Adaptive Friction Compensation for Humanoid Robots without Joint-Torque Sensors

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Abstract—This paper presents a novel approach for friction compensation on humanoid robots originally designed for position control in order to enable torque-based control methods on such systems. Due to their design, this kind of robots lacks joint-torque sensors and is equipped with high-reduction gearboxes. Nevertheless, we can still apply torque commands using torque estimation from motor currents. Moreover, the high gear reduction ratio produces high dynamic friction which significantly affects the robots drives and must be taken into account. Considering the LuGre friction model, an adaptive friction compensator based on a second-order sliding mode is developed and illustrated on a humanoid robot. The proposed method only relies on IMU data as well as joint position and velocity measurements from the joint encoders and is applied to the 12 DoFs of the robot's legs for CoM motion. The proposed control approach does not require the FT sensors mounted on the ankles.

I. INTRODUCTION

Humanoid robots are required to safely interact and collaborate with humans. For this purpose, robustness with respect to sudden disturbances and compliant behavior are key requirements. Torque-based control techniques have therefore received more attention among researchers in the field of humanoid robots [1], [2], [3], [4], [5]. In contrast to position-based control techniques, which require high gains and stiffnesses in order to remain accurate while sacrificing the ability to react to sudden disturbances, torque-based control techniques are inherently compliant and robust. Many robots such as Pal Robotics' REEMC, which is subject of research, are still designed for classical position control. The robot with its most important specifications is depicted in Fig. 1. Position-controlled robots are oftentimes equipped with motor reducers of high ratio that produce high dynamic friction and also lack torque sensing capability. The effect of joint friction greatly deteriorates the performance of any torque-based approach. In order to make such methods still work for this type of robot, friction needs to be considered in the controller design.

A. State of the Art

Friction compensation techniques are already thoroughly studied in the literature. Since it is not possible to cover all works in depth, a general overview over is given here.

There are three main approaches to deal with the problem. The first category includes model-based friction compensation. The underlying friction model is identified and used it as a feed-forward term in the derivation of the control law.



Fig. 1. The humanoid robot REEMC developed by Pal Robotics. The important specifications are depicted in the figure.

Mallon et al. [6] assumed a set-valued dry friction model including the Stribeck effect neglecting dynamical friction phenomena. They investigated the effects of modeling errors in the friction model and found that overcompensation leads to limit cycles which can cause undesirable oscillations and even instability. Undercompensation, however, leads to the existence of an equilibrium set and a non-zero steady state error. Del Prete et al. [7] applied model-based friction identification and compensation in the context of humanoid robots. Their approach relies on incorporating a simple friction model assuming Coulomb and viscous friction in the torque control law. For obtaining the friction model, several different identification techniques were tested. Since a least-squares fit for the friction identification and a piecewise linear fit resulted in a torque that was unstable in open-loop, they deployed asymmetric penalty identification. This type of identifictation is a more conservative method penalizing overfitting over underfitting.

Friction observers fall in the second category of friction compensation techniques. Le Tien et al. [8] designed a friction observer, whose output corresponds to the low-pass

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filtered friction torque. It relies, however, on joint torque measurements.

Since all identification methods lead to modeling errors either due to simplifications or unmodeled effects, some authors use adaptive friction compensation techniques, in which the friction model is adapted online to account for occuring errors. Panteley et al. [9] adopted a regressorbased approach for both the robot's dynamics model and the friction model based on joint errors. They casted the friction compensation problem as a disturbance rejection problem and designed an inner loop that passified the system and a relay-based outer loop for the disturbance rejection. Since their approach represents a first-order sliding mode with a discontinuos virtual regressor, it can lead to chattering and instability. Garcia-Valdovinos and Parra-Vega [10] extended the approach by adopting a higher-order sliding mode to avoid chattering.

