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► **To cite this version:**

Quentin Le Lidec, Justin Carpentier. Reconciling RaiSim with the Maximum Dissipation Principle. IEEE Transactions on Robotics, In press. hal-04438175v2

HAL Id: hal-04438175

<https://hal.science/hal-04438175v2>

Submitted on 25 Sep 2024

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Reconciling RaiSim with the Maximum Dissipation Principle

Quentin Le Lidec^{1,†} and Justin Carpentier¹

Abstract—Recent progress in reinforcement learning (RL) in robotics has been obtained by training control policy directly in simulation. Particularly in the context of quadrupedal locomotion, astonishing locomotion policies depicting high robustness against environmental perturbations have been trained by leveraging RaiSim simulator. While it avoids introducing forces at distance, it has been shown recently that RaiSim does not obey the maximum dissipation principle, a fundamental principle when simulating rigid contact interactions. In this note, we detail these relaxations and propose an algorithmic correction of the RaiSim contact algorithm to handle the maximum dissipation principle adequately. Our experiments empirically demonstrate our approach leads to simulation following this fundamental principle.

I. INTRODUCTION

Over the past few years, RaiSim simulator [1] gave rise to successful applications of policy learning to solve real-hardware robotic locomotion tasks in uncontrolled environments with a remarkable agility [2], [3], [4]. For all these applications, the control policies achieve good performances in practice, even if learned purely in simulation. Although it would require further evaluation, the capacity of RaiSim to solve the frictional contact problem without introducing interactions at distance, as it is done in some popular physical engines, might be an ingredient explaining its success. However, in a recent study [5], we have shown RaiSim is still making some approximations, particularly in the way it fulfills the so-called maximum dissipation principle (MDP) introduced by Jean-Jacques Moreau [6]. In this note, we propose a correction to the vanilla version of RaiSim to mitigate these approximations via a simple and computationally free correction. This note is organized as follows. In Section II, we quickly revisit the hypotheses of contact modeling and, in particular, of RaiSim’s contact model. Section III depicts the main limitation of the RaiSim contact model and extends it to account for the MDP adequately. Finally, this correction is evaluated through various illustrative examples in Section IV. This note is based on a more general study of the most common contact models employed in robotics simulators [5].

II. BACKGROUND

Contact modelling. Using generalized coordinates $q \in \mathcal{Q} \cong \mathbb{R}^{n_q}$ and the joint velocity $v \in \mathbb{R}^{n_v}$ to describe the state of the system, the discrete Lagrangian equations of motion write

$$Mv^{t+1} = Mv^t + (\tau - b(q^t, v^t)) \Delta t, \quad (1)$$

where M is the joint space inertia matrix, τ the joint torque vector while $b(q, v)$ accounts for the centrifugal and Coriolis effects, and for the generalized gravity, and Δt is simulation time-step. We denote $v_f \stackrel{\text{def}}{=} v^t + M^{-1}(\tau - Cv^t - g) \Delta t$ as the free velocity corresponding to the solution of (1) w.r.t. v^{t+1} . When contacts occur *i.e.* the normal component of the separation vector $\Phi(q)$ (Fig. 1) between the objects in contact is non positive, (1) is modified according to Gauss’ least constraint principle

$$Mv^{t+1} = Mv_f + J^\top \lambda, \quad (2)$$

where $J = \partial\Phi/\partial q$ is the contact Jacobian which can be computed efficiently via the rigid body dynamics algorithms [7].

¹Inria - Département d’Informatique de l’École normale supérieure, PSL Research University. Email: `firstname.lastname@inria.fr`

[†]Corresponding author

To avoid interpenetration, the normal contact point velocities, and contact forces are both required to be positive in order to avoid interpenetration and to allow only repulsive contact forces. Moreover, contact forces can act on rigid bodies only when in contact. These hypotheses lead to the so-called *Signorini condition* which can be written at the velocity level

$$\forall i, 0 \leq \lambda_N^{(i)} \perp c_N^{(i)} - c_N^{(i)*} \geq 0, \quad (3)$$

where the super-script i refers to the i^{th} contact point, the sub-script N accounts for the normal component, $c = Jv^{t+1}$ is the contact points velocity and c^* is the reference velocity of the contact points.

