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Robust Balance Optimization Control of Humanoid Robots with Multiple non Coplanar Grasps and Frictional Contacts

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***Abstract*— While realizing a task, human-beings are able to use grasping inside their environment in order to keep the most stable balance. Although such a behavior is quite natural for humans, it is very difficult to find the best formulation to adapt human motion to humanoid robots. This paper proposes a conceptually simple framework of human posture control based on optimization which takes into account grasp and friction and achieves robustness against external disturbances. A new stability criteria is also introduced.**

Contrary to most other approaches, our method deals not only with unilateral contacts with friction but also with bilateral grasps. This allows for arbitrarily pulling, pushing or twisting on a handhold. Additionally, and in contrast to classical methods based on ZMP, our method also accounts for contacts not being all in the same plane.

***Index Terms*— Humanoid robot motion, Robust posture, Dynamic balance control, Multiple non-coplanar contacts, Grasp control, Frictional contacts.**

I. Introduction

A. Problem Statement

Human-beings are able to climb a rock using available holds. Grasps and friction allow them to climb up their natural environment while realizing tasks. HR (Humanoid robots) are expected to work in place of human-beings and to have similar behavior in various environments. For instance, we could think of a HR on a ladder realizing a task like painting while keeping its balance robustly. Although numerous HR controllers are today available, robust control for various environments still remains a challenge.

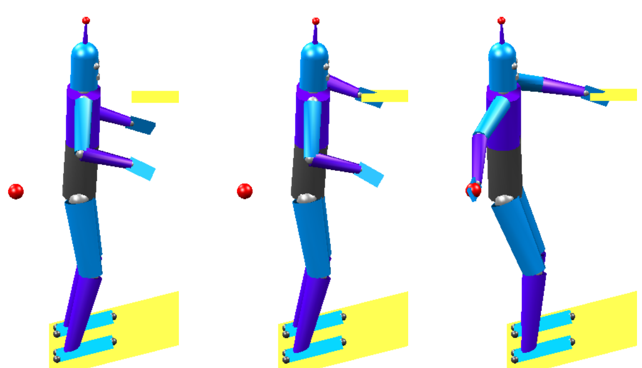


Fig. 1. In order to catch the red object, Humanoid Robot takes a hold with his left hand to keep its balance.

B. Related Work

Two usual stability criteria for a HR standing on a horizontal ground are the Center of Mass (CoM) and Zero Momentum Point (ZMP) criteria. In quasi-static situations, a HR will remain static if its CoM projects vertically inside the convex hull of the contact points. In the dynamic case, the ZMP takes into account inertial and Coriolis wrenches. A HR is able to realize a specified movement if the ZMP projects vertically inside the convex hull of the contact points. However, in case of irregular ground or grasping, CoM and ZMP are not adapted.

Some authors work on more global balance criteria in complex environments. Recently, H. Hirukawa *et al.* [12] proposed a universal stability criterion of two-legged robots having multiple non-coplanar contacts. However, it does not deal with hand contacts, grasps and robustness to disturbance.

T. Bretl *et al.* [3] [4] present a general framework for planning the quasi-static motion of a three-limbed climbing robot in a vertical natural terrain. To prevent the robot from falling as it moves a limb to reach a new hold, the algorithm exploits friction at supporting holds and adjusts the robot's internal Degrees of Freedom (DoF). Y. Or and E. Rimon [14] characterized robust balance in a 3D gravity environment with multiple non-coplanar contacts. The evolution area of the CoM is a convex vertical prism. It is a global geometrical approach in the static case and can be applied to HR balance. But it is difficult to make use of this analytic approach. However, both approaches do not deal with robustness to disturbance. They are only static; dynamic simulation and HR posture are not taken into account. In terms of robustness, X. Zhu *et al.* [22] [23] present a quality index for multi-fingered grasps, which measures the maximum magnitude of the wrench that can be resisted by the grasp in the worst case. Disturbance directions are not treated simultaneously but successively which implies the resolution of a set of linear programming problems. While this method characterizes the achievable robustness, it does not provide a unique control able to resist to various perturbations.

Other teams work on HR grasping. For instance, Ch. Ott *et al.* [15] present a humanoid two-arm system developed as a research platform for studying dexterous two-handed manipulation but do not deal with balance. K. Harada *et al.* [10] [11] worked on dynamics and balance of a humanoid robot during manipulation tasks. Their HR may push an object, but is not able to grasp it. Moreover, its balance during disturbance is not robust.

Since the 80's, L. Sentis *et al.* [19] use projection method which have been fully tried and tested. However, robustness to disturbance is not taken into account and projection methods present passivity issues [18].

