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Whole-Body Compliant Dynamical Contacts in Cognitive Humanoids

D3.2
Local solver in compliant-world cases

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Abstract	This deliverable provides an overview of the whole-body control strategies proposed within the framework of the CoDyCo project for balancing by means of compliant contacts. We first recall the general structure of the whole-body controller used in the CoDyCo project. This controller is written as a quadratic multi-objective optimization problem under linear constraints and priorities between the objectives can be dealt with through strict of soft hierarchy. This controller has to be modified in order to deal with compliant cases and two cases are then distinguished. In the first one, a contact model is supposed to be known and using that knowledge a control strategy is derived. In the second case, no model of the environment is assumed to be known and an adaptive force regulation task is added in order to account for the compliance of the environment. This deliverable is strongly related to deliverable 5.3 CITEdeliverable53 which discusses the technical details and choices for the implementation of the year-3 validation scenario.
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Table of Contents

Index of Figures

1 Introduction

Under-actuated robots, such as free-floating humanoid robots, usually need to make contacts with their environments to achieve some goal directed whole-body movements. Most researches on whole-body control assume that the environment of a robot is rigid. This means that no adaptation to the environment compliance is needed for controllers. In reality, there is no completely rigid surface but in practice we can assume a surface to be rigid if it is stiff enough (i.e. deflection is negligible). However, many objects in a human environment cannot be considered as stiff enough and there compliance has to be accounted for (e.g. a soft cushion, a sofa, a yoga carpet). Indeed, in these cases, a controller that does not take into account the rigidity properties of the contact material is not sufficient: the compliance of the contact has to be considered by the controller, otherwise the robot may fail to properly balance and fall over. For example, pushing too strongly against a rigid object may result in damages to the robot or the environment; and pushing too weakly against a compliant object may not provide the robot with enough reaction forces to support its whole-body tasks. The problem becomes more complex when the rigidity of the object in contact is unknown a priori to robotic controllers, which is usually the case in many scenarios.

The humanoid whole-body control problem has been addressed by different types of whole-body controllers, using analytical approaches [1, 2, 3], constrained quadratic programming [4, 5, 6, 7, 8], or a mixture of them [9, 10]. These controllers are either developed for rigid environments, or validated only in rigid contact scenarios. In general, a valid set of contact forces during whole-body task control can be found by solving a multi-objective problem with a set of elementary task objectives as well as constraints, such as whole-body dynamics, friction cone constraints for non-sliding contacts, and linear complementarity conditions [11, 8, 6, 7], which implies zero relative motions between two bodies in contact when normal contact force is non-negative. In the case of rigid contact with static environment, the linear complementarity condition implies two constraints: (i) the motion of the contact point is zero and (ii) the contact force along the normal to the contact surface is non-negative. The zero motion constraint may not necessarily be true in the case of non-rigid contacts, since the velocities or accelerations of contact points may be non-zero, although the relative motion between the two contact points remains zero. In this case, hybrid control methods [12] that control forces and motions in orthogonal directions are not applicable. Therefore, the controller should take into account the dynamic relation between the contact point position and the contact force, rather than just control the contact force alone.

Such physical interaction dynamics is taken into account in impedance control [13] with the idea of controlling the relation between the contact point motion and the reaction force. Traditional impedance control [13, 14, 15] computes the target impedance of the robot according to the estimated impedance of the environment, which requires high quality measurement of interaction forces. In [16, 17], learning approaches are applied to optimize the robot impedance. Such approaches do not require interaction force sensing and can be adaptable to variable environment impedance. However, the application of such approaches in the context of humanoid balance control with non-rigid contacts is not suitable. First, these methods rely on trajectory-based learning and adaptation algorithms, whereas there is not necessarily a reference motion trajectory for each support contact in the whole-body balancing context considered here. Furthermore, they need to explore the entire state-action space if a globally optimal solution is to be found, which is impossible for high dimensional robots such as humanoids.

The problem of humanoid balance control with deformable contact support was addressed in [18], which proposed a posture planning approach assuming that the contact material properties are known. Compliant contacts between robots and their environments have been studied by some researchers in other areas such as grasping [19] and animated characters [20]. However, there has not been much research efforts on balancing legged robots on compliant surfaces.

This deliverable provides an overview of the whole-body control strategies proposed within the framework of the CoDyCo project for balancing by means of compliant contacts. It is organized as follows. We first recall the general structure of the whole-body controller used in the CoDyCo project. This controller is written as a quadratic multi-objective optimization problem under linear constraints and priorities between the objectives can be dealt with through strict of soft hierarchy. This controller has to be modified in order to deal with compliant cases and two cases are then distinguished. In the first one, a contact model is supposed to be known and using that knowledge a control strategy is derived. In the second case, no model of the environment is assumed to be known and an adaptive force regulation task is added in order to account for the compliance of the environment.

2 General structure of the whole-body controller in the CoDyCo project

Even though it is not often formulated as such, control of dynamical systems is an optimization problem. Within the framework of the CoDyCo project, the whole-body controller is written as a quadratic multi-objective optimization problem under linear constraints where priorities between the objectives can be dealt with through strict of soft hierarchy. Deliverable 3.1 CITEdeliverable31 exposes the reasons why it is preferable to express controllers in this way. The logic behind this choice can be briefly summarized in a very straightforward way:

1. the equation of motion and joint space to task spaces mappings can be written as equalities but they are not sufficient to describe the overall dynamics and physical behaviour of a robot.

2. Indeed, other intrinsic physical constraint have to be accounted for at the joint level as well as in Cartesian space. These constraints do not solely describe relationships between physical quantities but also limits which cannot (control input saturation) or should never be crossed in order to maintain the robot and its environment in proper working conditions.