To model friction, the phenomenological Coulomb’s law of friction is classically adopted. It states that contact forces should lie inside a second-order cone

$$\lambda \in K_\mu = \prod_{i=1}^{n_c} K_{\mu^{(i)}}, \quad (4)$$

where $K_{\mu^{(i)}} = \left\{ \lambda^{(i)} \mid \lambda^{(i)} \in \mathbb{R}^3, \lambda_N^{(i)} \geq 0, \|\lambda_T^{(i)}\|_2 \leq \mu^{(i)} \lambda_N^{(i)} \right\}$ and the sub-script T accounts for the tangential components.

In addition, according to the Maximum Dissipation Principle (MDP), frictions should maximize the dissipated energy, and, combined with Coulomb’s set of admissible friction forces, this writes

$$\forall i, \lambda_T^{(i)} = -\mu^{(i)} \lambda_N^{(i)} \frac{c_T^{(i)}}{\|c_T^{(i)}\|_2}, \text{ if } \|c_T^{(i)}\|_2 > 0. \quad (5)$$

Reworking the equations (2) (3) (4) (5) leads to the following nonlinear complementarity problem (NCP)

$$\forall i, K_{\mu^{(i)}} \ni \lambda^{(i)} \perp c^{(i)} + \Gamma(c^{(i)}, \mu^{(i)}) \in K_{\mu^{(i)}}^*. \quad (6)$$

where $c = G\lambda + g$ is the contact point velocity, $G = JM^{-1}J^\top$ is the so-called Delassus matrix, $g = Jv^f$ is the free velocity of contact points and Γ is the de Saxcé function defined by $\Gamma : (c, \mu) \in \mathbb{R}^3 \times \mathbb{R} \mapsto [0, 0, \mu\|c_T\|_2]$. The deviation from the physical principles can be measured via the primal and dual errors, respectively $\epsilon_p^{(i)} = \text{dist}_{K_{\mu^{(i)}}}\left(\frac{\lambda^{(i)}}{\Delta t}\right)$ and $\epsilon_d^{(i)} = \text{dist}_{K_{\mu^{(i)}}^*}\left(c^{(i)} + \Gamma(c^{(i)}, \mu^{(i)})\right)$, and the complementarity $\epsilon_c^{(i)} = \left| \left\langle \frac{\lambda^{(i)}}{\Delta t}, c^{(i)} + \Gamma(c^{(i)}, \mu^{(i)}) \right\rangle \right|$. In our experiments, we use ϵ_{abs} , defined as the maximum of ϵ_p , ϵ_d and ϵ_c , to quantify the physical accuracy.

A more exhaustive introduction to contact models in robotics can be found in [5].

RaiSim uses a contact model inspired by MuJoCo’s Cone Complementarity Problem (CCP). CCP relaxes the NCP (6) by ignoring de Saxcé corrective term, thus, transforming the contact problem into a Quadratically Constrained Quadratic Program (QCQP). This results in the violation of the *Signorini condition* whenever a contact point is sliding. RaiSim intends to fix this by enforcing λ to lie on the

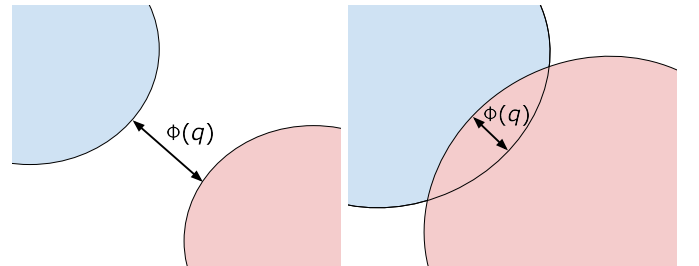


Figure 1. **The separation vector Φ** represents the displacement of minimal norm which puts objects in contact.

