Proposal on Master Thesis

Accurate trajectory tracking on the KUKA youBot manipulator: Computed-torque control and Friction compensation

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1 Introduction

A robotic manipulator can be represented as a series of rigid bodies that are connected together by joints which can be a prismatic or revolute joint. The equations of motion for such a robot manipulator are non-linear and coupling of the links induce dynamic effects in high-speed motions. Since the robot manipulation task execution heavily relies on the kinematic specifications and the dynamic model parameters. The parameter estimation becomes important for the model based controllers as discussed in [2]. These estimates are useful in predicting torques which are close-enough to the real robot. There are three kinds of linear controllers that have been widely discussed to control the non-linear systems and it can be classified as the computed-torque like control, computed-torque control and the impedance control. Impedance control describes the relationship between the force and the joint information such as joint angle, velocity and acceleration. The computed-torque control is one of the linear control schemes that has been proposed by many researchers in getting the compliant motion and the advancements are also proposed for the torque-control scheme. Computed-torque control provides the linearization based on the feedback loop for the non-linear systems. The computed torque-like control provides the discussion where a compensation is required since the accurate feedback linearization is not possible due to the parameter uncertainty.

This work proposes the PD (Proportional-Derivative) control based computed-torque control scheme. The standard robot controller suffers with the high rise times and slow settling-times when applying the position set-points, so there is a need of the high-level linear PD control for the non-linear systems in order to resolve the position errors that occur due to the non-optimal gains of the controller and to resolve the problem with the wrong initial conditions of the joints. The robot joints can take position, velocity and torque inputs. In position control mode, the joint angle inputs are commanded in the joint and the trajectory tracking in the Cartesian space suffers due to the noises in the observed results. In the velocity mode, the velocity command is commanded to the joint till the target is reached. Both these modes induce deviations in the trajectory tracking. Whereas, the torque control considers both the dynamics of the manipulator and the joint configuration [3] and the torque is commanded for executing the particular tasks. The parameter estimates and the control scheme are going to be verified in the simulation at first and the visualization of the manipulator is going to be implemented in the Simbody visualizer [10]. Then the estimates and the control schemes are going to be used in the KUKA youBot manipulator. Another important effect that needs to be accounted in the dynamic model of the manipulator is friction. The frictional effect influences the manipulator performance in both the static and the dynamic configurations which could cause instability in the control. The friction can be compensated in two different ways such as model and non-model based scheme. The static friction estimates were obtained manually through the automated testing in the previous work [9] for the youBot manipulator is useful in doing the compensation in the dynamics of the manipulator. This work proposes the model based dynamic friction identification and compensation in the manipulator joints.

1.1 Problem Statement

What is the problem?

- Implementation issues with the parameter estimation method [9].
- The unmodeled dynamics affect the controller performance.
- Friction effects are not modeled and compensated in the dynamic model of the manipulator.
- Verification of the estimated dynamic robot model parameter.

Why is it relevant?

- Parameter estimation method [9] needs to be debugged in order to identify accurate model parameters for the manipulator links.
- To achieve the precise control of the robot manipulator, PD computed-torque control scheme (feedback linearization) has to be introduced.
- One of the important effects that affect the accurate trajectory tracking in the end-effector is friction.

Why is that not sufficient?

- Accurate model parameters are the basic need of the computed-torque control and the existing model parameters are not accurate.
- Computed-torque control is to achieve precision in the manipulator movement.
- An important requirement is modeling and compensation of the frictional effects in the dynamic model.

What is your contribution?

- Solving the implementation issues in [9] and the validation of the estimated dynamic model parameter.
- Visualization of the youBot manipulator in Simbody [10].
- PD computed-torque control law.
- Static friction compensation on the dynamics model of the manipulator.
- Investigation and the implementation of the kinetic friction modeling and compensation.

1.2 Assumptions

- It is assumed that the kinematic specifications are right.
- Computed-torque control can provide precise control when using the model specifications from the manufacturer.

2 Related work

This section provides the detailed state-of-the-art analysis of this work.

2.1 Parameter estimation

This module is the continuation of the previous research project [9] where the domain-specific estimation procedure is investigated and implemented in order to identify the accurate model parameters of the manipulator links. The implementation and the logical issues need to be resolved and the result can be used in the computed-torque control method which is an ultimate goal of this project.

