Parameter Identification of the KUKA LBR iiwa
Robot Including Constraints on Physical Feasibility

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Abstract: The newly released KUKA LBR iiwa 14 R820 robot stands for intelligent industrial work assistant (iiwa) and is, like its predecessor LBR IV, equipped with torque sensors in each joint, and can be controlled through a real-time interface. Although the dynamic model of the robot is not published by the manufacturer, its knowledge is indispensable for simulation and control based on the system model. This paper presents the identification of the minimal set of base parameters, as well as a consistent set of physical parameters for a rigid-link model of the KUKA LBR iiwa 14 R820 robot, including friction. The experiments on the robot are conducted based on optimized excitation trajectories. The physical parameters, which are required for stable dynamic simulations, are identified by solving a nonlinear optimization problem, where constraints are included to ensure physical feasibility. A validation and cross-validation in simulation and experiments show a very accurate representation of the robot’s dynamics by the resulting models. As a result, both sets of identified parameters are given.

Keywords: Robots manipulators, parameter identification, constrained parameters, robot dynamics, industrial robots

1. INTRODUCTION

More and more tasks in various sectors, as in medical care or domestic and industrial applications, are assisted by or completely transferred to robotic manipulators. Robots are also planned to be used in the future in the construction industry, where more complex goals should be accomplished, such as cooperative tasks. The KUKA LBR iiwa 14 R820 is especially suited for research in robotics, as it is accessible through a real-time interface named Fast Robot Interface, see KUKA Robot Group (2015b). Moreover, it is mainly designed for interactions with humans, and is therefore equipped with torque sensors after the gearbox of each actuated joint, which allows for cooperative interaction control. In order to develop model-based controllers for a robotic manipulator, its dynamic model is needed. Furthermore, if complex multi-robot tasks are considered, it is valuable to do dynamic simulations of the robots’ motions and interactions. In order to obtain reliable simulation results, it is again crucial to know the robot’s model parameters.

In Bargsten et al. (2013), the identification of the dynamic parameters of the KUKA LBR IV, the predecessor of the LBR iiwa, is considered, and an identification procedure is outlined, but no parameters are published. Its dynamic parameters are published in Jubien et al. (2014b), and other approaches for the identification of the parameters used by KUKA for the LBR IV are proposed in Jubien et al. (2014a) and in Gaz et al. (2014). Although the LBR iiwa and its predecessor are similar, their dimensions are slightly different, and their parameters are not identical. In Besset et al. (2016), a method for static calibration of the geometric parameters of the LBR iiwa is proposed, but to the best of our knowledge, no dynamic model parameters are currently publicly available for the KUKA LBR iiwa 14 R820.

In Albu-Schaffer and Hirzinger (2001) and Ott (2008), models for robots with flexible links are considered, which include joint elasticity and damping. However, as the joint stiffness of the KUKA LBR iiwa is very high, despite its torque sensors, a model of rigid links is used in this paper. Its validity is confirmed by the high accuracy of the results. Rigid link models can be formulated in terms of a minimal set of dynamic parameters, the base parameters, see Gautier and Khalil (1990), which can be beneficial in some cases. However, for dynamic simulations, a consistent set of the robot’s physical parameters is required. This is the case for the open-source robotics simulation software Gazebo, see Koenig and Howard (2004), gazebosim.org (2015). Therefore, both the set of base parameters and the set of consistent physical parameters of the KUKA LBR iiwa 14 R820 robot are identified.

For the identification of base parameters, the inverse dynamics model is used, as the dynamic parameters enter it linearly, see Siciliano et al. (2010). In order to maximize the information about the parameters in the robot’s motion, optimal excitation trajectories are designed, which are tracked by the robot in experiments. Based on the measured joint torques and positions, the resulting equations, which are linear in the unknown parameters, are solved through a least-squares approach. To obtain physical parameters, which are usable in dynamic simulations, the identified parameters need to be physically consistent, as shown in Mata et al. (2005). Therefore, constraints are included in the identification, resulting in a nonlinear optimization problem. The resulting physical parameters are thus physically feasible and consistent with the robot’s dynamics. However, they do not necessarily match reality, when there are more physical parameters than degrees of freedom in the dynamics. But a
consistent set of parameters is obtained, which is suitable for reproducing the exact robot dynamics in stable simulations.