In terms of control computation, optimization techniques have been studied. P.B. Wieber [21] proposes an interesting optimization formulation for walking robot problems. Contact forces are taken into account in the control law. However, his formulation is only applied to walking stability and do not deal with robustness. Recently, Y. Abe *et al.* [1] proposed an interactive multi-objective control with frictional contacts, but did not consider grasp and robustness.

C. Contribution

As a contribution to this challenge, this paper proposes a new general HR controller which deals with non coplanar unilateral as well as bilateral contacts with friction, and which is able to achieve the best available robustness to external perturbations. A new stability criteria is also introduced. The key features of our controller are the following:

- **Stability margins:** We deal with stability against disturbances. We compute the biggest disturbance wrench which can be compensated by non-sliding contact and saturated grasp wrenches: the norm of this biggest disturbance is the stability margin of the posture. The bigger this biggest disturbance wrench, the better the posture stability. This stability margin allows to quantify the robustness of a contact and grasp configuration. Moreover, we compute the most suitable CoM position, robust contact and grasp wrenches.
- **Dynamic HR control:** It is based on a previous work, detailed in [6]. It computes motor joint torques to try to reach the goal CoM position, contact and grasp wrenches. The latter are computed with stability margins taken into account, and are given to the optimization process as desired, not necessarily feasible goals.
- **Unilateral frictional contact and bilateral grasp contact considered simultaneously:** In complex environments, HR at work use both hands and feet to keep their balance. Contrary to classical methods based on ZMP, we account for unilateral frictional contacts not being all in the same plane, like for instance simultaneous hand-wall and feet-ground contacts. Moreover, as grasping a handhold is a very common every-day gesture, we account for bilateral grasp contact for pulling, pushing or twisting. For dealing with different kind of contacts, a unified control formulation is proposed.

In the following section, we present the modeling hypotheses for control. In section III, we briefly present dynamic balance control of HR. In Section IV, we detail robust posture computation by introducing wrench stability margin. Section V presents the first results of robust posture control. Finally, section VI summarizes the presented control and indicates some possible future research directions.

II. Modeling Hypotheses for Control

A. Humanoid Robot

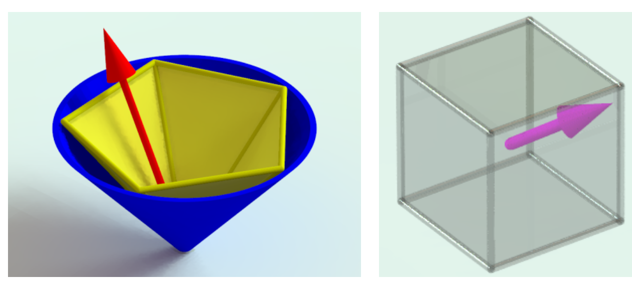
We use a robotic approach and more precisely joint control to handle HR dynamics. Our HR is a set of articulated branches of rigid bodies, organized into a highly redundant arborescence (n_{dof}: number of degrees of freedom). It consists of 32 joints (Fig. 1). The skeleton is modeled as a multibody system. The root body of the HR tree is the thorax. This root has 6_{root} DoF and is not controlled. We decided to use human data for modeling our HR [13][9][7].

B. Contact

Unilateral contacts seen as Coulomb frictional contacts are ruled by a non linear model *i.e.*: $|f_c^t| < \mu\, f_c^n$ with f_c^n, f_c^t respectively the normal and tangent contact forces and μ, the dry-friction factor. As a linear formulation for our optimization problem is needed, we use a linearized Coulomb model. Like J.C. Trinkle *et al.* [20], contact cones are linearized into multifaceted friction cones in order to get linear constraints (Fig. 2(a)). The linearized contact force of the k-*th* contact (denoted f_c^k, 3 DoF) computed by our control law must lay inside the friction cone,that is: $\forall i \in [1, n_e]$, $E_{c_i}^k f_c^k + d_{c_i}^k \geq 0$ with n_e, the number of edges, and $E_{c_i}^k f_c^k + d_{c_i}^k$, distance between f_c^k and each i-*th* oriented facet.

C. Grasp

The grasp wrench (denoted W_g, 6 DoF) computed by our control law must not exceed a certain limit wrench, which we write: $|W_g| \leq W_g^{\max}$. Geometrically, that means that W_g must lay inside a certain polytope of $\mathbb{R}^6$; if we restrain the wrench to its force or torque component only, it must lay inside a cube (Fig. 2(b)).



