circumstances, such as the case of external forces that induces the
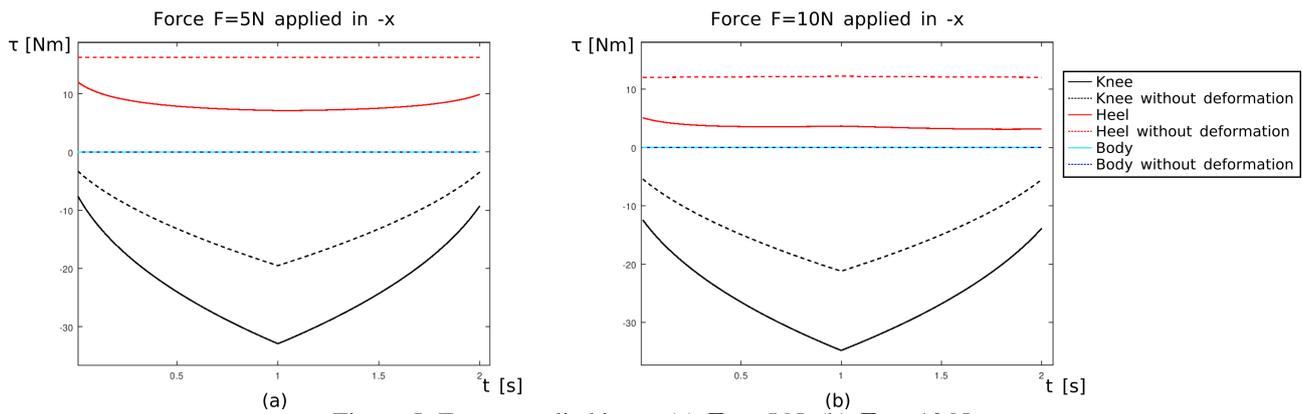
Figure 5: Forces applied in -x: (a) F_x = -5 N; (b) F_x = -10 N.

system to go near the conditions of equilibrium.

This equilibrium situation can be evaluated by the maximum friction analysis, in the toe and heel, comparing these maximum frictions on both points with the required friction on both situations (with and without deformation on the complacent element), as presented in Fig. 6. When evaluating the condition for -5 N horizontal force, the presence of the complacent element do not change the stability status, but the margin is smaller on the complacent scenario.
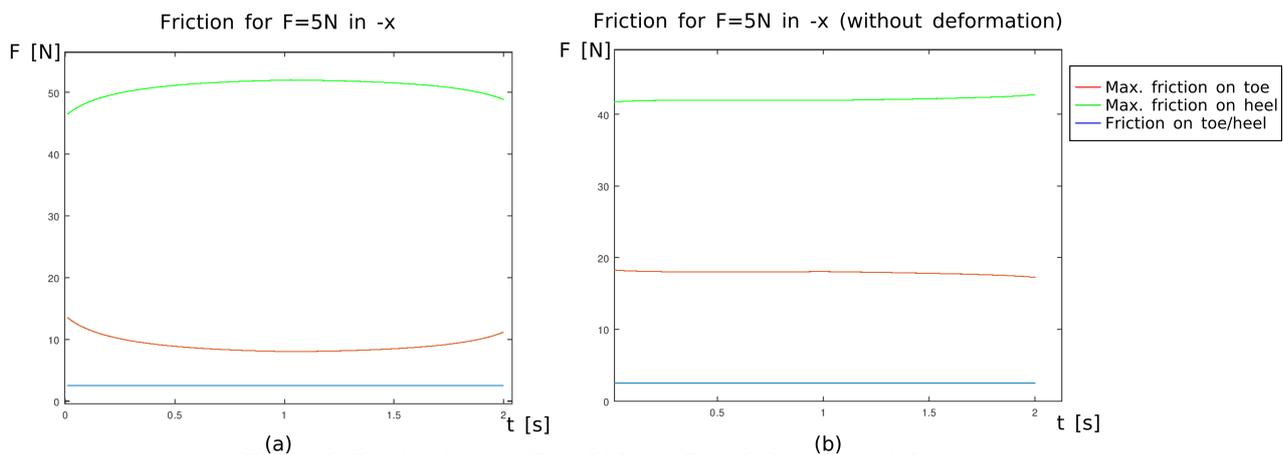

Figure 6: Friction for: (a) F_x = -5 N; (b) F_x = -5 N (without deformation).

When the external force is increased to 10 N on -x direction, the equilibrium is compromised for the complacent scenario, even though the stability is secured without the complacency (Fig.7). In this scenario the required friction is greater than the maximum friction for the toe in the case there is deformation, and, by the other hand, when there is no deformation, the required friction is always smaller than the maximum, assuring the system stability.

5. CONCLUSIONS

The procedure for the kinetostatic model resolution provide a method to compute the equilibrium conditions for kinematic and static with the presence of complacent elements. With this procedure, it is possible to compute torques and positions of the joints for both scenarios. The results for this method are presented for a planar legged robot, but there is no obstacle in generalizing for spacial robots. In this first development, the option for a planar robot was made in order to prove the model viability and the early results extraction.