2.2 Computed-torque control

The computed-torque control [5] [7] is an active research area where the smooth transition of the trajectory is an important requirement. In order to achieve the precise control, advanced model-based controllers need to be considered than the standard controllers. Keiser et. al. [3] presents the computed-torque control for the youBot manipulator which considers both the feed-forward torques and the feedback control law for grasping the objects with the smooth transition in the Cartesian space. The cartesian trajectory inputs are mapped to the joint space by using the closed-form inverse kinematics solution. This work results in a smooth transition of the end-effector which follows a straight-line with very minimal deviations when tracking the trajectories but this approach could be very efficient when the parameter estimates are used. Whereas, Alberto et.at. [1] proposes the computed-torque control with variable gains that is applicable for the different situations such as the model is certain and also if it is uncertain. This kind of a learning method can learn dynamic models with the low gain feedback control.

2.3 Friction modeling and compensation

The static friction estimates were obtained in [9] facilitates the compensation of the static friction torque on the dynamic model of the robot manipulator. The friction compensation overview given by Bona et. al. [4] provides the detailed evaluation of the available compensation methods. This work focuses to model the friction when the manipulator joints are at motion which is a quite complex phenomenon. But this metod allows the manipulator to improve the tracking accuracy by computing the torque that is needed to compensate the friction effects. Since the manipulator interpretation are highly parametric, the measurements differ for the different configuration of the manipulator. A model based friction compensation proposed by Lischinsky et.al. [8] can be used in the applications where the high precision is mandatory. The basic model which is the combination of Coulomb(static friction) and Viscous(kinetic friction) friction is used in many industrial manipulators [12] [6].

3 Approach

3.1 Description of the hardware platform

This work uses the KUKA youBot manipulator for the parameter estimation and computed-torque control. The model parameters and kinematic, geometric specifications are referred from the youBot-store [13].

Figure 3.1: The KUKA youBot base and 5 DoF manipulator. Image courtesy[1]

3.2 Description of the software platform

3.2.1 Python, C++

These two programming languages are used for the parameter estimation and torque control implementations in this work.

3.2.2 Orocos KDL

Orocos KDL [11] is going to be used in this work to validate the estimated model parameter against the existing model parameters. Another use of this library is to compute the feed forward torque based on the given joint angle, velocity and acceleration.

3.2.3 Simbody

Simbody [10] is a powerful simulation engine which can be used to build and simulate the youBot manipulator and this library is useful in testing the computed-torque control law.

[1] https://static.generation-robots.com/5045/kuka-youbot-robot-mobile-omni-directionel-avec-bras.jpg

3.3 Computed-torque control

The dynamic model [3] of the robot manipulator can be given as

$$\tau = M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + N(\theta, \dot{\theta}) \tag{3.1}$$

where τ is the torque applied to the manipulator links. **M** represents the manipulator inertia matrix and **C** represents the Coriolis and Centrifugal forces. **N** represent the vector of external forces acting on the manipulator links such as gravity and friction effect. The non-linear dynamic equation of motion for the manipulator can be used to compute the joint torques for the given joint position, velocity and acceleration. This results in a open loop torque control on the individual joints of the manipulator. In order to achieve the precise control of the manipulator movements, feedback control has to be introduced in the dynamic model. So, the above equation (3.1) can be rewritten for the PD computed-torque control law as

$$\tau = M(\theta)(\ddot{q}_d + K_V \cdot \dot{q}_e + K_P \cdot q_e) + C(\theta, \dot{\theta})\dot{\theta} + N(\theta, \dot{\theta}) \tag{3.2}$$

The pictorial representation of the control scheme (3.2) is given in Fig. 3.2. The following equation (3.3) can be regarded as the closed-loop error dynamics where the K_I term is equal to 0 and it is referred from the article [7] [5].

$$\ddot{q}_e = (K_P \cdot q_e) + (K_V \cdot \dot{q}_e) + \ddot{q}_d \tag{3.3}$$

where K_P, K_V represents the proportional and derivative gains of the PD control respectively and the gains are going to be optimized by manually tuning for each and every link of the manipulator. The manual tuning can be done based on the experiments by investigating the individual step responses for the particular joints. Otherwise, overshoot occurs when the gains are not optimal and the stability of the system can't be achieved. $q_e, \dot{q}_e$ represents the position and the velocity error as given in the following equations

$$q_e = q_d - q_m \tag{3.4}$$

$$\dot{q}_e = \dot{q}_d - \dot{q}_m \tag{3.5}$$

where q_d represents the desired joint angle and q_m represents the measured joint angle of an individual joint. $\dot{q}_d$ represents the desired joint velocity and $\dot{q}_m$ is the measured joint velocity of an individual joint.

