Balancing a humanoid robot with a prioritized contact force distribution

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***Abstract*— Humanoid robots propel themselves and perform tasks by interacting with their environment through contact forces. Typically, nonuniqueness of these forces is dealt with by distributing them evenly between the contacts. In the present paper, we introduce strict prioritization in contact force distribution, to reflect situations when an application of certain contact forces should be avoided as much as possible, for example, due to a fragility of the support. We illustrate this by designing a whole body motion controller for a setting with multiple noncoplanar contacts, where application of an optional contact force is allowed only if it is necessary to maintain balance and execute a task. Balance preservation is addressed by imposing a capturability constraint based on anticipation with a linear model adapted to multiple noncoplanar contacts. The controller is evaluated in simulations.**

I. Introduction

Humanoid robots belong to the class of floating base systems, and, consequently, the contacts with the environment play a crucial role in their control. The interaction with the environment can be studied by focusing on different aspects such as force distribution between contacts, balance preservation, contact planning for realization of locomotion and manipulation tasks. In the present paper we primarily address the first two aspects in a setting with multiple noncoplanar contacts.

II. Prioritized contact force distribution

Let us consider the problem of force distribution. In most settings with multiple contacts there exists an infinite number of force distributions that achieve the same base motion. The typical approach to resolve this ambiguity is to make contacts as robust as possible, by keeping each contact force far from the bounds of the respective friction cone, and distribute the forces evenly between all the contacts [1], [2], [3].

There are situations, however, such as when a contact area is fragile, when it is preferable to avoid using it unless strictly necessary for balance. We propose therefore to introduce a prioritized distribution of the contact forces, with the help of hierarchical optimization [1], [4], [5]. We demonstrate our idea in the following setting: a humanoid robot has to reach a target with a hand while standing, it can optionally exploit a contact of the other hand with an additional support to maintain balance. The control goal can be expressed with the following informal hierarchy, which allows the application of an optional contact force, only if it is necessary to accomplish the reaching task and maintain balance:

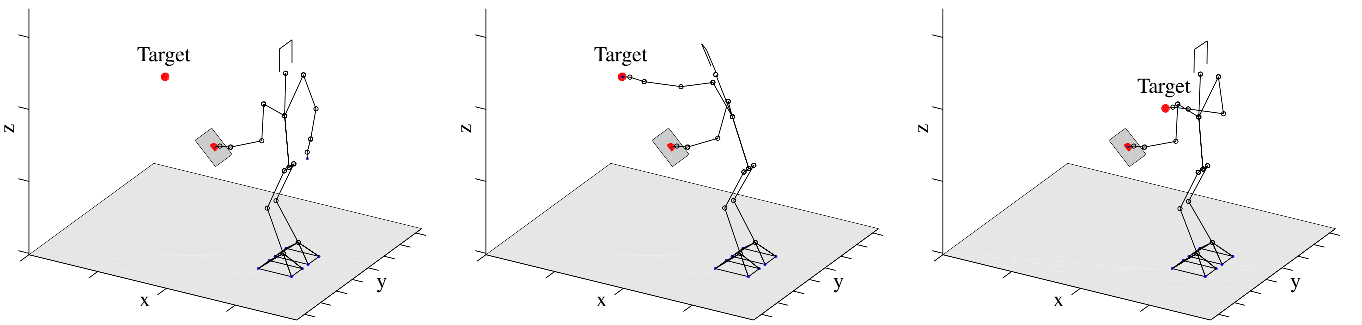
Hierarchy (1)

1: maintain balance
2: reach the target
3: minimize optional contact force

III. Balance preservation

The highest priority in Hierarchy 1 is to preserve balance, *i.e.*, avoid falling. Similarly to [6], [7] we analyze the problem of balance preservation in terms of viability theory [8]. It defines a state to be viable, if there exists at least one evolution starting from this state and not resulting in a fall. In practice, most viable states of interest, when walking, are 2- or 3- step capturable, what means that the robot is able to stop in 2 or 3 steps [7], [9]. Based on this observation, we already proposed to anticipate the future motion of the robot, and impose that it must be able to stop some time (corresponding to 2 steps) in the future [10], *i.e.*, be able to reach a statically balanced state. Similarly to the terminal constraints in Model Predictive Control (MPC) schemes [11], we impose that the robot stops at a time in the future which is continuously postponed. As a result, it is not imposed that the robot actually stops, but only that it maintains the capacity to stop, *i.e.*, capturability.

