Torque-Based Velocity Control for Safe Human-Humanoid Interaction

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Abstract. Torque-controlled robots are essential for safe human-robot interaction (HRI). In this paper we address the question of how joint level torque control can be implemented and seamlessly integrated into tasks that require precise velocity control.We present a control scheme that takes a desired velocity and torque as input to generate control output driving the joints at this velocity, and simultaneously realizing compliant behavior for safe HRI. We propose a novel method to integrate torque and velocity control into a single controller. The controller consists of an inner torque control loop embedded in an outer velocity control loop, and is hence called *Torque-Based Velocity Control* (TBVC). Experiments demonstrating the performance of the proposed control scheme are carried out on the humanoid ARMAR-6.

Keywords: Humanoid robotics, Torque control

1 Introduction

Robotic manipulators with serial kinematics, such as the arms of a humanoid robot, typically consist of a chain of rigid elements and individually controllable joints [1]. To achieve a desired behavior or motion of the end-effector, the joint actuators must be controlled precisely and synchronously. Common control modes are position, velocity and torque control [2]. There also exist approaches to combine different control modes, such as torque, position and impedance in a unifying framework (e. g. [3]). However, it is generally not straight-forward to simultaneously control both joint torques and joint velocities in a seamless manner. This is mainly due to implementations of torque and velocity control as two separate control loops that do not take each other's effects into account.

In this paper we focus on the merits of velocity and torque control and propose a novel method to combine them into one integrated joint level control mode for electric actuators. We call this control mode *Torque-Based Velocity Control* (TBVC).

For a wide range of tasks that robot manipulators typically do, such as reaching, grasping and manipulating by following predefined trajectories in a

Fig. 1: Snapshots of the experiments used for collecting the data presented in section 3. The human initially pushes the elbow into the extended position (1,2,3). Upon release, it bends with the desired velocity (4,5). The human stops the motion through physical contact and the robot applies the desired torque (6).

controlled environment free of unforeseen obstacles, high-gain velocity control is the method of choice for joint-level control. For many of the more complex tasks that modern robots are faced with, such as interacting with soft objects or even humans, velocity control without torque or force control is not suitable. The ability to directly command desired torques to the actuators of a robot is therefore of advantage [4,5]. Joint-level torque control allows for the implementation of mechanical compliance not only at the end-effector but for the whole body [6]. This feature is fundamental when physically interacting with humans, where compliance of the robot facilitates intuitive physical interaction and, most importantly, can limit interaction forces and thereby dramatically increases safety [7].

However torque-control is not straight-forward to use for *trajectory tracking*. Tracking a desired trajectory in torque control mode can be achieved by using inverse dynamics. These methods rely on accurate dynamic models and require perfect torque tracking [8,9]. Another way to achieve trajectory tracking in torque control mode is to use torque-based position tracking, i. e. (active) impedance control schemes [10]. Achieving good position/velocity tracking performance with this method requires proper selection of the impedance parameters. This is generally difficult, partially due to the configuration-dependent dynamics of the robot, and partially due to the effects of the environment's dynamics when in contact [1].

In this paper we propose a torque-based velocity controller (TBVC), a control method that provides the ease-of-use of joint-level velocity control for trajectory tracking combined with the safe interaction characteristics of compliant torque control when in contact with the environment.

2 Control Method

The presented control method relies on accurate and reliable torque-control on the joint level. For the demonstrated experiments it furthermore requires model-based feed-forward gravity compensation to achieve feedback linearization, i. e.

the computation of gravity induced torques. This section is therefore split into two main parts: We will first very briefly describe the key components of the actuator and the Low-Level Torque Control (LLTC) with a brief introduction of gravity compensation and active damping for torque controlled robot arms. Secondly we will describe how active damping can be expanded to TBVC.

2.1 Low-Level Torque Control (LLTC)

Hardware and modeling Achieving accurate torque-control on the joint level highly depends on the hardware that is used, since this hardware will affect the modeling and ultimately the controller synthesis. The hardware setup in our case consists of a brushless DC motor, a strain-wave gear with a reduction ratio of 1:160 and a custom, strain gauge based output torque sensor. Current control of the motor is handled by a commercial motor controller. A detailed description of the actuation units is presented in [11].