B. Contribution

Friction compensation for humanoid robots is mainly considered in terms of low-level current control loops [11], [7], [12]. In order to keep the estimation in general terms, we propose a solution that does not depend on a specific robot model and does not require access to the lower level subroutines. Since no torque-sensors are available, the compensator must rely on position and velocity sensing only. The actual friction is a very complex phenomenon that varies with the current motor position, temperature and wearout, thus every model that is chosen is prone to errors. Moreover, humanoid robots are a special case of floatingbase systems that are subject to contact forces. Taking all these aspects into account, we propose the following controller: An underlying balancing controller for regulating the Center of Mass position and the base attitude by contact force distribution similar to [4] is introduced. On top of the balancing controller, an adaptive higher-order sliding mode controller compensating the friction and extending the work of [10] for humanoid robots is proposed. Thus, the dimensionality of the problem is reduced by raising the abstraction layer to the torque level, no torque sensors are necessary and modeling uncertainties are dealt with by the adaptive controller. The adaptive function uses an error function in task space, which in our case is the CoM position and base orientation. The changes in parameter compensation are directly based on these errors and contrary to [9], [10] not the joint errors. Thus, the whole controller is more sensitive to the task definition, which is especially important for naturally unstable systems with fast dynamics such as bipedal humanoid robots.

C. Organization

This work is organized as follows. In section II, a balancing controller based on contact force distribution is reviewed. Section III focuses on the design of the adaptive friction compensation. The performance of the controller is evaluated in section IV. Finally, a conclusion is given in section V.

II. BALANCING CONTROL

In this section, the underlying balance controller is introduced. The main idea for the controller is to regulate the CoM position and base orientation by manipulating the contact forces. A block diagram of the control system is depicted in Fig. 2. Since the controller is based on the dynamics of the robot, they are described in section II-A. Section II-B explains, how to obtain the commanded torques for a desired force reference. In section II-C, a force reference is derived from the dynamics of the robot's centroidal momentum.

A. Robot Dynamics

Humanoid robots have two distinctive properties that distinguish them from classical industrial manipulators. First, humanoid robots have a free-floating base, which can be moved arbitrarily with respect to an inertial reference frame. The floating base can be modeled by adding a 6-DoF joint to the robots configuration. Since it is not possible to directly measure the state of this joint, an Extended Kalman Filter as in [13] is used for estimation. The second property is the contact with the environment, which imposes constraints on the robots motion. Both these properties lead to the constrained equation of motion which can be stated as

$$\underbrace{\begin{bmatrix} M_b & M_{bj} \\ M_{bj}^T & M_j \end{bmatrix}}_{M(q)} \underbrace{\begin{bmatrix} \ddot{x}_b \\ \ddot{q}_j \end{bmatrix}}_{\dot{q}} + \underbrace{\begin{bmatrix} h_b \\ h_j \end{bmatrix}}_{h(q,\dot{q})} - \underbrace{\begin{bmatrix} J_{cb}^T \\ J_{cj}^T \end{bmatrix}}_{J_c(q)^T} F = \underbrace{\begin{bmatrix} 0_{6\times n} \\ I_{n\times n} \end{bmatrix}}_{S^T} \tau \quad (1a)$$
$$J_c \ddot{q} - \dot{J}_c \dot{q} = 0 \quad (1b)$$

where $q \in \mathbb{R}^{n+6}$ are the generalized coordinates, $x_b \in \mathbb{R}^6$ represents the pose of the floating base, $q_j \in \mathbb{R}^n$ depicts the joint positions, $M \in \mathbb{R}^{(n+6) \times (n+6)}$ represents the inertia matrix, $h \in \mathbb{R}^{(n+6)}$ is the combined vector of gravitational, centrifugal and Coriolis terms, $S \in \mathbb{R}^{n \times (n+6)}$ is a joint selector matrix that characterizes the underactuation and τ is the vector of joint torques. It is assumed, that the robot is in double support phase and that the contact forces lie within the friction cone. Furthermore, we assume that there are always positive ground reaction forces. Each foot has four contact points. Each contact point is constrained in position which imposes six constraints on the foot. Following our assumptions, the contact points cannot move alongside the constrained directions, so the time derivatives of the contact points become zero. This leads to the contact condition Eq. (1b). The stacked vector of external wrenches $F \in \mathbb{R}^{12}$ is connected to the equation of motion by means of the contact Jacobian $J_c \in \mathbb{R}^{12 \times (n+6)}$.