3. Theses limits translate into inequalities.

4. Assuming a convex solution space, the optimal solution of the control problem lie at the boundary of the feasible (constraint compliant) solution space.

5. Finding the optimal solution thus boils down to finding the active constraint set, *i.e.* on which boundary it lies.

6. Optimization problem solvers are designed to optimally choose this subset of constraints that should be considered when computing the optimal solution of the control problem.

7. The strong mathematical background in convex optimization is such that optimization based methods mostly outperform analytical methods attempting to heuristically activate constraints.

Based on this formulation choice, the reactive control problem aims at finding at each control instant the actuation torque minimizing $T(\mathbb{X})$, some tasks related function to minimize, given the equation of motion of the multi-body system as well as other equality and inequality constraints. This can be written:

$$\tau^* = \underset{\mathbb{X}}{\operatorname{argmin}} \quad T(\mathbb{X}) \tag{1a}$$

$$\text{subject to} \quad M(q)\dot{\nu} + C(q,\nu)\nu + G(q) = B\tau + \underbrace{\sum_{k=1}^{n_c} J_{\mathcal{C}_k}^\top(q) f_k}_{J^\top(q) f} \tag{1b}$$

$$A(q,\nu)\mathbb{X} = b(q,\nu) \tag{1c}$$

$$D(q,\nu)\mathbb{X} \le h(q,\nu) \tag{1d}$$

where:

- $\tau \in \mathbb{R}^n$ is the internal actuation torque with $n+1$ the number of rigid bodies – called links – connected by n actuated joints with one degree of freedom each.
- $q \in \mathbb{R}^3 \times SO(3) \times \mathbb{R}^n$ is the generalized coordinates that parametrizes the configuration of the free-floating system. q is a triplet composed of the origin and orientation of the base frame expressed in the inertial frame $\left({}^{\mathcal{I}}p_{\mathcal{B}}, {}^{\mathcal{I}}R_{\mathcal{B}}\right)$ and the n joint angles q_j.
- $\nu \in \mathbb{R}^{n+6}$ is the system velocity, a triplet concatenating the floating-base twist $\left({}^{\mathcal{I}}\dot{p}_{\mathcal{B}}, {}^{\mathcal{I}}\omega_{\mathcal{B}}\right)$ and the joint velocities $\dot{q}_j$.
- $J(q) = \left[J_{\mathcal{C}_1}^\top(q) \ \ldots \ J_{\mathcal{C}_k}^\top(q)\right]^\top$ is the contact Jacobian matrix for all k contact points.
- $f = \left[f_1^\top \ \ldots \ f_k^\top \ \right]^\top$ is the vector of external contact wrenches applied by the environment on the links.
- $\mathbb{X} = (\dot{\nu}, \tau, f)$ gathers the dynamic variables of the multi-body system.
- $M \in \mathbb{R}^{n+6 \times n+6}$ is the mass matrix.
- $C \in \mathbb{R}^{n+6 \times n+6}$ is the Coriolis and centrifugal effects matrix.
- $G \in \mathbb{R}^{n+6}$ is the gravity term.
- $B = (0_{n\times 6}, 1_n)^\top$ is a selection matrix.
- $A(q,\nu)\mathbb{X} = b(q,\nu)$ gathers kinematics constraints related to the velocity of the contact points.

- $D(q,\nu)\mathbb{X} \leq h(q,\nu)$ gathers inequality constraints related to joint limits (position and velocity), control input saturation, contact forces (existence and friction limits) and potentially obstacle avoidance.

The control problem is often multi-objective and the tasks-related function $T((X))$ can actually be written:

$$T(\mathbb{X}) = T\left(\lambda_1, T_1(\mathbb{X}), \lambda_2, T_2(\mathbb{X}), \ldots, \lambda_{n_t}, T_{n_t}(\mathbb{X})\right) \tag{2}$$

where $T_i(\mathbb{X})$ is the i-th task among n_t operational tasks to be achieved with $J_i(q)$ its associated task Jacobian and λ_i its priority level. T_i is generally of three types:

$$\begin{array}{ll} \bullet\ \text{Operational space acceleration} & T_i = J_i(q)\dot{\nu} + \dot{J}_i(q_t,\nu)\nu - \ddot{x}^d \\ \bullet\ \text{Joint space acceleration} & T_i = \dot{\nu} - \dot{\nu}^d \\ \bullet\ \text{Operational space force} & T_i = f_{\mathcal{C}_i} - f^d_{\mathcal{C}_i} \end{array} \tag{3}$$

where $\ddot{x}^d$, $\dot{\nu}^d$ and $f^d_{\mathcal{C}_i}$ are desired Cartesian space acceleration, configuration space acceleration and contact wrench respectively, the desired value itself being the outcome of some higher level control architecture (Proportional–Derivative–Integral regulators and/or Momentum regulators and/or Model Predicitve Controllers and/or Trajectory planners providing a feedfoward reference, *etc*).

T_i usually appears in T under the form of a weighted, euclidean norm thus leading to a quadratic cost associated to each task. This quadratic form and the linearity of the constraints allows to resort to the convex optimization techniques, more particularly Linear Quadratic Programs. Then, depending of the type of retained prioritization scheme, the optimization problem 1 can be solved:

- at once using a single LQP and soft prioritization where T is written as a weighted sum of quadratic costs and where λs play the role of weights for each task, see [21, 22] for examples;

- using a cascade of LQPs thus inducing strict prioritization between tasks (in that case λs are used to defined a lexicographic order), see [8, 23, 24] for examples;

- using a representation able to convey both soft and strict prioritization, see [25, 26].

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