This paper is organized as follows. Section 2 states the equations of motion and the inverse dynamics model. In Section 3, the identification of the physical parameters is given as a nonlinear optimization problem. Section 4 gives experimental results and Section 5 concludes the paper. The identified base parameters and physical parameters are given in the Appendix.

2. DYNAMIC MODEL OF THE ROBOT

2.1 Equations of Motion

Despite the compliance due to its torque sensors, the KUKA LBR robot can be accurately modelled with rigid links. The equations of motion, as in Siciliano et al. (2010), are given by

$$\tau = B(q) \dot{q} + C(q, \dot{q}) \dot{q} + g(q) + F_v \dot{q} + F_e \text{sign}(\dot{q}),$$

(1)

where $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$, with $n$ the number of joints of the robot, are the vectors of joint position, velocities and accelerations, respectively. $B(q) \in \mathbb{R}^{n \times n}$ is the inertia matrix, $C(q, \dot{q})$ is the vector of torques due to centrifugal and coriolis effects and $g(q)$ is the gravity vector. $F_v$ and $F_e \in \mathbb{R}^{n \times n}$ are diagonal matrices of the viscous and coulomb friction parameters. The terms in (1) depend on the configuration and motion of the robot, and on its physical parameters, which we stack for each link $i$ in the vector

$$\mu_i := [m_i, I_{ixx}^i, I_{iyy}^i, I_{izz}^i, I_{ixx}^i, I_{iyy}^i, I_{izz}^i, F_v^i, F_e^i] \top,$$

(2)

where $m_i$ is the mass of link $i$, the vector $[I_{ixx}, I_{iyy}, I_{izz}]$ defines the distance from the center of the $i$-th link frame to the center of mass of link $i$. The parameters $I_{ixx}, I_{iyy}, I_{izz}$ form the symmetric inertia tensor of link $i$, defined relative to the center of mass of link $i$ in the $i$-th link frame, as

$$I_i^j := \begin{bmatrix} I_{ixx} & I_{iyy} & I_{izz} \\ I_{iyy} & I_{ixx} & I_{izz} \\ I_{izz} & I_{iyy} & I_{ixx} \end{bmatrix}.$$ 

$F_v$ and $F_e$ are the parameters for viscous and coulomb friction, respectively. All physical parameters of the robot form the stacked vector $\mu := [\mu_1^\top, \ldots, \mu_n^\top] \top$. Note that we neglect the kinetic and potential energy from the joint actuators, as their contributions are low in relation to the energy of the links, and no measurements of the rotors’ angular velocity are available.

2.2 Inverse Dynamics Model (IDM)

For the identification of the dynamic model of rigid robots, the so-called inverse dynamics model is used. The dynamics equations are expressed linearly w.r.t. a set of dynamic parameters, which are stacked in the vector $\pi := [\pi_1^\top, \ldots, \pi_n^\top] \top$, where for each link $i$, $i = 1, \ldots, n$, the parameter vector $\pi_i$ is defined as

$$\pi_i := [M_i, MX_i, MY_i, MZ_i, XX_i, XY_i, XZ_i, YY_i, YZ_i, ZZ_i, FV_i, FS_i] \top.$$ 

(3)

The relationship between the dynamic parameters in (3) and the physical parameters in (2) are given by

$$\begin{align*}
M_i &= m_i, \\
MX_i &= m_i I_{ixx}^i, \\
MY_i &= m_i I_{iyy}^i, \\
MZ_i &= m_i I_{izz}^i, \\
XX_i &= I_{ixx}^i + m_i (l_{Cxx}^i + l_{Cyy}^i), \\
XY_i &= I_{ixx}^i + m_i (l_{Cxx}^i + l_{Cyy}^i), \\
XZ_i &= I_{ixx}^i + m_i (l_{Cxx}^i + l_{Cyy}^i), \\
YY_i &= I_{iyy}^i + m_i (l_{Cxx}^i + l_{Cyy}^i), \\
YX_i &= I_{iyy}^i + m_i (l_{Cxx}^i + l_{Cyy}^i), \\
YZ_i &= I_{iyy}^i + m_i (l_{Cxx}^i + l_{Cyy}^i), \\
FV_i &= F_v^i, \\
FS_i &= F_s^i.
\end{align*}$$

(4)

The inverse dynamics model is derived from measurements of $q$ and estimates of $\dot{q}$ and $\ddot{q}$.