hyperplane of null normal velocity $V_N^{(i)} = \{\lambda^{(i)} | G_N^{(ii)} \lambda^{(i)} + \tilde{g}_N^{(i)} = 0\}$ where $\tilde{g}^{(i)} = g^{(i)} + \sum_{j \neq i} G^{(ij)} \lambda^{(j)}$ is the i^{th} contact point velocity as if it were free, and where we generalized the superscript (resp., subscript) notation to block operations on matrices with the first superscript (resp., subscripts) denoting the indexes of the rows while the second one refers to columns. This choice induces solutions conforming to the *Signorini condition*. When a contact point is sliding, the bisection algorithm is used to solve the following QQP

$$\min_{\lambda \in \partial K_{\mu^{(i)}} \cap V_N^{(i)}} \frac{1}{2} \lambda^\top G^{(ii)} \lambda + \tilde{g}^{(i)\top} \lambda. \quad (7)$$

The set $\partial K_{\mu^{(i)}} \cap V_N^{(i)}$ being an ellipse, RaiSim leverages its analytical expression and the associated polar coordinates to write (7) as a 1D optimization problem on the angle θ before solving it via a dichotomous algorithm. We refer to [1] and [5] for a more detailed description of the Gauss-Seidel bisection algorithm.

III. LIMITS AND EXTENSIONS OF RAI-SIM'S CONTACT MODEL

RaiSim's limitations. Writing the Karush-Kuhn-Tucker (KKT) optimality conditions of the problem (7) yields

$$G^{(ii)} \lambda + \tilde{g}^{(i)} + \gamma_1 G_N^{(ii)} + \gamma_2 \begin{bmatrix} \lambda_T^{(i)} \\ \|\lambda_T^{(i)}\|_2 \\ -\mu^{(i)} \end{bmatrix} = 0, \quad (8a)$$

$$\|\lambda_T^{(i)}\|_2 = \mu^{(i)} \lambda_N^{(i)}, \quad (8b)$$

$$G_N^{(ii)} \lambda^{(i)} + \tilde{g}_N^{(i)} = 0, \quad (8c)$$

where $\gamma_{1,2}$ are the dual variables associated to (7) and $\|\lambda_T^{(i)}\|_2 > 0$ in the sliding case. Recalling that $c^{(i)} = G^{(i)} \lambda + g^{(i)}$ and injecting (8b),(8c) into (8a) gives

$$\gamma_1 G_{NN}^{(ii)} - \gamma_2 \mu^{(i)} = 0, \quad (9a)$$

$$c_T^{(i)} + \gamma_1 G_{NT}^{(ii)} + \gamma_2 \frac{\lambda_T^{(i)}}{\|\lambda_T^{(i)}\|_2} = 0. \quad (9b)$$

Finally, using (9a) to express γ_1 in (9b) leads to the following

$$c_T^{(i)} \propto -\lambda_T^{(i)} - \frac{\mu^{(i)2} \lambda_N^{(i)}}{G_{NN}^{(ii)}} G_{NT}^{(ii)}, \quad (10)$$

which indicates that the contact model (7) proposed in [1] violates the MDP (5) whenever the Delassus matrix is not decoupled *i.e.* $G_{NT}^{(ii)}$ is not null.

De Saxcé correction. To retrieve the MDP, we propose to reintroduce de Saxcé's correction [8], which was neglected in the CCP formulation (Fig. 2). Because this correction is nonlinear in λ , directly incorporating it would make the algorithmic complex. In a Gauss-Seidel spirit, the corrective term can be approximated by a constant value using the latest estimate of the contact forces λ^- , leading to

$$K_{\mu^{(i)}} \ni \lambda \perp G^{(ii)} \lambda + \tilde{g}^{(i)} + \Gamma(c^-, \mu^{(i)}) \in K_{\mu^*}, \quad (11)$$

which constitutes the KKT conditions of the following problem

$$\min_{\lambda \in K_{\mu^{(i)}}} \frac{1}{2} \lambda^\top G^{(ii)} \lambda + (\tilde{g}^{(i)} + \Gamma(c^-, \mu^{(i)}))^\top \lambda, \quad (12)$$

and where $c^- = G^{(ii)} \lambda^- + \tilde{g}^{(i)}$. At convergence $c^- \rightarrow c^{(i)}$ and (11) becomes exactly (6).