(a) Linearized friction cone (b) Grasp force/torque limits

Fig. 2. Control modeling

III. Dynamic HR Control

Although the lower level of our controller is not a new contribution [6], a rough description is given hereunder. The goal of this module is to compute all the control torques which have to be applied to HR joints. To this end, as in [21] [1], the control problem is stated as a constrained optimization problem (Quadratic Programming : QP). All wrenches affecting the HR (control torque, contact and grasp wrenches) are taken into account, as well as joint acceleration. The solution of the dynamic QP problem induces a realizable set of desired forces acting on the HR. However, only the control torques result are useful for the control.

We assume physically meaningful equations on the HR motion which are at the core of the control law since they are used as constraints for the dynamic QP problem (Fig. 3):

- **Inputs**
  Global state: dynamic model, friction μ, contact, grasp, CoM and environment localization.
  Goals: CoM, contact and grasp wrenches.
- **Constraints and Optimizations**
  Constraints: To keep stable contacts, contact acceleration must be null and contact forces must be inside the friction cones. If the contact is broken, the HR tries to use the nearest environment to keep its balance. Dynamic equation have to be respected. The joint control torques and grasp wrenches are saturated so that our HR cannot apply unrealistic wrenches.
  Optimizations: It adapts its posture. HR tries to reach the CoM goal position, contact and grasp wrench goals which are required (computed in the next section).
- **Outputs**
  They are obtained as the result of constrained QP. Only the control joint torque results are useful in the physical simulation.

We propose in the next section a method to compute a HR configuration robust with respect to a disturbance, *i.e.* robust CoM position, contact and grasp wrench goals.

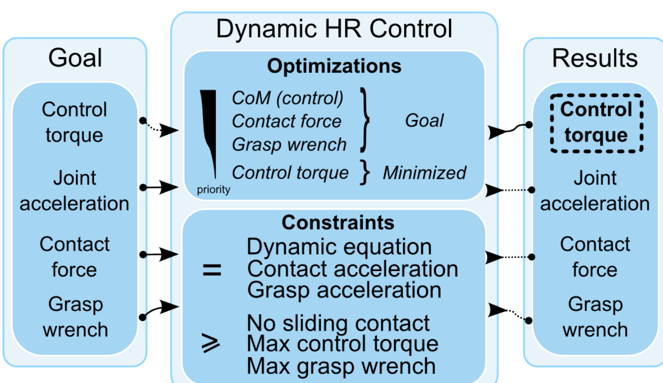


Fig. 3. Dynamic HR control. Only the control torque results are useful in the physical simulation. In the optimizations, CoM, contact and grasp wrench goals are required. In section IV, we compute a posture that is robust with respect to a disturbance *i.e.* robust CoM, contact and grasp wrench goal.

IV. Robust Posture Control

This chapter presents our main innovation.

A. General Outline

In order to simplify the problem and its presentation, HR posture, considered rigid enough, is reduced to its CoM, subject to the acceleration of gravity, contact and grasp wrenches. In a first step, the stability margins of the HR configuration are estimated.

These margins are related to disturbance wrenches $\Delta\Omega$ which are applied to the CoM. These wrenches are decomposed through an amplitude λ and a normalized direction vector $\delta\omega$ of dimension 6. $\Delta\Omega = \lambda\,\delta\omega$. For a given disturbance shape $\delta\omega$ of our choice, we compute:

- **Maximal disturbance wrench:** In IV-D, we compute the maximal amplitude disturbance $\lambda^{\max}$ for a given $\delta\omega$. It is a stability criteria of the best HR configuration toward current contact points and grasp hold. We formulate a LP optimization.
- **Admissible disturbance wrench:** In IV-E, we choose the amplitude disturbance λ' (lower than $\lambda^{\max}$). We compute CoM position, prestressed contact and grasp wrenches for any kind of admissible disturbance. We formulate a QP optimization. It was first studied by A. Rennuit [17].

We make the following assumptions. Contact points and grasp localizations are known. CoM position, contact and grasp wrench are unknown. These unknowns must respect several constraints. First of all, equality constraint is composed of static equations. Then, inequality constraints respect the following assumptions: contact wrenches must be inside the friction cones and grasp wrenches inside the $\mathbb{R}^6$ polytope. In IV-B and IV-C, we introduce the stability margin in this constraint formulation.

We introduce the following notation, Y unknown vector, A, b, C and d matrices and vectors which express linear equality and inequality constraints.