B. Complete Force Control

With the *Task Space Inverse Dynamics* (TSID) framework by Del Prete [14], it is possible to make the system follow a wrench reference F^d . The commanded joint torques τ^d are chosen to match a desired vector of contact wrenches as close as possible, while ensuring the contact condition (1b)



Fig. 2. Block diagram of the proposed balancing controller with friction compensation. For estimating the base state x_b , an Extended Kalman Filter similar to [13] is used. The CoM r_C is obtained using forward kinematics (FK). No FT sensor feedback is used in the control loop. The friction parameters are adapted directly using the task space error.

and equation of motion (1a) hold. This can be expressed as

$$\tau^{d} = -(J_{c}\bar{S})^{T}F^{d} + N_{j}^{-1}\ddot{q}_{j}^{d} + \bar{S}^{T}h - D\dot{q}$$
(2a)
$$\ddot{q}_{i}^{d} = (J_{c}\bar{S})^{\#}(J_{cb}M_{b}^{-1}(h_{b} - J_{cb}^{T}F^{d}) - \dot{J}_{c}\dot{q})$$

$$= (J_c \bar{S})^{\#} (J_{cb} M_b^{-1} (h_b - J_{cb}^T F^d) - \dot{J}_c \dot{q}) + (I_{n \times n} - (J_c \bar{S})^{\#} (J_c \bar{S})) \ddot{q}_{j0},$$
(2b)

where $\bar{S} = \begin{bmatrix} -M_{bj}^T M_b^{-1} & I \end{bmatrix}^T$, $N_j^{-1} = M_j - M_{bj}^T M_b^{-1} M_{bj}$, $D \in \mathbb{R}^{n \times n}$ is a joint-wise damping term, and \ddot{q}_{j0} is an arbritrary joint acceleration vector that lies in the nullspace of the generalized Jacobian $(J_c \bar{S})$. The $()^{\#}$ -operator denotes the generalized inverse.

C. Centroidal Momentum Control

A sufficient condition for maintaining stationary balance is that the CoM of the robot stays over the support polygon, which is the region that is formed by enclosing all contact points between the robot and the ground. In order to analyze the dynamics of the robots' translational and rotatory motion in terms of external wrenches, it is worth to investigate the centroidal momentum of the system, which comprises both the net linear and angular momentum around the CoM [15]. The time derivative of the systems' centroidal momentum can be expressed as

$$\dot{\mathcal{P}} = mg + f \tag{3a}$$

$$\mathcal{L} = r_C \times mg + n. \tag{3b}$$

Here, r_C denotes the vector from world frame Σ_W to the CoM as depicted in Fig. 2 and the gravity vector is defined

as $g = [0, 0, -9.81 \frac{\text{m}}{\text{s}^2}]^T$. The time derivative of the linear momentum $\dot{\mathcal{P}}$ is directly connected to the ground reaction forces f expressed in the world frame and the gravitational force mg. The time derivative of the angular momentum $\dot{\mathcal{L}}$ depends on the moment generated by the gravitational force $r_C \times mg$ and the ground reaction moments n expressed in the world frame. By means of the wrench transformation matrix

$${}^{p_i}X_o = \begin{bmatrix} I_{3\times3} & 0_{3\times3} \\ \hat{r}_{S_i} & I_{3\times3} \end{bmatrix}$$
(4)

which maps the ground reaction forces and moments to a wrench acting at an arbitrary contact point *i*. Here, r_{P_i} is the vector from world frame to contact point, $r_{S_i} = r_{P_i} - r_C$ is the vector from CoM to contact point and \hat{r}_{S_i} is the skew-symmetric matrix generated by r_{S_i} . The complete rate of change of centroidal momentum can be directly expressed in terms of the contact wrenches

$$\dot{\mathcal{H}} = \begin{bmatrix} \dot{\mathcal{P}} \\ \dot{\mathcal{L}} \end{bmatrix} = XF + F_g, \tag{5}$$