For a sliding contact, (11) involves that $\lambda \in \partial K_{\mu^{(i)}} \cap V_N^{(i)}$ [9], and thus, (12) can be equivalently restrained over this sub-set

$$\min_{\lambda \in \partial K_{\mu^{(i)}} \cap V_N^{(i)}} \frac{1}{2} \lambda^\top G^{(ii)} \lambda + (\tilde{g}^{(i)} + \Gamma(c^-, \mu^{(i)}))^\top \lambda \quad (13)$$

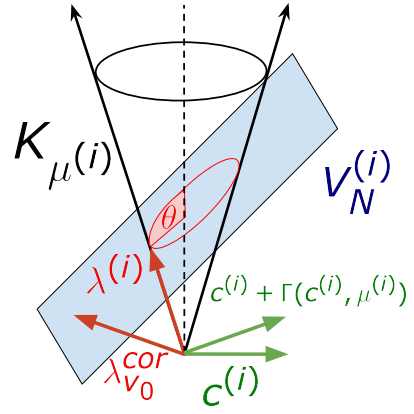


Figure 2. **RaiSim contact problem** (7) for a sliding contact point consists in finding the element of $\partial K_{\mu^{(i)}} \cap V_N^{(i)}$ (represented above by the intersection of the blue plane and the border of the cone) which is the closest to $\lambda_{v_0}^{cor}$ (Alg. 1, line 11). Our approach preserves this structure and adds de Saxcé correction to $\lambda_{v_0}^{cor}$ to retrieve the original NCP (13). In both cases, the feasible set is an ellipse which is represented in red on the figure. Exploiting the analytical expression of this ellipse, the problem boils down to a 1D problem on θ using polar coordinates. This figure is inspired by Fig. 2 of [1].

Algorithm 1: De Saxcé correction of the Gauss-Seidel bisection algorithm

Input: Delassus matrix: G , free velocity: g , friction cones K_{μ}

Output: Contact forces: λ

```

1 for  $k = 1$  to  $M$  do
2   for  $i = 1$  to  $m_c$  do
3      $\tilde{g}^{(i)} \leftarrow g^{(i)} + \sum_{j \neq i} G^{(ij)} \lambda^{(j)}$ ;
4      $\lambda_{v_0}^{(i)} \leftarrow -G^{(ii)^{-1}} \tilde{g}^{(i)}$ ;
5     if  $\tilde{g}_N^{(i)} > 0$  then
6       // takeoff
7        $\lambda^* \leftarrow 0$ ;
8     else if  $\lambda_{v_0}^{(i)} \in K_{\mu^{(i)}}$  then
9       // stiction
10       $\lambda^* \leftarrow \lambda_{v_0}^{(i)}$ ;
11    else
12      // sliding
13       $\tilde{g}^{cor} \leftarrow \tilde{g}^{(i)} + \Gamma(G^{(ii)} \lambda^{(i)} + \tilde{g}^{(i)}, \mu^{(i)})$ ;
14       $\lambda_{v_0}^{cor} \leftarrow -G^{(ii)^{-1}} \tilde{g}^{cor}$ ;
15       $\lambda^* \leftarrow \text{bisection}(G^{(ii)}, \tilde{g}^{cor}, K_{\mu^{(i)}}, \lambda_{v_0}^{cor})$ ;
16    end
17     $\lambda^{(i)} \leftarrow (1 - \alpha) \lambda^{(i)} + \alpha \lambda^*$ ;
18     $\alpha \leftarrow \gamma \alpha + (1 - \gamma) \alpha_{min}$ ;
19  end
20 end

```

which corresponds to the corrected variant of (7). Checking $\tilde{g}_N^{(i)} > 0$ (Alg. 1, line 5), ensures the feasible set of (13) is non-empty before solving it (Alg. 1, line 12). Practically, the original per-contact bisection algorithm can be adapted to (13) by iteratively updating the latter correction (Alg. 1, lines 10, 11), in a similar way to [10]. In this paper, we qualify the algorithm as Gauss-Seidel rather than per-contact as it is a more standard terminology in the optimisation literature. The resulting algorithm is called RaiSim+DS as it consists in a variant of RaiSim which includes a de Saxcé correction.