Linear Programming: F_1 is a line vector of weighing.

$$\max\,(F_1\,Y_1) \quad \text{such that} \quad \begin{cases} A_1\,Y_1 + b_1 = 0 \\ C_1\,Y_1 + d_1 \geq 0 \end{cases} \tag{1}$$

Quadratic Programming: Y_2^{des} is a desired but not necessarily accessible solution and Q_2, a quadratic norm.

$$\min \tfrac{1}{2}\|Y_2 - Y_2^{\text{des}}\|^2_{Q_2} \quad \text{such that} \quad \begin{cases} A_2\,Y_2 + b_2 = 0 \\ C_2\,Y_2 + d_2 \geq 0 \end{cases} \tag{2}$$

B. Introduction of Stability Margin in the Static Equation

We introduce the following notation: x_G the CoM position, f_c the linearized contact wrenches and W_g the grasp wrenches. The vector f_c is of dimension $3\,n_c$ with n_c, the number of contacts. The vector W_g is of dimension $6\,n_g$ with n_g, the number of grasps to take into account. With the gravity $W^{\text{scene}}_{\text{Mass}}$, contact $W^{\text{scene}}_{\text{Contact}}$ and grasp $W^{\text{scene}}_{\text{Grasp}}$ wrenches applied to HR and expressed in the scene coordinate system, the static balance equation is: $W^{\text{scene}}_{\text{Mass}} + W^{\text{scene}}_{\text{Contact}} + W^{\text{scene}}_{\text{Grasp}} = 0_6$. We can easily find:

$$W^{\text{scene}}_{\text{Mass}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -m\,g & 0 \\ m\,g & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} x_G + \begin{bmatrix} 0 \\ 0 \\ -m\,g \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

which we rewrite $W^{\text{scene}}_{\text{Mass}} = E_{x_G}\, x_G + P$. We can also define a matrix E_{f_c} such as $W^{\text{scene}}_{\text{Contact}} = E_{f_c}\, f_c$ and E_{W_g} such as $W^{\text{scene}}_{\text{Grasp}} = E_{W_g}\, W_g$. Hence, the static equation may be writen:

$$\left[\begin{array}{ccc} E_{x_G} & E_{f_c} & E_{W_g} \end{array}\right] \left[\begin{array}{ccc} x_G^T & f_c^T & W_g^T \end{array}\right]^T + P = 0 \quad (3)$$

A disturbance $\Delta\Omega$ introduced in the Eq. 3 can be compensated by adding contact and grasp wrench variations respectively noted δf_c and δW_g. We remark than $\delta x_G = 0$ because we only consider disturbances which can be compensated by a realizable set of contact and grasp wrenches without CoM displacement.

$$E\, \delta f + \Delta\Omega = 0 \quad (4)$$

with $E = \left[\begin{array}{cc} E_{f_c} & E_{W_g} \end{array}\right]$ and $\delta f = \left[\begin{array}{cc} \delta f_c^T & \delta W_g^T \end{array}\right]^T$. The matrix E is generally not invertible and an infinity of δf are solutions in a rigid framework to Eq. 4. The solution which minimized the following quadratic norm is held:

$$\min \tfrac{1}{2}\|\delta f\|^2_G \quad \text{such as} \quad E\, \delta f + \Delta\Omega = 0$$

δf minimizes a spring potential energy. G is a symmetric positive matrix such as G^{-1} is homogenous to an articular spring. It may be constructed using a weighing between the different end-effector muscular strengths. The detailed construction of this matrix is spared for future works. We resolve analytically this problem by introducing a lagrangian.

$$L = \tfrac{1}{2}\, \delta f^T\, G\, \delta f + \sigma^T (E\, \delta f + \Delta\Omega) \quad \text{and} \quad \frac{\partial L}{\partial(\delta f)} = 0$$

L is the lagrangian and σ is lagrangian coefficient. The resolution of this problem gives:

$$\begin{array}{lll} G\, \delta f + E^T \sigma = 0 & \Rightarrow & \delta f = -G^{-1} E^T \sigma \\ & \Rightarrow & E\, \delta f = -E\, G^{-1} E^T \sigma = -\Delta\Omega \end{array}$$

$$\Delta\Omega = E\, G^{-1} E^T \sigma \quad \Rightarrow \quad \sigma = \left(E\, G^{-1} E^T\right)^{-1} \Delta\Omega$$

$$\delta f = -E^* \Delta\Omega \quad \text{with} \quad E^* = G^{-1} E^T \left(E\, G^{-1} E^T\right)^{-1} \quad (5)$$

with E^* a generalized inverse of E, $E^*_{f_c}$ the first $3\, n_c$ lines of E^* and $E^*_{W_g}$ the last $6\, n_g$ lines of E^*. Be careful that $E^*_{f_c}$ and $E^*_{W_g}$ are not pseudo-inverse of E_{f_c} and E_{W_g} respectively.

C. Introduction of Stability Margin in the Inequality Constraints

We now write the linear inequality constraint. Contacts must be non-sliding (Subsection II-B) *i.e.* $E_c\, f_c + d_c \geq 0$. Moreover, grasp wrenches are saturated because of the motor limitations (Subsection II-C) *i.e.* $|W_g| \leq W_g^{\max}$.