where $X = \begin{bmatrix} p_1 X_o & \dots & p_k X_o \end{bmatrix}$ is the stacked matrix of wrench transformations. By means of the rate of change in centroidal momentum, a reference for regulating the robots' CoM and base orientation is designed. For the linear momentum the reference is formed using a PD control law for the CoM. In the case of angular momentum, a virtual spring is used that aligns the real base orientation to a desired orientation also according to a PD control law [16]. Under the assumption that contact forces do not leave the friction cone and that ground reaction forces always stay positive, we state the combined PD control law

$$e^{d} = \begin{bmatrix} -K_{P,C}(r_{C} - r_{C}^{d}) - K_{D,C}(\dot{r}_{C} - \dot{r}_{C}^{d}) \\ -2(\eta I_{3\times 3} + \hat{\epsilon})K_{P,O}\epsilon - K_{D,O}(\omega - \omega^{d}) \end{bmatrix}, \quad (6)$$

where $K_{P,C}, K_{P,C}, K_{P,O}, K_{D,O} \in \mathbb{R}^{3\times3}$ are positive definite gain matrices and η and ϵ are the scalar and vector part of the quaternion resulting from $Q_d * Q^{-1}$, respectively. The contact wrench reference is obtained by substituting the PD law in Eq. (5) and solving for the contact forces

$$F^{d} = X^{\#}(e^{d} - F_{g}).$$
⁽⁷⁾

III. FRICTION COMPENSATION

In this section, a friction compensation technique based on position and velocity sensing is proposed. First, the friction model is introduced in section III-A. Then, a higher order sliding mode for compensation is described in section III-B.

A. Friction Model

In order to accurately represent the friction phenomenon, the *LuGre* [17] friction model is considered. Two overlying surfaces are in contact at a number of asperities at the microscopic level. These protuding irregularities can be interpreted as elastic bristles. If an external tangential force is applied, the bristles will deflect to a certain extent, then slip. The aggregated behaviour of the bristles gives rise to the friction torque, which can be expressed as



Fig. 3. Visualization of the bristle deflection interpretation of friction according to the *LuGre* model [17].

$$\tau^f(\dot{q},\xi,\dot{\xi}) = \sigma_0\xi + \sigma_1\dot{\xi} + \sigma_2\dot{q} \tag{8a}$$

$$\dot{\xi} = -\sigma_0 k(\dot{q})\xi + \dot{q} \tag{8b}$$

$$k(\dot{q}) = \frac{|q|}{\alpha_0 + \alpha_1 \exp\left(-\frac{\dot{q}}{\dot{q}_s}\right)^2},$$
 (8c)

where $\xi \in \mathbb{R}^n$ is the vector of average bristle deflections and $\sigma_0, \sigma_1, \sigma_2 \in \mathbb{R}^{n \times n}$ are diagonal matrices, which correspond to the stiffness, damping and viscous friction coefficients for each joint, $k(\dot{q})$ is a parametrization of the Stribeck effect with $\alpha_0, \alpha_1 > 0$ and $\dot{q}_s \in \mathbb{R}^n$.

B. Higher-Order Sliding Mode

As in [9] the friction model is rearranged, so the friction force can be modeled as a disturbance. Substituting Eq. (8b) in (8a) yields

$$\tau^{f} = \underbrace{(\sigma_{0} - \sigma_{0}\sigma_{1}k(\dot{q}))}_{\tau^{f}_{d}} \xi + (\sigma_{1} + \sigma_{2})\dot{q}, \qquad (9)$$

where τ_d^f can be interpreted as a disturbance. Since some damping is actually needed in the control law (2a) in order to avoid nullspace motion, the compensation of viscous friction is not considered here. As explained in [9], we assumed that the initial bristle deflection is bounded $|\xi(0)| \leq \alpha_0 + \alpha_1 = \alpha_{01}$. Then the inequality $k(\dot{q}) \leq (1/\alpha_0)|\dot{q}|$ holds and the first part of Eq. (9), which corresponds to the disturbance, can be bounded as

$$|\tau_d^f| = |(\sigma_0 - \sigma_0 \sigma_1 k(\dot{q}))\xi| \tag{10}$$

$$\leq \sigma_0 \alpha_{01} + \frac{\sigma_{01} \alpha_{01}}{\alpha_0} |\dot{q}|. \tag{11}$$