It is worth noting that the proposed correction offers no convergence guarantees just like the original algorithm. However, this is also true for

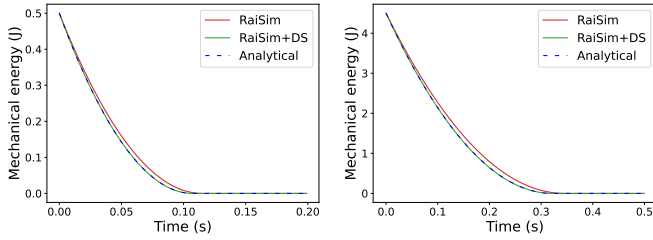


Figure 3. **A cube sliding on a plane**, with an initial tangential velocity of 1 m/s (Left) and 3 m/s (Right). Because RaiSim’s contact model violates the MDP, the dissipated energy decreases more slowly than expected by the analytical solution governed by the maximum dissipation principle. On the contrary, with de Saxcé’s corrective term, the contact model recovers the expected evolution.

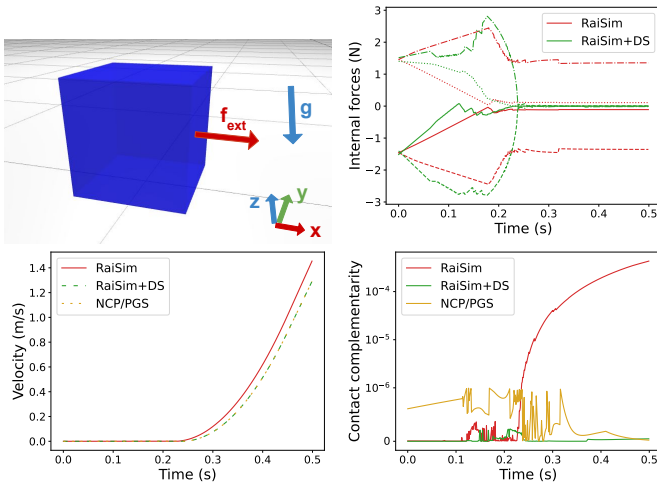


Figure 4. **Top left:** A cube is dragged on a plane by an increasing external tangential force along the x -axis. When the cube starts to slide along the x -axis, according to the MDP, the tangential contact forces should be colinear to the same direction. **Top right:** The curves represent the internal force along the y -axis at each of the four contact points. RaiSim exhibits some remaining internal forces while our de Saxcé correction results in zero internal forces. **Bottom left:** because the dissipation is not maximal, the velocity simulated by RaiSim grows faster than what is obtained by our approach or a more classical PGS algorithm. **Bottom right:** the violation of the MDP is confirmed by a jump of the NCP criterion ϵ_{abs} when the cube is sliding, while the proposed correction keeps this criterion at a relatively low level.

algorithms solving the NCP in general as they only exhibit empirical evidence. In practice, over-relaxation with a decreasing α (Alg. 1, lines 14,15) is required to stabilize the algorithm and, thus, even at convergence correctness is not guaranteed. Alternatively, one could have exploited the analytical solution to the one contact point problem (6) proposed in [11]. As a future work, it would be interesting to study how this compares to our approach.

IV. EXPERIMENTS

The RaiSim algorithm and our proposed correction are implemented in ContactBench [5], a generic framework implementing contact solvers commonly used in robotics and leveraging the Pinocchio [12] and HPP-FCL [13] C++ libraries. ContactBench will be publicly available upon publication acceptance. Here, we run experiments inspired by the same previous work [5] in order to observe RaiSim’s approximation pointed out in Section III and how our corrected contact model improves simulation.

A. Experiment 1: sliding cube

An experiment as simple as a cube sliding on a horizontal plane allows us to visualize how RaiSim’s contact model violates the MDP, as evidenced by (10). Indeed, in this case, Fig. 3 exhibits a gap between the analytical evolution of the mechanical energy and its simulation via RaiSim’s contact model. Moreover, the same experiment reveals that our approach using de Saxcé’s correction allows us to bridge this gap.