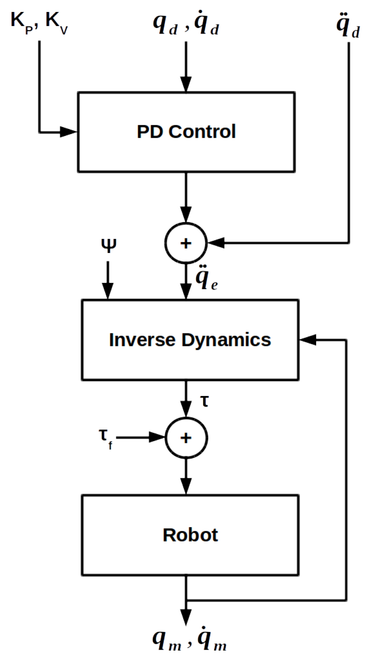


Figure 3.2: Computed-torque control scheme. ψ represents the estimated model parameters.

An important feature that needs to be considered in order to avoid the damages to the manipulator is torque limiting and it relies on the torque limit of the individual joints that are provided by the manufacturers. Keiser [3] discusses that the torque controller suffers in tracking the trajectories perfectly due to the maximum torque limits that are specified by the manufacturers are not sufficient for the certain configuration of the manipulator. The friction τ_f modeling is discussed in the following section and it can be compensated in the dynamic model by

$$\tau = \tau_{ID} + \tau_f \tag{3.6}$$

where τ represents the total torque and τ_{ID}, τ_f represents the torque resulting from the inverse dynamics computation and friction torque respectively.

3.4 Friction modeling and compensation

In order to improve the control efficiency of the manipulator, it is necessary to account the unmodeled dynamics of the manipulator. One of the important effects that needs to be modeled in the manipulator joints is friction. Friction is a non-linear phenomenon that has been researched extensively over the years in the field of robotics and it can be classified into two categories such as static and dynamic/kinetic friction. The static friction on the youBot manipulator joints are estimated in the previous work [9] and the compensation is going to be done in this work with the dynamic model. It is complex to estimate the kinetic friction on-line when the manipulator is at motion and there are many model based techniques to estimate the kinetic friction. The viscous friction model is going to be used to model the dynamic friction when the velocity is non-zero. The Stribeck [6] friction model which can also be called as the steady-state friction force/torque is the basis of this work which comprises the negative viscous friction, Coulomb and viscous friction model and it can be computed as follows

$$\tau_f = (\tau_c + (\tau_s - \tau_c)e^{(v/v_s)^{\alpha}}) \cdot sign(v) + f(v) \text{ [6]} \tag{3.7}$$

where the friction torque is τ_f, τ_s represents the static friction which is already known for the youBot manipulator and v represents velocity and v_s represents how fast τ_c is reached from the break-away point. α value is assumed to be 1 in this work and it represents the shape of the Stribeck curve and f(v) represents the viscous friction. The exponential term represents the negative viscous friction. Sign(v) represents the direction of the velocity.

The pictorial representation of the same model is given in the Fig. 3.3.

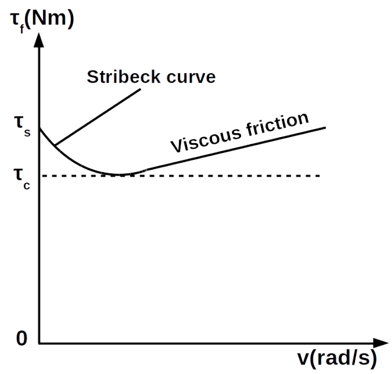


Figure 3.3: Friction model referred from [6].

$$f(v) = \sigma v \tag{3.8}$$

where the viscous friction parameter σ has to be identified by estimating the friction for the number of constant velocities. The static friction compensation happens when the velocity is less than zero and the dynamic friction compensation happens when the velocity of the joints are greater than the threshold. The model based friction estimation will be investigated further in this work.