Introduction of a stability margin in the inequality constraints consists in adding δf_c and δW_g to f_c and W_g respectively. Using the variable substitution in Eq. 5, we can easily rewrite the inequalities with $\Delta\Omega$. An originality of our approach is that we may considere simultaneously several disturbances: $\delta\omega$ may be a vector as in section IV-A, but also a matrix composed of several disturbance directions, forming a disturbance polytope in $\mathbb{R}^6$. This enables us to choose the shape of the disturbances, choose to explore some direction rather than another or all the directions fairly. For the final inequalities, we select the most constraining disturbances and get the following results:

$$\left\{\begin{array}{l} E_c\, f_c + d_c - \max\left(E_c\, E^*_{f_c}\, \Delta\Omega, \vec{0}\right) \geq 0 \\ +\ W_g + W_g^{\max} - \max\left(E^*_{W_g}\, \Delta\Omega, \vec{0}\right) \geq 0 \\ -\ W_g + W_g^{\max} + \min\left(E^*_{W_g}\, \Delta\Omega, \vec{0}\right) \geq 0 \end{array}\right. \quad (6)$$

The next two sections are dedicated to resolution.

D. Maximal Disturbance Wrench: LP Formulation

In this section, the maximal disturbance amplitude which resisted to imposed contact points and grasps is computed by resolving a LP problem. The unknowns are the amplitude disturbance λ, the position of the CoM x_G, the contact wrenches f_c and the grasp wrenches W_g. They are expressed into a vector: $Y_1 = \left[\begin{array}{cccc} \lambda & x_G^T & f_c^T & W_g^T \end{array}\right]^T$ of dimension $1 + 3 + 3\, n_c + 6\, n_g$. We restrict the solution area of x_G in a cube thanks to the following inequality: $x_G^{\min} \leq x_G \leq x_G^{\max}$. With this simple condition, we suppose that the computed CoM can be reached by the HR. Moreover, equations (3) and (6) may be rewritten:

$$A_1\, Y_1 + b_1 = 0 \quad \text{with} \quad \left\{\begin{array}{l} A_1 = \left[\begin{array}{cccc} 0 & E_{x_G} & E_{f_c} & E_{W_g} \end{array}\right] \\ b_1 = P \end{array}\right. \quad (7)$$

$$C_1\, Y_1 + d_1 \geq 0 \quad \text{with} \quad (8)$$

$$\left\{\begin{array}{l} C_1 = \left[\begin{array}{cccc} 0 & +\, I_3 & 0 & 0 \\ 0 & -\, I_3 & 0 & 0 \\ -\max\left(E_c\, E^*_{f_c}\, \delta\omega, \vec{0}\right) & 0 & E_c & 0 \\ -\max\left(E^*_{W_g}\, \delta\omega, \vec{0}\right) & 0 & 0 & +\, I_{6\, n_g} \\ +\min\left(E^*_{W_g}\, \delta\omega, \vec{0}\right) & 0 & 0 & -\, I_{6\, n_g} \end{array}\right] \\ \\ d_1 = \left[\begin{array}{ccccc} -x_G^{\min\, T} & x_G^{\max\, T} & d_c^{\ T} & W_g^{\max T} & W_g^{\max T} \end{array}\right]^T \end{array}\right.$$

The goal is to compute the maximal λ so we write the following maximization:

$$\max\left(F_1\, Y_1\right) \quad \text{with} \quad F_1 = \left[\begin{array}{cccc} 1 & 0 & \ldots & 0_{3+3\, n_c+6\, n_g} \end{array}\right] \quad (9)$$

We group equations (7), (8) and (9) to solve the LP problem (Eq. 1). We rename λ in $\lambda^{\max}$ in the next section. It is the maximal amplitude disturbance for the chosen directions $\delta\omega$.

E. Admissible Disturbance Wrench: QP Formulation

In this section, λ is known and noted $\lambda' \in [\ 0\ ,\ \lambda^{\max}\ ]$. The goal of this section is to compute x_G, f_c and W_g for a given λ'. (We have already computed these data in the previous section (IV-D) for $\lambda' = \lambda^{\max}$). The unknowns are expressed into a vector $Y_2 = \left[\ x_G{}^T \quad f_c{}^T \quad W_g{}^T\ \right]^T$ of dimension $3+3\,n_c+6\,n_g$. We rewrite the same constraints (Eq. (3) and (6)):

$$A_2\,Y_2 + b_2 = 0 \quad \text{with} \quad \begin{cases} A_2 = \left[\ E_{x_G} \quad E_{f_c} \quad E_{W_g}\ \right] \\ b_2 = P \end{cases} \tag{10}$$