In terms of results for complacent elements, it was noted that, beside the common knowledge that these elements introduce desirable features on mobile robotic systems, such as greater disturbance tolerance and better dynamic behavior, there are situations in which the deformation implies greater torques on motors, and eventually they could lead the system to unbalanced situations.

Because of that there is a need for additional strategies in order to sustain the system's stability. This study doesn't explored the solutions for this question, but it is possible to define some strategies to advance in these questions.

The first strategy to be evaluated is the use of variable stiffness: if it is necessary to counter-balance continuous efforts that lead the system to a situation of near instability, it is possible to increase stiffness. This way, the behavior of the system becomes more like the one of a non-complacent system. On the absence of this external efforts, it is possible to use a lower stiffness, which make it possible for the system to benefit from the presence of a complacent element.
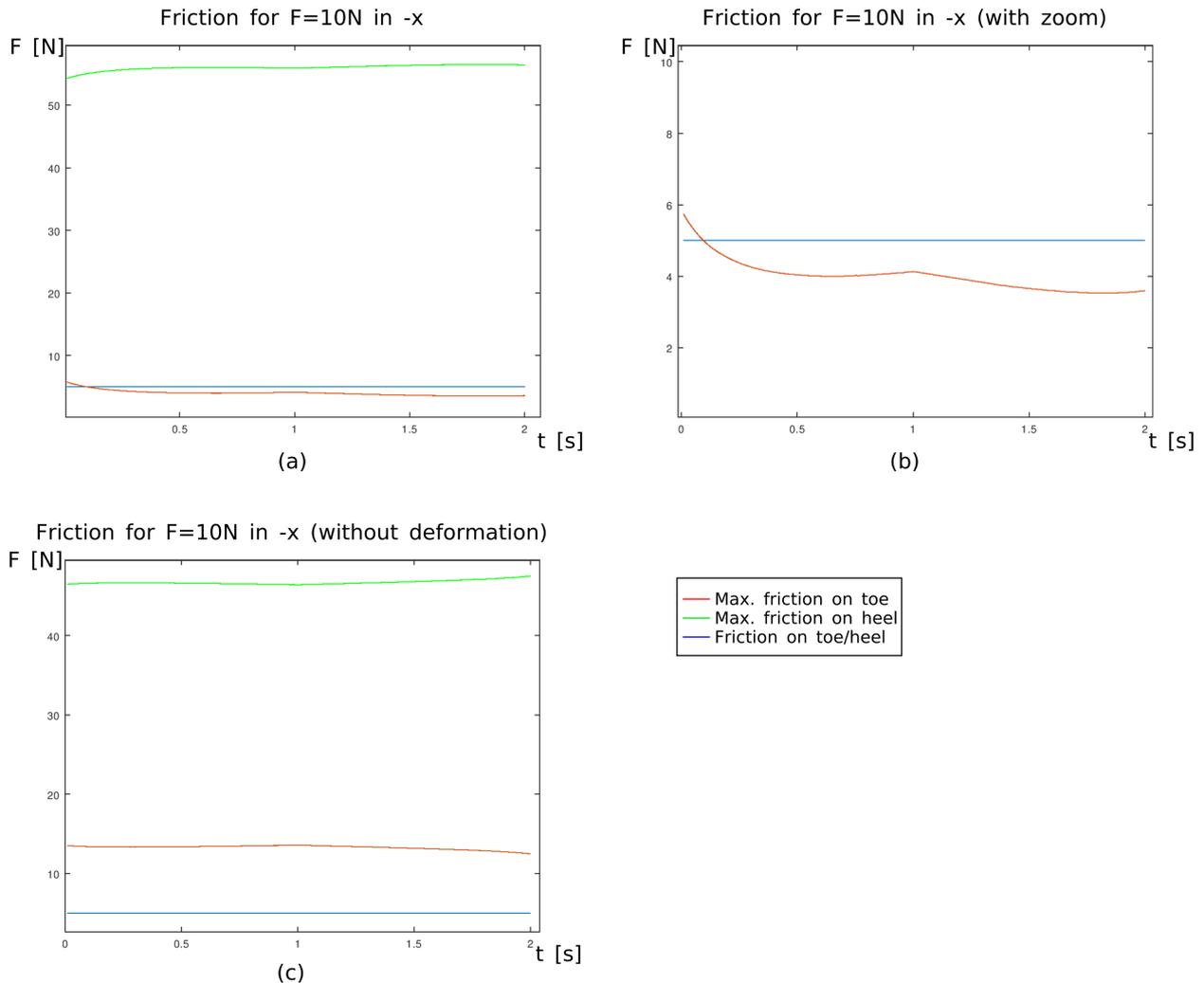
Figure 7: Friction for: (a) F_x= -10 N; (b) F_x= -10 N (with zoom) ; (c) F_x= -10 N (without deformation).

Other strategies could be based on the kinetostatic coupling, allowing some small variations on the kinematics that could compensate the efforts and pose variation caused by the deformation, in order to reach the desired behavior on the static. These strategies could make use of expected deformation estimatives, that could eventually have some difference when compared to real deformation, and the impact of this uncertainties on the deformation modeling must be evaluated on these cases.

As future works, it is planned to include the analysis of two legged planar robots with many compliant joints, as well as spatial quadruped robots. After that, a generalized methodology for legged robots with many compliant joints might be proposed.

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