4 Use case scenario

The use case scenario of this work is to compare the trajectory tracking accuracy when using the standard controller with the advanced model-based controller which is the scope of this work. A sample trajectory is going to be selected in order to verify the performance of the controllers. The sample target trajectories for the end-effector will be generated as a straight line or a curved path for this evaluation. Based on this use case, it is possible to verify the effectiveness of the computed-torque control scheme.

5 Expected Results

Minimum Deliverables:

- The visualization of the youBot manipulator in Simbody [10]
- Computed-torque control for the KUKA youBot manipulator

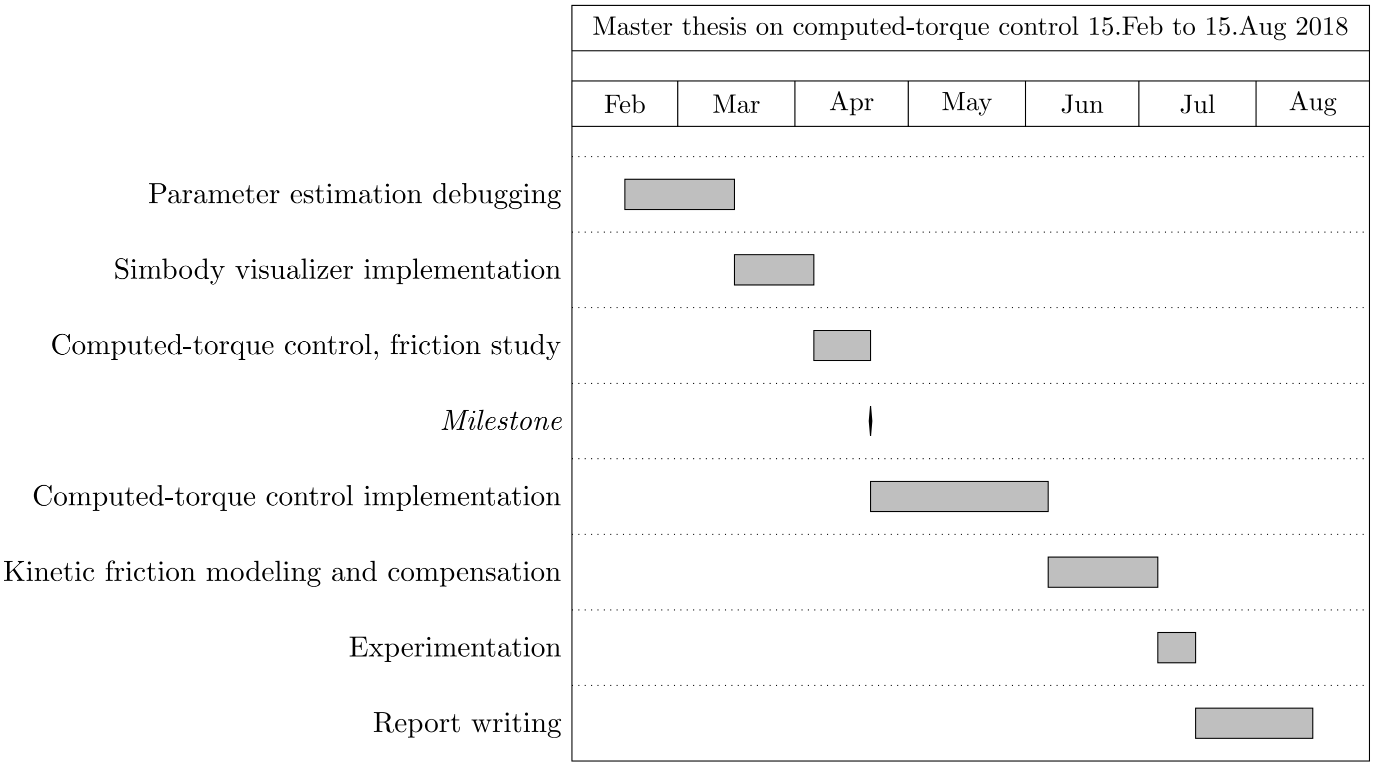
Expected Deliverables:

- Solving the implementation issues with the estimation of the dynamic robot model parameter
- Static friction compensation

Maximum Deliverables:

- Kinetic friction modeling and compensation

6 Project Plan



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