$$C_2\,Y_2 + d_2 \geq 0 \quad \text{with} \quad C_2 = \begin{bmatrix} +\,I_3 & 0 & 0 \\ -\,I_3 & 0 & 0 \\ 0 & E_c & 0 \\ 0 & 0 & +\,I_{6\,n_g} \\ 0 & 0 & -\,I_{6\,n_g} \end{bmatrix} \tag{11}$$

$$\text{and} \quad d_2 = \begin{bmatrix} -\,x_G^{\min} & \\ +\,x_G^{\max} & \\ +\,d_c & -\,\max\left(E_c\,E_{f_c}^{*}\,\delta\omega, \vec{0}\right)\lambda' \\ +\,W_g^{\max} & -\,\max\left(E_{W_g}^{*}\,\delta\omega, \vec{0}\right)\lambda' \\ +\,W_g^{\max} & +\,\min\left(E_{W_g}^{*}\,\delta\omega, \vec{0}\right)\lambda' \end{bmatrix}$$

There is a lot of solutions which respects these constraints. Thus we choose to consider the one that minimizes a certain quadratic norm. We give a desired CoM x_G^{des}, a desired contact wrench distribution f_c^{des} (generally homogeneous for a standing posture) and desired grasp wrenches W_g^{des} of our choice. We prioritize the optimization criteria thanks to the weighing matrix Q_2.

$$\min \frac{1}{2}\|Y_2 - Y_2^{\text{des}}\|_{Q_2}^2 \tag{12}$$

$$\text{with} \quad \begin{cases} Q_2 = \operatorname{diag}(Q_{x_G},\ Q_{f_c},\ Q_{W_g}) \\ Y_2^{\text{des}} = \left[\ x_G^{\text{des}\,T} \quad f_c^{\text{des}\,T} \quad W_g^{\text{des}\,T}\ \right]^T \end{cases}$$

We group equations (10), (11) and (12) to solve the QP problem (Eq. 2).

Up to now, we have considered CoM position as an unknown and computed the most robust CoM localization. However, for a fixed HR configuration and CoM, it is also interesting to compute the maximal resistible disturbance and the corresponding prestressed contact and grasp. It gives an estimation of stability margins of a fixed HR configuration and CoM. All we have to do is to rewrite previous LP and QP with a given x_G, the fixed position of CoM in the simulation.

V. Results

In Fig. 4, we propose a case study that illustrates the influence of various criteria in stability margin computation. HR is standing with a hand-wall contact (4(d) 4(h)). We study a simplified HR contact configuration: two point contacts on the ground and one point contact on the wall. On every figure, we put for reference the CoM position and contact wrenches without stability margin. It corresponds to x_G^{des} and f_c^{des} of Eq. 12. We remark that no hand contact forces are desired *c.f.* 4(d). We propose several disturbance shapes: isotropic or unilateral distribution. The influence of limiting the available domain for the computed CoM (constraint $x_G^{\min} \leq x_G \leq x_G^{\max}$) may be observed by comparing Fig. 4(a) and 4(b). We resist to stronger disturbance wrenches without the CoM localization constraint; it is a most robust posture. The problem is that CoM is not necessary reachable by a HR, as joint limits and imposed contact configurations restrict its movement. That is why in the other examples, we keep this constraint and supposed that the HR is able to reach the x_G^{goal}. Reducing the dry-friction factor μ reduces the stability margin (Fig. 4(b) and 4(e)). At least, reducing by a half the disturbance wrench (Fig. 4(b) and 4(f)) thanks to Section IV-E gives a more realizable set of contact wrenches.