In order to compensate the disturbance, Panteley et al. defined a sliding-surface s in joint space and used the inequality (11) to obtain a control law τ^c satisfying $s^T(\tau^c - \tau_d^f) \leq 0$, which cancels out the disturbance

$$\tau^{c} = \underbrace{\left[\operatorname{diag}(u) \quad \operatorname{diag}(|\dot{q}|u)\right]}_{Y_{f}} \underbrace{\left[\frac{\sigma_{0}\alpha_{01}}{\sigma_{01}\alpha_{01}}\right]}_{\theta_{f}}.$$
 (12)

Here, Y_f is a regressor matrix θ_f is the vector of friction parameters and u = -sign(s). Instead of a sliding surface defined by joint space errors, we use the error function in task space defined in (6)

$$s = J_s^{\#} e^d + N_s \dot{q}_d, \tag{13}$$

where $J_s = \begin{bmatrix} J_C & J_O \end{bmatrix}^T$ is a stacked Jacobian with the Center of Mass Jacobian J_C and the Jacobian corresponding to the orientation part of the base J_O and N_s is a nullspace matrix. Since the parameters θ_f are generally unknown, an adaptive control law as in [9] is chosen as

$$F^c = Y_f \tilde{\theta}_f$$
 (14a)

$$\tilde{\theta}_f = -\Gamma Y_f^T s, \tag{14b}$$

where $\tilde{\theta}_f$ is an estimation of the real parameters and $\Gamma \in \mathbb{R}^{n \times n}$ is a positive definite gain matrix. The combined torque that is applied to the robot can now be stated as

$$\tau = \tau^s + \tau^c + \tau^d. \tag{15}$$

Here, the term $\tau^s = -K_P s$ corresponds to the task, τ^c corresponds to friction and τ^d corresponds to the dynamics. To avoid discontinuities in the regressor, we chose u as a higher-order sliding mode. Higher-order sliding modes act on higher derivatives of the system deviation from the constraint, to achieve a continuous control signal. An r-th order sliding-mode, not only steers s to zero, but also it's r-th time derivatives. A simple version of a second-order sliding mode that requires no knowledge on the time derivative of the sliding surface is described by Levant [18]

$$u = u_1 + u_2 \tag{16a}$$

$$u_{1} = \begin{cases} -\gamma_{1}\sqrt{|s_{0}|}\tanh(\lambda s), & \text{if } |s| > s_{0} \\ -\gamma_{1}\sqrt{|s|}\tanh(\lambda s), & \text{else} \end{cases}$$
(16b)

$$\dot{u}_2 = \begin{cases} -u, & \text{if } |u| > 1\\ -\gamma_2 \tanh(\lambda s), & \text{else} \end{cases}$$
(16c)

where s_0 is a user-defined upper bound for the sliding surface and $\gamma_{1,2}$ are positive definite gain matrices. The tanh-function is chosen as a smooth replacement for the sign-function, with λ being a coefficient that affects the steepness of the function.

IV. RESULTS

In order to evaluate the controller performance, it is tested first on a 3-DoF robot in simulation. This is summarized in section IV-A. Then, a set of experiments is conducted on a real humanoid robot. The results are given in section IV-B.

