Contact observer based on tracking joint position discrepancies for Pepper

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***Abstract*— We propose a novel approach for proprioceptive sensor based contact sensing suitable for affordable robots with no force/torque or electric current sensing. We combine robot model knowledge and the output of quadratic programming whole-body controller to make a prediction of expected tracking error for computing our proposed contact observer signal.**

I. Introduction and Background

We want to enable real-time contact sensing for Pepper humanoid robot. This topic is particularly challenging for low-cost personal robots where the embedded sensors are limited and the design mechanics and kinematics do not obey high precision requirements. We describe an approach which aims to overcome those limitations. Our main contributions:

1) We derive a formula for expected tracking error computation for a DC motor controlled with PD scheme;
2) With the ability to predict tracking error part related to free motion, we propose a contact observer signal incorporating collision direction and intensity;
3) We perform experiments with a Pepper platform, demonstrate high sensitivity of our contact observer, good contact detection (with direction and intensity).

The overview of proprioceptive sensor based contact sensing techniques is documented in the survey paper on robot collisions [1], where the best performing method proved to be the momentum observer [2]. This method has been extended for the floating base (humanoid) systems in [3]. It has been augmented to include common non-linear effects (large backlash and friction) encountered on low-cost platforms [4]; updated momentum observer was implemented and tested on the Romeo robot arm, also produced by Soft Bank Robotics.

Due to motor friction, motor-joint backlash and absolute current measurement, classical momentum observer cannot be applied to platforms like Pepper robot. We could use the method developed in [4] to overcome friction and backlash; yet it requires having two encoders per joint. As for now, we do not have access to Pepper motor-side encoders.

To overcome these constraints, we address the contact observer by means of monitoring the difference between measured tracking error and predicted expected tracking error given known robot's model and desired trajectory. In our work, Pepper is controller by acceleration resolved quadratic programming controller (QP) [5]. QP computes desired link position q_d, velocity $\dot{q}_d$, acceleration $\ddot{q}_d$ and torque τ_{ld} for a given motion task, which we use to make a prediction of expected tracking error value ϵ_{exp}, which is then used to compute our contact observer signal (Sec II).

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II. Proposed contact observer method

We are challenged to use only position tracking error to extract the collision event information: intensity, direction and link. However, we assume the contrition of having a compliant (low PD gains with or without feedforward terms, semi-reversible or totally reversible actuators).

In order to define a tracking error based contact observer, we eliminate from the tracking error the part that refers to normal joint motion and leave only the part of the tracking error which is caused by collision. In order to achieve that, we identify the relationship between our intention in terms of desired trajectory and expected tracking error.

For a DC motor regulated by the PD controller with K_p and K_d gains, simplified analytical relation between tracking error ϵ and external torque applied on the load τ_{ext} is (Eq 1).

$$K_p\epsilon + K_d\dot{\epsilon} = \frac{R}{K_t}J_m\dot{\omega} + \left(\frac{R}{K_t}\mu + K_e\right)\omega + \frac{R}{K_t}(M(q)\ddot{q} + c(q,\dot{q}) - \tau_{\text{ext}}) \tag{1}$$

where ω is motor speed, J_m is motor inertia, K_t and K_e are current to torque and motor speed to electromotive force constants, R is motor resistance and μ is friction constant.

Assuming the motion of the load free of external collisions, i.e. $\tau_{\text{ext}} = 0$ we can use Eq. 1 in order to compute expected (under free motion assumption) tracking error ϵ_{exp} from the value of desired position, speed and acceleration of the load $q_d, \dot{q}_d, \ddot{q}_d$ (Eq. 2).

$$\begin{aligned}\epsilon_{\text{exp}} &= \frac{RJ_mN}{K_tK_p}\ddot{q}_d + \left(\frac{R}{K_t}\mu + K_e\right)\frac{N}{K_p}\dot{q}_d + \\ &+ \frac{R}{K_tK_p}\left(M(q_d)\ddot{q}_d + c(q_d,\dot{q}_d)) - \frac{K_d}{K_p}\dot{\epsilon}_{\text{exp}}\right)\end{aligned} \tag{2}$$

where N is gear reduction ratio ($\omega = N\dot{q}$).

The model errors and nonlinear effects (e.g. backlash, flexibility) are not included in Eq. 2. We, thus, choose to identify a non-linear model. We select a binary-tree prediction model. Non-smooth activation function of a binary-tree nonlinearity estimator is suitable in our particular case, because it is capable of modeling sudden abrupt changes in the tracking error signal, unlike nonlinearity estimators with smooth activation function, such ass sigmoid or wavelet networks [6], which we also experimented with. Thus, the final form of the $\tilde{\epsilon}_{\text{exp}}$ expression is (Eq. 3)

$$\tilde{\epsilon}_{\text{exp}}(t) = \texttt{binary\_tree}(\epsilon_{\text{exp}}(t-1), \epsilon_{\text{exp}}(t-2), \dot{q}_d, \ddot{q}_d, \tau_{l_d}) \tag{3}$$

With the identified model that is capable to accurately predict expected tracking error, we can compute the part of tracking error that is related only to the collision. We do that by subtracting predicted tracking error value from the measured tracking error to compute our contact observer signal $r = \epsilon - \epsilon_{\text{exp}}$.