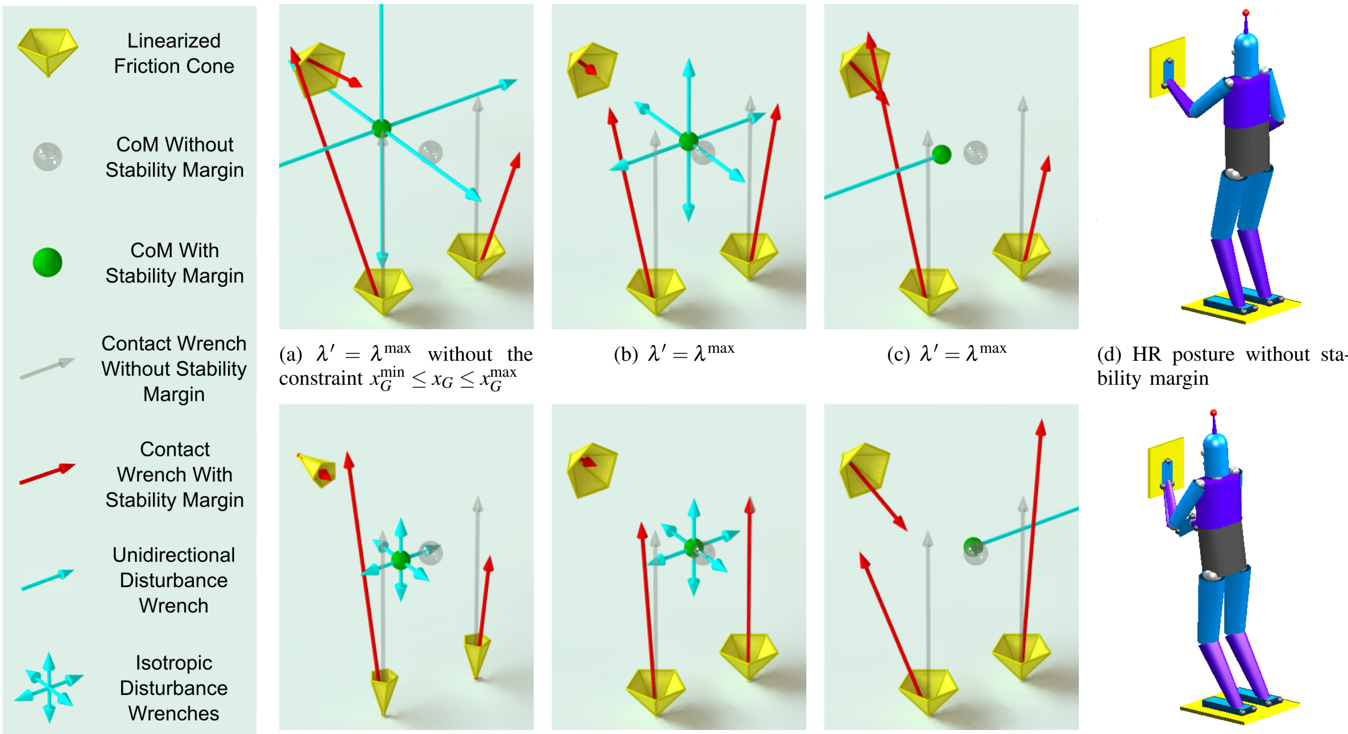
In the example on Fig. 5, the ground pitches downwards at an unchanging rotational velocity. At the beginning of the scene, the HR is upright and its hand grasps are deactivated (Fig. 5(a)). Because of frictional contacts, balance is broken for a two feet standing posture at too important ground inclinations. The goal of the HR control is to keep robust balance when the environment changes. Thanks to grasp holds, the HR is able to maintain its balance. To this end, HR grasps are deactivated/activated as the simulation carries on. This behavior is based on the computation of stability margin which gives a good characterization of balance breakdown. For the current posture, we compute the maximal disturbance wrench. When this stability margin is lower than a given amplitude, we activate a better configuration. We choose an isotropic disturbance distribution.

The graph curves present the maximal disturbance wrench, function of the base overturn angle. First of all, we can remark that the more the ground overturns, the less the stability margin. We studied several systems: two foot, two foot and one hand, two foot and two hands. The current HR configuration drifts from a previous configuration to another in order to keep a required minimum stability margin, thanks to an automaton. For instance, on Fig. 5(c), angle $= 25^o$, the stability margin of the two foot system becomes inferior to the minimum stability margin: this triggers the HR decision to use its left hand and grasp hold. Then, the two foot and one hand system have a better stability margin. On Fig. 5(d), current HR configuration is below the minimum stability margin (Fig. 5 curve: under point **d**) because it takes time to HR to reach the second hand hold. It anticipates a better configuration.

This problem involves multiple grasps and non coplanar frictional contacts and our algorithm allows us to stabilize the motion. The HR converges to a stable and robust posture.

VI. Conclusion

We introduced a new robust balance control of HR with multiple grasps and non coplanar frictional contacts. HR can pick up a robust posture for complex contact and grasp



(a) $\lambda' = \lambda^{\max}$ without the constraint $x_G^{\min} \leq x_G \leq x_G^{\max}$ (b) $\lambda' = \lambda^{\max}$ (c) $\lambda' = \lambda^{\max}$ (d) HR posture without stability margin

(e) $\lambda' = \lambda^{\max}$ with smaller μ (f) $\lambda' = \frac{\lambda^{\max}}{2}$ (g) $\lambda' = \lambda^{\max}$ (h) HR posture with stability margin

Fig. 4. Influences of various criteria in stability margin computation.

configuration. We deal with stability margin with respect to disturbance wrenches. Thanks to constrained optimization formulations (LP and QP), we characterize balance breakdown by computing the biggest wrench disturbance which can be compensated by contact and grasp. It can be considered like a new stability criterion. Moreover, we compute the CoM position and admissible robust contact and grasp wrenches which allow the HR to grab strongly its complex environment. Thus, HR behavior brings both balance and autonomy. Dynamic HR control deals with HR redundant postures to reach the feasible CoM position.