Controller With standard methods of robust control theory for plant analysis and control synthesis we find that the system can be stabilized with a PI-controller that converts a desired torque to an input current i_{set} and achieves good torque tracking over a wide range of torques and actuator speeds.

Gravity Compensation Using a model of the robot arm, the joint torques that are induced by gravity can be computed by summing over the cross product of the gravitational forces and vectors from the rotational axis of the joint in question to the center of masses of all following links. Applying the so computed torques to the robot joints using joint-level torque control results in a linearization of the torque feedback with respect to the joint position.

Active Damping Using torque control in a kinematic chain where all the joints along the chain influence each other can lead to oscillations even if each joint-level torque controller on its own is stable. To mitigate this problem we add a velocity dependent term to influence the controller set point, which we call active damping. The actual shaft velocity ω_{act} is multiplied by a positive constant value k_d and the result gets subtracted from the torque set point. Using suitable values for k_d on the joint level suppresses torque-oscillations in the actuators along the kinematic chain but preserves the good torque tracking capabilities of the torque controllers.

2.2 Torque-Based Velocity Controller

The idea of torque based velocity control directly arises from the concept of active damping introduced in 2.1. Active damping introduces a velocity feedback loop around the inner torque-control loop, which allows influencing the speed of the actuator, while the underlying control mode is still torque control with

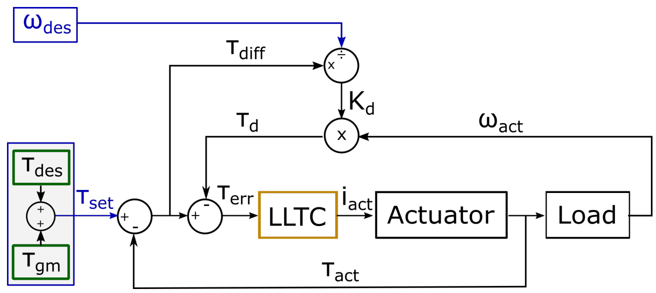


Fig. 2: Block diagram of the joint-level torque-based velocity control scheme.

all its benefits of safe interaction and backdrivability. To achieve a desired velocity, the active damping parameter k_d needs to be set accordingly, effectively implementing a velocity control loop. This turns the single input control system (desired torque) into a dual input system (desired torque τ_{des}, desired velocity ω_{des}).

The underlying idea can be summarized as follows: If the system is at rest and not moving, for example when it is restricted due to physical contact, the desired torques should be acting in the joints. If the system is freely moving with the desired velocity, only the gravity compensating torques should be acting in the joints, resulting in zero acceleration and joint motions with the desired velocities. We propose a mapping between the two states in which the system is (i) not moving at all and therefore applying the desired torques and (ii) moving with the desired velocity and therefore not applying any torque other than what is necessary to compensate for influences of gravity.

Naive approach From the basic idea, an appropriate k_d can be computed from the two inputs τ_{des} and ω_{des} from the following condition

$$\omega_{act} k_d = \tau_{des} \text{ for } \omega_{act} = \omega_{des} \tag{1}$$

as follows:

$$k_d = \frac{\tau_{des}}{\omega_{des}} \tag{2}$$

This naive approach leads to a control scheme where velocity feedback is used to adjust the input of the underlying torque controller. Here, k_d is constant for constant τ_{des} and ω_{des}. While this control scheme does not interfere with the torque controller, it does not lead to satisfactory results with respect to velocity tracking as unmodelled effects can not be compensated.

Proposed approach To overcome the velocity control insufficiencies of the naive scheme, we preserve the basic idea but modify the implementation slightly to make the controller more robust against model inaccuracies and unmodeled dynamic effects. For this purpose we replace τ_{des} in the computation of k_d as shown in Equation 2 by the difference τ_{diff} of the set torque (the sum of the model-based gravity compensating torque τ_{gm} and desired torque τ_{des}) and the measured joint torque τ_{act}. This modified control scheme is depicted in Figure 2 where k_d is computed as

$$k_d = \frac{\tau_{diff}}{\omega_{des}}. \tag{3}$$

Note that the active damping term k_d now depends on the torque measurement and is therefore constantly changing. Including the torque feedback into the velocity feedback loop in this manner results in the desired robustness.

