Abstract—This paper overviews the whole-body force control framework implemented on the iCub humanoid platform. This framework consists in a hierarchy of two tasks, where the highest priority task is a force control task, and the lowest one a postural task. The force task achieves the stabilization of a desired centrodial dynamics, i.e., a desired linear and angular momentum of the multi body system. These forces are generated by the internal joint torques, which are related to forces through the rigid constraint equations and the free-floating dynamics. Validation of the framework has been conducted on a real scenario involving the iCub robot balancing on one foot while safely interacting with people.

I. INTRODUCTION

Forthcoming robotic applications require robots to safely interact with the environment. This requirement is different from those of classical industrial applications where robots are primarily required to perform positioning tasks. Another key element for innovative robotics is the need of increased mobility and adaptation to human-centered environment, e.g., walking while performing interaction tasks. Within this context, physical interaction influences stability and balance. To allow a proper coordination between interaction and posture control, robotics research needs to investigate the principles governing whole-body control with contact dynamics. This paper presents a control strategy for one-foot balancing tasks of humanoid robots. The control strategy ensures a degree of compliance for the multi-body system that allows safe human robot interaction.

Fixed-base robots have long attracted the attention of the scientific community. These robots are usually confined in a protected and well-known environment, and have thus called for an augmentation of their degrees of mobility. Augmenting mobility requires to move from the conventional fixed-base theoretical framework to free-floating approaches, whose control has been addressed only during recent years. Full feedback linearization of free-floating mechanical systems is forbidden because of their underactuated nature [1], thus prohibiting the application of classical methodologies. The problem becomes even more complex when these systems are constrained, that is, their dynamics are subject to a set of (possibly time-varying) nonlinear constraints. This is the typical case for legged robots for which motion is constrained by rigid contacts with the ground.

This paper presents the control framework implemented on the humanoid robot iCub for one foot balancing and motion control. This framework ensures a degree of compliance for the multi-body system, which allows for safe human robot interaction.

II. BACKGROUND

A. System modelling

The system dynamics are characterized by the following differential equations:

\begin{align}
M(q)\ddot{q} + h(q, \nu) - J^T(q)f &= S\tau, \\
J(q)\dot{q} + \dot{J}(q)\nu &= 0,
\end{align}

where \( q \in SE(3) \times \mathbb{R}^n \) represents the configuration of the free floating system, which is given by the pose of a base-frame and \( n \) generalized coordinates \( q_j \) characterizing the joint angles. The vector \( \nu \in \mathbb{R}^{n+6} \) represents the robot velocity (it includes both \( q_j \in \mathbb{R}^n \) and the linear and angular velocity of the base-frame \( v_b \in \mathbb{R}^6 \)), the system acceleration is denoted as \( \dot{\nu} \), the derivative of \( \nu \), the control input \( \tau \in \mathbb{R}^n \) is the vector of joint torques, \( M \in \mathbb{R}^{(n+6)\times(n+6)} \) is the mass matrix, \( h \in \mathbb{R}^{n+6} \) contains both gravitational and Coriolis terms, \( S \in \mathbb{R}^n \times (n+6) \) is the matrix selecting the actuated degrees of freedom, \( f \in \mathbb{R}^6 \) is the external, contact wrench, and \( J \in \mathbb{R}^{6 \times (n+6)} \) is the contact Jacobian.

B. Problem statement

The control objective is the asymptotic stabilization of a desired centrodial dynamics [2]. Let \( \dot{H} \) denote the centrodial momentum of the robot. Then, the time derivative of \( H \) is equal to the summation of the external wrenches acting on the multi-body system. When the robot stands on one foot and the centrodial momentum is expressed with respect to the center of mass, one has

\[ \dot{H} = Xf + mg = \left( \frac{m\ddot{x}}{H_\omega} \right) \]

where \( m \) is the mass of the robot, \( q \in \mathbb{R}^6 \) is the gravitational acceleration, \( \ddot{x} \in \mathbb{R}^3 \) is the acceleration of the center of mass, \( H_\omega \in \mathbb{R}^3 \) is the angular momentum of the robot, and the matrix \( X \) maps the wrench acting on the left foot with respect to the center of mass.

The control objective is to find a control law for the inputs \( \tau \) such that \( x \to x(0) \) and \( H_\omega \to 0 \). This choice is sufficient for balancing purposes. Also, while achieving this control objective, the system shall have a degree of compliance.
III. THE CONTROL STRATEGY

The control strategy is composed of two steps. We first choose the external force $f$ such that $x \to x(0)$ and $H_\omega \to 0$. Then, we generate this force through the internal torques. Since iCub possesses more than six degrees-of-freedom, which are necessary to generate the contact force $f$, we choose the remaining control inputs so that to have compliance at the joint level.

A. The choice of the contact force

Being the matrix $X$ invertible, the contact force $f$ achieving the control objective may be chosen as follows:

$$f = -X^{-1} \left[ k_d H + k_p \begin{pmatrix} x - x(0) \\ 0_{3 \times 1} \end{pmatrix} + mg \right],$$

with $k_d$ and $k_p$ two positive constants.

In order to keep the foot on the ground, the above wrench must satisfy some constraints, e.g., the contact force must belong to the associated friction cones. In general, the contact constraints can be represented by inequalities of the form $Cf < d$, with the matrix $C$ and the vector $d$ properly chosen. Then, we choose the contact wrench as follows:

$$f = \arg\min_{\xi \in \mathbb{R}^6} \|\xi - f_d\|^2$$

subject to $C\xi < d,$

with the desired wrench $f_d$ given by (3).

B. The choice of the joint torques

The control input $\tau$ must generate the force $f$. The relationship between the contact wrench and the joint torques can be obtained by using the constraint equation along with the free-floating dynamics, i.e., Eq. (1). One can show that the torques generating $f$ are given by the summation of two terms, i.e.,

$$\tau = \tau_f + N\tau_0,$$

where $\tau_f$ ensures $f = f_d$, the matrix $N \in \mathbb{R}^{n \times n}$ is the null space projector of $JM^{-1}S$, and $\tau_0$ is a vector that can be chosen at will. To obtain compliance at joint level, we choose $\tau_0$ similar to a gravity and external force compensation, plus a term of the form

$$-k(q_j - q_d),$$

which ensures compliance at joint level.

IV. EXPERIMENT

We implemented the proposed control strategy on the iCub platform. The control framework is composed of two loops. The inner loop is in charge of stabilizing desired joint torques, while the outer loop is governed by Eq. (5). Both loops runs at the same frequency of 100 Hz.

The experiment consists in two phases. In the first phase, we change the desired $q_d$ in order to generate internal motions, which do not perturb the stability of the robot momentum thanks to the prioritization of tasks described in the previous section. In the second phase, we apply external perturbations by interacting with the robot. This interaction results to be safe thanks to the compliance at joint level. A video of the experiment is available for the interested reader.

For more detailed information and description of the system architecture (comprising torque and forces estimation and low level torque control) see [3].

V. CONCLUSIONS

The present paper presented the control strategy implemented on the iCub platform for the balancing on one foot. Safe interaction with the robot is achieved thanks to the compliance that the strategy ensures. Interaction with the environment is still possible and this does not affect the stability of the balancing task.

REFERENCES


https://www.youtube.com/watch?v=VrPBSSQEr3A.