Future motion can be anticipated using a whole body model [12], [13], [14]. However, it necessitates the use of nonlinear optimization, which can be computationally expensive and is still in the process of being extended to hierarchies [14]. For these reasons, it is common to resort to anticipation with simplified models. In the case of multiple noncoplanar contacts, such models typically involve the contact forces, but neglect the robot's structure and tasks associated with it, such as the reaching task in Hierarchy 1 [15], [16], [17]. As a result, the Hierarchy 1 needs to account for two models at the same time: a whole body model for the reaching task, and a simplified model for balance preservation. A similar approach has already been used in the case of walking on a flat ground [10]. It can be seen as a whole body MPC, where the whole body model is replaced by a simplified model everywhere except the current time instance. The simplified model adopted in [10] cannot be employed in a setting with multiple noncoplanar contacts. That is why here we rely on a different linear model derived from the relationship between the momenta of the robot and the contact forces [15], [16]. We use this model to preview evolution of the momenta over N sampling



(a) initial (b) after 15 seconds (c) after 25 seconds

Fig. 1: Configurations of the robot during the simulation. Grey areas represent contact surfaces.

intervals in the future. In the end of preview horizon the final state and controls are subject to static balance (*i.e.*, capturability) constraints, which require that the linear and angular momenta, as well as their rates, are zero.

IV. Controller

We formalized Hierarchy 1 using the standard inverse dynamics approach [18]:

Hierarchy (2)

1: Equality constraints
- equation of dynamics
- fixed contact positions
- constant height of the CoM

2: Inequality constraints
- joint limits
- friction constraints

3: Capturability constraint
4: Reaching task
5: Minimization of the optional contact force
6: Final objectives
- Maintaining the reference configuration
- Minimization of all contact wrenches

Decision variables are the generalized accelerations and previewed contact wrenches. The controller based on Hiearchy 2 assumes that the contact positions are given by an offline planner. Since the exact time, when the optional contact is used, is not known in advance, we also assume that the support hand is at the contact position from the beginning.

V. Simulations

We evaluate Hierarchy 2 in simulations using the HRP-2 robot. We have observed that particular choices of the preview horizon length and its discretization have little effect on the overall behavior of the robot across all our tests. In all the following tests the MPC parameters are set as follows: the number of sampling intervals in the preview $N = 4$, with a duration of one interval $T = 100$ms. In order to successfully complete these tests, it is necessary to regularize Hierarchy 2 in the presence of conflicts between its levels [5]. We perform regularization of the levels 4 and 5 using the weighted objective from the last level 6.

We evaluated several versions of the controller in a setting, where the robot has to reach the moving target with the right hand while the left hand positioned on an additional support. The target is initially set to be far from the robot and then moved closer as demonstrated in Figure 1. The controllers differ in the way the optional contact force is minimized:

- only at the current time instance $\boldsymbol{f}_{opt,0} = \boldsymbol{0}$
- or over the whole preview horizon $\boldsymbol{f}_{opt,k} = \boldsymbol{0}$ with $k = 0, \ldots, N-1$.

When the first version is used, the increase of the contact force is very sharp (Figure 2) and the robot does not return close to the initial state after the hand target is moved back. The sharp increase of the contact force occurs due to the fact that the the current force minimization favors large future contact forces. In the second part of the motion it also prevents the controller from momentarily increasing the current optional contact force $\boldsymbol{f}_{opt,0}$, what is necessary to move the CoM back towards the initial state. The second formulation does not have such drawbacks as can be seen in Figures 1 and 2. In order to demonstrate, that the capturability constraint is crucial for balance, we tested the same formulation without this constraint. In this case the robot falls towards the target eventually causing a major violation of the constraints (see Figure 2).