We are currently planning to use this control architecture in an interactive demo. The basic algorithm is fast enough to be used real-time. At last, we would like to work on more complex behaviors with several step control and predictive control [2].

Videos illustrating our previous work [5] [6] are available on cyrillecollette.blogspot.com.

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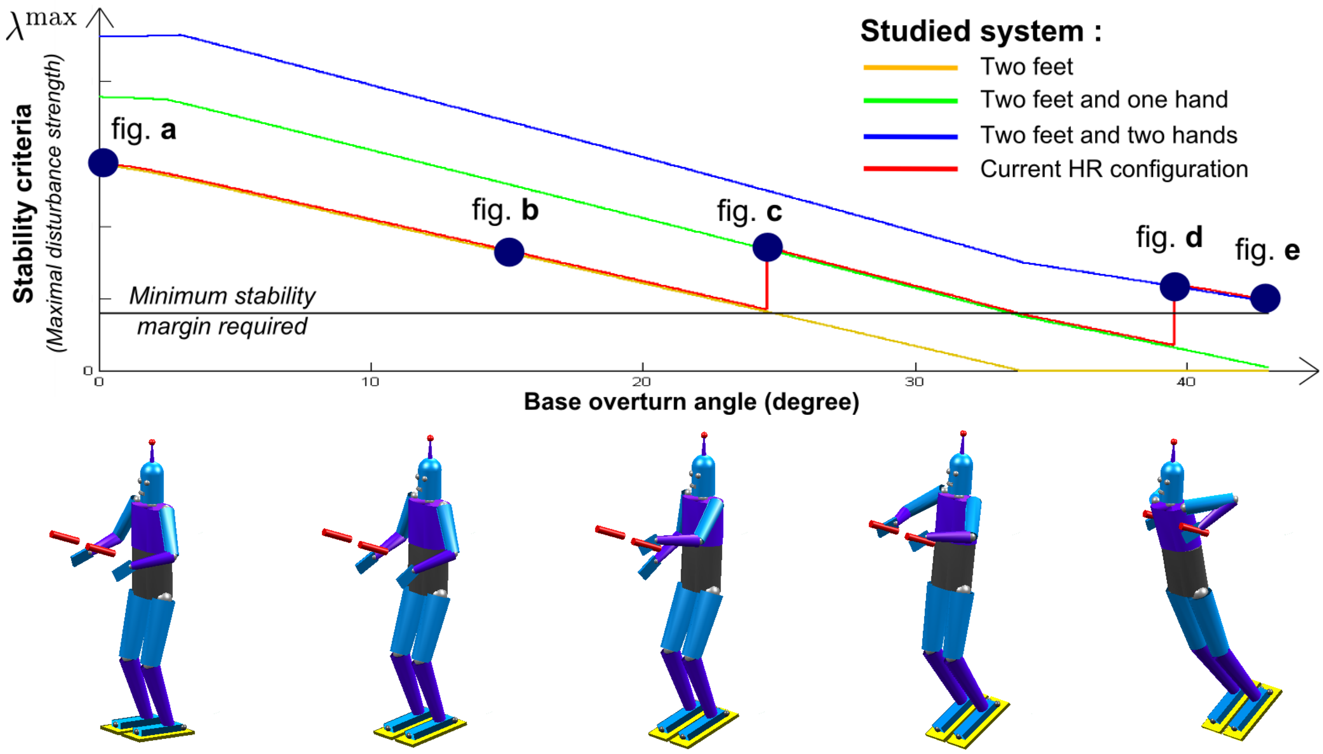

(a) angle = 0^o (b) angle = 15^o (c) angle = 25^o (d) angle = 38^o (e) angle = 43^o

Fig. 5. Example of HR balance control based on stability margin computation. The ground pitches downwards at an unchanging rotational velocity. We choose an isotropic disturbance distribution to compute $\lambda^{\max}$ for each studied system. The HR keeps balance using its hand grasps. Grasp simulation model is a damped spring between hand and environment. A damped spring consists in a spring (mapping from $SE(3)$ to $se(3)^*$) and a damper (mapping from $se(3)$ to $se(3)^*$). The spring is chosen as deriving from a potential [8]. Dynamic simulation environment "Arboris" is developed by CEA/ISIR in Matlab, 2006. Dynamic model elaboration comes from J. Park [16].

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