2.3 Reduction to Base Parameters

Depending on the kinematic structure, the complete set of dynamic parameters is not required to uniquely specify the robot’s motion, see Gautier and Khalil (1988). Therefore, the set of parameters to be identified can be reduced to a minimal set of parameters, as shown in Gautier and Khalil (1990), which are referred to as base parameters, $\pi_b$. The relationship between the complete vector of dynamic parameters, $\pi$, and the vector of base parameters, $\pi_b$, is linear. Details about the regrouping can be found in Khalil and Dombre (2004). The equations for regrouping $\pi$ to $\pi_b$, for the KUKA LBR iiwa, with $n = 7$, are

$$\begin{align*}
ZZR_1 &= ZZ_1 + YY_2, \\
MYR_2 &= MY_2 + MZ_3 + rl_3 \cdot MR_3, \\
XX_2 &= XX_2 - YY_2 + YY_3 + 2 \cdot rl_3 \cdot MZ_3 + rl_2^2 \cdot MR_3, \\
ZZR_2 &= ZZ_2 + YY_3 + 2 \cdot rl_3 \cdot MZ_3 + rl_2^2 \cdot MR_3, \\
MR_3 &= M_3 + MR_4, \\
XXR_3 &= XX_3 - YY_3 + YY_4, \\
MYR_3 &= MY_3 + MZ_4, \\
ZZR_3 &= ZZ_3 + YY_4, \\
MR_4 &= M_4 + MR_5, \\
MYR_4 &= MY_4 - MZ_5 - rl_5 \cdot MR_5, \\
XXR_4 &= XX_4 + YY_3 - YY_4 + 2 \cdot rl_3 \cdot MZ_3 + rl_2^2 \cdot MR_5, \\
ZZR_4 &= ZZ_4 + YY_5 + 2 \cdot rl_3 \cdot MZ_3 + rl_2^2 \cdot MR_5, \\
MR_5 &= M_5 + MR_6, \\
MYR_5 &= MY_5 - MZ_6, \\
XXR_5 &= XX_5 - YY_3 + YY_6, \\
MR_6 &= M_6 + M_7, \\
ZZR_5 &= ZZ_5 + YY_6, \\
XXR_6 &= ZZ_6 + YY_7, \\
XXR_7 &= XX_7 - YY_7.
\end{align*}$$

(6)

The inverse dynamics model from (5) with $\pi_b$ thus becomes

$$\begin{align*}
\tau &= Y_b(q, \dot{q}, \ddot{q}) \pi_b, \\
\text{where the observation matrix } Y &\text{ from (5) is transformed into } Y_b, \\
&\text{according to the linear regrouping transformation of (6).}
\end{align*}$$

3. METHODS FOR DYNAMIC IDENTIFICATION

3.1 Least-Squares Approach

The dynamic model identification is based on the measurements of joint torques, $\tau_{meas}$, and joint positions, $q_{meas}$, of the robot during dynamic experiments. The joint velocities and accelerations, $\dot{q}_{meas}$ and $\ddot{q}_{meas}$, respectively, are computed from the measurements. From this data, the matrix $Y_b(q_{meas}, \dot{q}_{meas}, \ddot{q}_{meas})$ in (7) can be constructed, see Siciliano et al. (2010). During the experiment, $M$ measurements along the trajectory are recorded. The $m$-th measurement is denoted by $q_{meas}(m)$. The resulting matrix equation is given by

$$\begin{align*}
\begin{bmatrix}
Y_1(q, \dot{q}, \ddot{q}) \\
Y_2(q, \dot{q}, \ddot{q}) \\
\vdots \\
Y_M(q, \dot{q}, \ddot{q})
\end{bmatrix}
\begin{bmatrix}
\pi_1 \\
\pi_2 \\
\vdots \\
\pi_M
\end{bmatrix}
\end{align*} = Y_b.$$
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