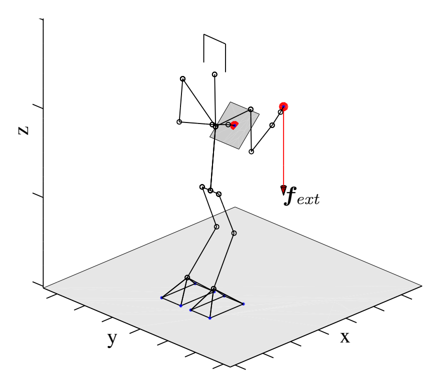


Fig. 4: Initial configuration of the robot in the test when the right hand has to maintain its position.

The successful version of the controller also produces satisfying behavior in a slightly modified setting where the right hand has to maintain a constant position under action

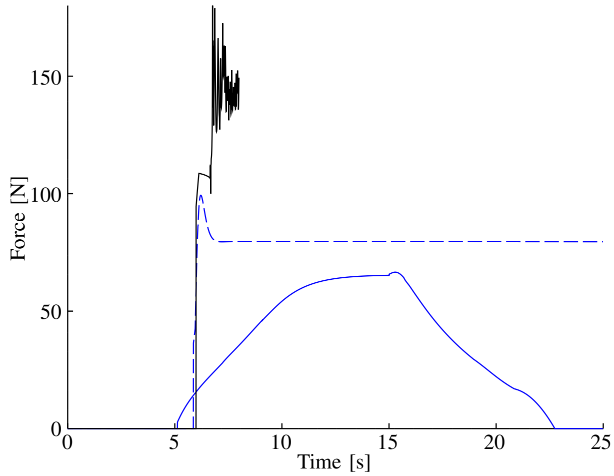


Fig. 2: Norm of the optional contact force $\boldsymbol{f}_{opt,0}$, when $\boldsymbol{f}_{opt}$ is minimized only at the current time instance (dashed blue) or over the whole preview horizon (solid blue), and when the capturability constraint is removed (solid black).

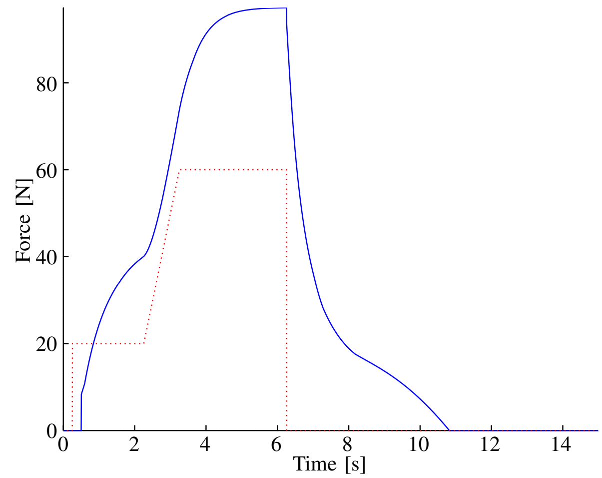


Fig. 3: Norms of the optional contact force $\boldsymbol{f}_{opt,0}$ (solid blue) and the external force $\boldsymbol{f}_{ext}$ (dotted red) in the test when the right hand has to maintain its position.

of an external force $\boldsymbol{f}_{ext}$, as shown in Figure 4. Thus, the goal of the controller is to maintain balance while holding a heavy object. The changing external force (see Figure 3) is assumed to be measured and its contribution is accounted for in the whole body dynamical model, but not in the preview.

VI. Conclusion

We designed a whole body motion controller with contact force prioritization and balance constraints for general multicontact scenarios. The controller was evaluated in simulations, which demonstrated that it is capable of applying an optional contact force only when necessary to execute tasks and maintain balance.

Acknowledgments

This work has been funded by the PSPC Romeo 2 project and EU H2020 Comanoid Research and Innovation Action (RIA).

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