B. Experiment 2: dragging a cube

For underdetermined cases, *e.g.* hyper-staticity, the contact problem can have an infinite set of solutions and so we denote by "internal forces", the contact force components deviating from the minimum norm solution. The second experiment, on a cube that is progressively dragged (Fig. 4), demonstrates that if both our approach and RaiSim lead to internal forces stretching the cube at stiction, the latter still induces to non-null internal components when the cube slides. The studied contact problem is under-determined at stiction, and internal forces do not affect the resulting trajectory. When the contact points are sliding, the friction forces are uniquely defined by the MDP (5) and should not exhibit any internal components. The correction results in a trajectory close to the one obtained via a Projected Gauss-Seidel (PGS) algorithm (see [5] for more details) which is an approach avoiding any physical approximation. This indicates that if RaiSim originally violates the MDP, adding a simple de Saxcé corrective term reconciles the simulator with this energetic principle.

C. Experiment 3: MPC for quadrupedal locomotion

Our last experiment aims to evaluate the impact of the de Saxcé correction on a more concrete application: Model Predictive Control (MPC) for quadrupedal locomotion with the Solo-12 robot. Running an MPC controller in a simulator using RaiSim’s contact model and solvers with and without de Saxcé correction leads to different behaviors (Fig. 5). In this experiment, the number of iterations is fixed which is why the PGS algorithm cannot always control the contact complementarity error. RaiSim also leads to large errors but increasing the number of iterations would not help in this case because the MDP is inherently approximated. Eventually, RaiSim’s algorithm when equipped with de Saxcé’s correction is able to keep this error at a lower level only with a small computational overhead.

V. CONCLUSION

In this note, following [5], we have shown that the RaiSim simulator can exhibit violation of the Maximum Dissipation Principle. Our study slightly modified the original algorithm to account for this principle. Throughout our experiments, we empirically demonstrate our modification can enforce the MDP during simulation without additional computational burden. We hope this note will motivate new developments and progress in contact simulation in robotics.

ACKNOWLEDGMENTS

We thank Jemin Hwangbo for providing useful details on the algorithm of the RaiSim simulator. This work was supported in part by L’Agence d’Innovation Défense, the French government under the management of Agence Nationale de la Recherche through the project INEXACT (ANR-22-CE33-0007-01) and as part of the "Investissements d’avenir" program, reference ANR-19-P3IA-0001 (PRAIRIE 3IA Institute), by the European Union through the AGIMUS project (GA no.101070165) and the Louis Vuitton ENS Chair on Artificial Intelligence. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them

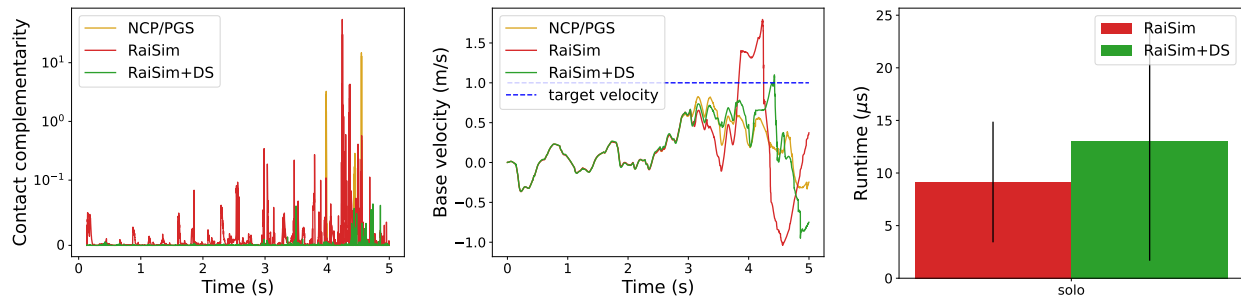


Figure 5. **MPC controller for Solo-12** is run in simulation with various contact models and solvers. The robot is operating on a bumpy and slippery terrain. Our approach using the De Saxcé correction controls the contact complementarity criteria ϵ_{abs} thus leading to a reduced error w.r.t. the original RaiSim solver which only uses a relative convergence criteria (**Left**). The correction also leads to very different controlled trajectories (**Center**). The additional computational burden induced by the more accurate control of the contact complementarity remains limited (**Right**)

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