III. Experimental Results

We show that our proposed contact observer signal r is suitable for contact detection and identification of contact direction and intensity. We set a fixed threshold $\theta = 2.5°$ for contact detection, whenever $|r| > \theta$ we consider that collision occurred. We show that our proposed method allows to detect even light collisions ($> 2.5°$). The sign and magnitude of r reveal the direction and collision intensity information respectively.

We use QP controller to generate sequence of right arm joints motion. During the execution of the motion several external collisions are triggered by touching the robot's right arm. The plot in Fig. 1 shows a ∼20 second segment of results from this experiment.

The results indicate, that our proposed method is capable of making precise prediction of expected tracking error and, thus, produce a contact observer signal r which remains below threshold θ when there is no collision. When collision occurs, r exceeds the fixed threshold. The direction and the intensity information about the collision event is correctly represented via the sign and magnitude of r.

The Tab. I reports the total amount of false positive #FP ($r > \theta$ without contact), false negative #FN ($r \leq \theta$ with contact) and true positive #TP ($r > \theta$ with contact) contact detections across the three experiments with various joints.

Experiment name	#FP	#FN	#TP
LSRoll experiment	2	2	18
RERoll experiment	0	3	19
RSRoll (with LSRoll binary tree)	0	3	18
Total:	**2**	**8**	**55**

TABLE I: Detection quality across the three experiments.

IV. Conclusion and Future Work

We have derived a simplified expression for computing expected value of the tracking error of a DC motor controlled with PD scheme given the knowledge of desired trajectory and desired load torque. This expression revealed that, under some conditions of compliance, low PD gains with feedforward terms or reversibility, the expected tracking error prediction does not require knowledge of the motor current or motor torque. We presented the results of expected tracking error prediction, which show good accuracy and generalization properties. We demonstrated how prediction of expected tracking error can be used for computing a contact observer signal, which incorporates intensity and direction information of the collision event.

In the continuation of this work we will investigate in more detail relation between our contact observer signal r and the value of the external torque τ_{ext}. Once this is done, it would

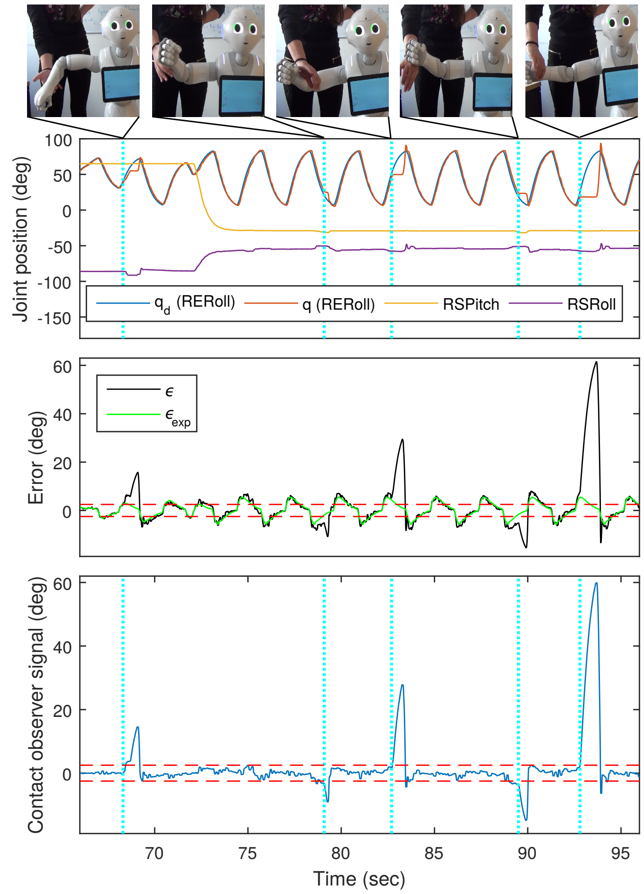

Fig. 1: RERoll experiment segment: joint trajectories (top); expected tracking error prediction (middle); contact observer signal r (bottom). Dashed blue lines indicate start of the contact. Dashed red lines indicate the threshold for r.

become possible to reconstruct the force which is causing the collision from r without ever measuring or estimating motor torque or the motor electric current.

Finally, our ultimate goal is to develop and test our proposed contact observer approach for its integration in the feedback signal of an adaptive control for physical human-robot interaction in motion assistance scenarios.

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