Comparison of the two approaches To illustrate why the proposed approach leads to better results in terms of robustness against modeling errors it is useful to examine the torque error τ_{err} that will be processed by LLTC in detail. The definition of τ_{err} is as follows:

$$\tau_{err} = \tau_{set} - (\tau_{act} + k_d \omega_{act}) \tag{4}$$

By substituting Equation 3 in Equation 4 and replacing τ_{diff} with $\tau_{set} - \tau_{act}$, τ_{err} takes the following form:

$$\tau_{err} = \tau_{set}(1 - \frac{\omega_{act}}{\omega_{des}}) - \tau_{act}(1 - \frac{\omega_{act}}{\omega_{des}}) \tag{5}$$

It can be seen from Equation 5 that if there is no motion (i. e. $\omega_{act} = 0$), the equation simplifies to $\tau_{err} = \tau_{set} - \tau_{act}$ and only the desired torque will be applied (state I). If $\omega_{act} = \omega_{des}$ the torque error τ_{err} will be zero (state II).

By definition, the set torque τ_{set} is the sum of the model-based gravity torque τ_{gm} and desired torque τ_{des}. τ_{act} can be presented as the sum of the real gravity torque τ_{grav} and other dynamical torques τ_{dyn}. Combining all of this leads to the error term

$$\tau_{err} = \tau_{des}(1 - \frac{\omega_{act}}{\omega_{des}}) + (\tau_{gm} - \tau_{grav})(1 - \frac{\omega_{act}}{\omega_{des}}) - \tau_{dyn}(1 - \frac{\omega_{act}}{\omega_{des}}) \tag{6}$$

Equation 6 shows that both the effects of the dynamic torques τ_{dyn} as well as the difference of model-based and actual gravity torques ($\tau_{gm} - \tau_{grav}$) vanish as ω_{act} reaches ω_{des}.

In contrast, the error term for the naive approach does not exhibit this property as there is no favorable scaling term for the effects of dynamics and model errors:

$$\tau_{err} = \tau_{des}(1 - \frac{\omega_{act}}{\omega_{des}}) + \tau_{gm} - \tau_{grav} - \tau_{dyn} \tag{7}$$

As can be seen from Equation 7, only the desired torque τ_{des} will be compensated as ω_{act} reaches ω_{des}. Dynamical torques as well as the difference between modeled and real gravity will affect the torque error τ_{err}, ultimately resulting in a deviation of actual velocity ω_{act} from the desired velocity ω_{des}.

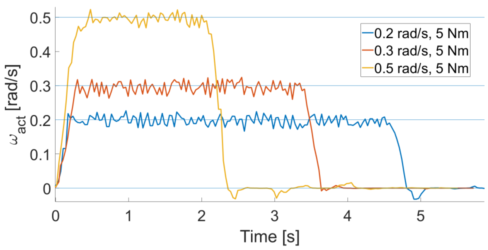
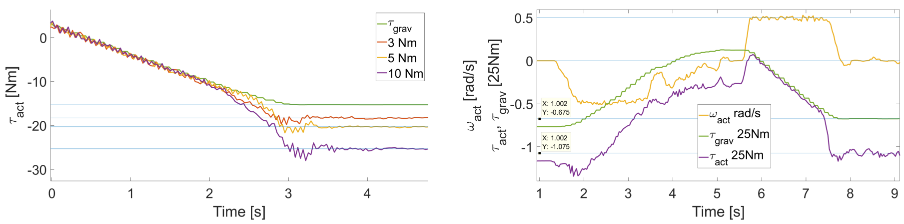


Fig. 3: Velocity plots for different target joint velocities at $\tau_{des} = 5\,\mathrm{Nm}$.



(a) Measured joint torque during three robot experiments with identical desired velocities (0.3 rad/s) and different desired torque values (3, 5 and 10 Nm).