A. Simulation Evaluation

u

For the simulation evaluation, a 3-DoF robot model with friction is built in Simulink. For controlling the cartesian position of the end-effector, the following control law is used:

$$\tau = M\ddot{q}^r + h + \tau^f,\tag{17}$$

where $\ddot{q}^r = J^{-1}(\ddot{x}^d - \dot{J}\dot{q} + K_P(x^d - x) + K_D(\dot{x}^d - J\dot{q}))$ and x^d, x is the desired and actual end-effector position. In the



Fig. 4. Simulation Test for a 3-DoF manipulator. The first subplot shows the z-position of the End-Effector. The second subplot shows the parameter evolution. It can be seen that the errors reduce in time. Since the tracking error is not completely reduced to zero in the end, the controller keeps adapting the parameters.

simulation test, a sine reference trajectory for the *z*-position of the end effector is designed and applied to the robot. Plots for the desired and actual position as well as the parameter evolution are shown in Fig. 4. It can be seen that directly after the first period, the parameters are adapted and the current position more and more approaches the reference. Since the error is not completely reduced to zero, the parameters are still being changed by the adaptive controller.

B. Experimental Evaluation

The humanoid REEMC used in the experiments is 1640mm tall, weighs about 86kg and has 6 DoFs per leg. REEMC was originally built for position control and only recently made effort-controllable by Pal Robotics - the manufacturer. The user now is able to command currents to the robot's motors. For the mapping of torques to currents, Pal Robotics provided a set of current-effort conversion factors. The hardware interface allows for a control frequency of 200Hz. In the course of the experiments, only the leg DoFs are controlled.

Before testing the friction compensator on the real robot, an initial value for the friction parameters had to be found. For each joint, the torque-velocity map was identified using the following excitation signal

$$q_d^i = a(t) \sin\left(\frac{2\pi}{T}t\right),\tag{18}$$

where a(t) is the continuously increasing amplitude and T is the period. An exemplary plot is shown in Fig. 5 (d). It is evident that in our case friction is highly nonlinear and can not be adequately represented by for example a simple Coulomb and viscous friction model. Furthermore, standard approaches use a fixed set of parameters that need to be reidentified, if there are any changes in the system. An adaptive controller can deal with this problem online. The starting values for the friction parameters in the adaptive controller were chosen using the torque-velocity map as an indication.

In order to evaluate the controller performance, the robot is commanded to follow a trajectory for the CoM while keeping the orientation. The CoM position as well as the base orientation and parameter evolution is shown in Fig. 5. The results are compared to the controller without friction compensation. In contrast to the controller without friction compensation, the controller with active compensation had a much better performance. Still, a steady-state error as well as some low-frequency oscillation could be observed. The steady-state error can be explained by mainly two facts: First, there is only a rough estimation of the inertial parameters of the robot. Some modification to the robot's links were recently conducted which led to further mismatch. Secondly, for the torques there is only a rough estimation from currents. It is evident that this estimation does not represent the actual torques that are present in the robot. The oscillation that can be observed is likely due to the low-frequency control loop.

V. CONCLUSION

The presented adaptive friction compensator was able to reduce the negative effects of dynamic friction that affects tracking using torque-based control approaches. As a first proof of concept, the paper showed that torque-based control methods on humanoid robots is possible, even if the friction parameters are unknown. It is important to highlight that the controller does not require any information from neither the FT sensors mounted on the ankles, nor the ones in the joints to track the desired CoM trajectory. However, a model mismatch in the inertial parameters and the low frequency control-loop still deteriorated the controller performance. In future work, the emphasis will therefore lie on improving the dynamical model of the robot or including the dynamic model parameters in the regressor to adapt these parameters as well.

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Fig. 5. (a) CoM trajectory for the squatting task with and without friction compensation. The blue line corresponds to the desired CoM trajectory which is defined as a 7th-order spline function. It can be observed that the friction compensated controller achieves much better tracking than the uncompensated one. (b) Roll angle of the base. A comparable performance was achieved for both cases. (c) Error $e_z = r_C^d - r_C$ for the squatting task. With friction compensation, the error could be significantly reduced. (d) Torque-velocity map for the third leg joint. The viscous and Coulomb friction model indicated in red can not accurately represent the real friction. (e)- (f) Evolution of the friction parameters for the third leg joint. Plot (e) shows the parameter $\theta_c = \sigma_0 \alpha_{01}$. Plot (f) shows the parameter $\theta_s = \frac{\sigma_{01} \alpha_{01}}{\alpha_{01}}$.

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