(b) Measured torque (purple), model based computed gravity torque (green) and rotational joint velocity (yellow) over one validation experiment.

Fig. 4: Torque data for three validation experiments.

3 Experimental Validation

Experimental validation of the proposed control method was carried out on the humanoid robot ARMAR-6 [12] as follows: With the elbow joint in TBVC mode with desired torque τ_{des} and desired velocity ω_{des}, the left arm was manually extended so that the forearm pointed downwards (1,2,3 in Figure 1). In this extended initial position, the arm was released. The elbow joint then started to bend with the desired angular velocity. Before the joint reached the 90° bent position it was stopped by a human, blocking the robot's forearm with his hand (4,5,6 in Figure 1). During these experiments the joint torque, joint position and joint velocity were recorded.

Velocity tracking Figure 3 shows the velocity curves for three of these experiments. The plots start when the joint is released in the extended position. The controller then adjusts the joint torque so that the desired velocity (horizontal reference lines) is reached and held throughout. Contact with the human is made and the joint rapidly slows down to zero velocity, exerting the desired torque (together with the gravity compensating torque).

Torque tracking Figure 4a shows torque curves for three experiments with identical desired velocities but different desired torque. Similar to the plots shown in Figure 3, the torque curves start at $t = 0$ when the joint is released. During the initial free movement of the arm, control is governed by the velocity control, and the joint torque very closely matches the gravity torque. After impact at about $t = 3\,\mathrm{s}$ and at zero velocity, control is governed by the torque component, and the measured torques are the sum of gravity compensation and the additionally desired torques. The light blue horizontal lines show the desired steady-state torque values with magnitudes of $|\tau_{grav}|{+}3\,\mathrm{Nm}$, $|\tau_{grav}|{+}5\,\mathrm{Nm}$ and $|\tau_{grav}|{+}10\,\mathrm{Nm}$.

Backdrivability The proposed torque control method allows for safe physical human-robot interaction in the sense that the robot stops its motion and only applies a pre-specified torque when contact with a human or any other physical object (see Figure 4a) occurs. Further, the robot is compliantly backdrivable against its intended direction of motion. The robot is in fact backdriven in the beginning of all of the experiments presented in the previous sections. Figure 4b shows joint torque and velocity over an entire experiment, where the moment of release in the extended position (where the other plots start) is at about $t = 5.8\,\mathrm{s}$. Once the joint is stopped at about $t = 7.6\,\mathrm{s}$, the velocity becomes 0 and the magnitude of the actual joint torque becomes $0.4 \times 25\,\mathrm{Nm} = 10\,\mathrm{Nm}$ higher than the torque needed for gravity compensation. 10 Nm was the desired torque during this experiment.

Practical Considerations A few considerations when applying the described control method in practice need to be taken into account to achieve reliable and predictable behavior as described above. In the case of backdriving the joint, k_d might become negative, leading to undesirable robot behavior. We therefore use the absolute values of k_d, which in turn necessitates manipulating the sign of τ_{des} to enable bi-directional joint movement. Since k_d is a ratio, it is not defined for $\omega_{des} = 0$ and becomes very large for $\omega_{des} \approx 0$. In practice, an effective countermeasure is to cap k_d and to adapt the PI-controller gains to changes of the k_d, i. e. using a k_d-adaptive LLTC.

4 Conclusion

We presented a joint-level control scheme for simultaneous joint torque and joint velocity control. The control scheme is derived from the desire to have the joint rotating with a desired speed when freely moving, and applying a specified torque when restricted in its motion by physical contact with its environment, e. g. a human. Since the inner control loop of this control scheme is a torque control loop that is enclosed by a closed velocity control loop, we call this scheme Torque-Based Velocity Control (TBVC). This controller can replace common stiff velocity control modes and enhance safety in human-robot interaction situations.

Evaluation experiments with the elbow joint of the full-sized humanoid robot ARMAR-6 were conducted in which a human safely interacted with the robot. We showed that the TBVC behaves as expected both when freely moving (applying gravity compensating torque and maintaining the desired velocity) and when in contact (applying gravity compensating torque plus desired torque).

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