Multibody Simulation of the Model-Based Controller for Lightweight Robot

Łukasz Woliński

Institute of Aeronautics and Applied Mechanics
Warsaw University of Technology
Nowowiejska 24, 00-665 Warsaw, Poland
lwolinski@meil.pw.edu.pl

Introduction

This article presents research on a model-based controller intended to be implemented in KUKA LWR4+ robot. Multibody simulation methods are employed to conduct the study.
Although model-based control is a well known concept (presented in many robotic textbooks, eg. [1]), classical PID controllers tend to be sufficient for most uses. When model-based control is implemented in commercial robots, it usually works as a *black box* with parameters unknown to the user. Situation is different with the KUKA LWR4+ robot. It is equipped with the so-called *Fast Research Interface* (FRI). This utility makes it possible to control the robot from a remote PC [2].

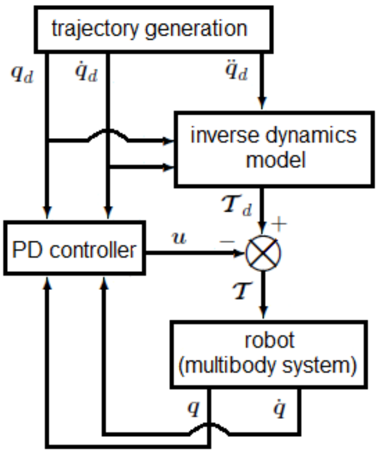

Figure 1: Schematic of a control system.

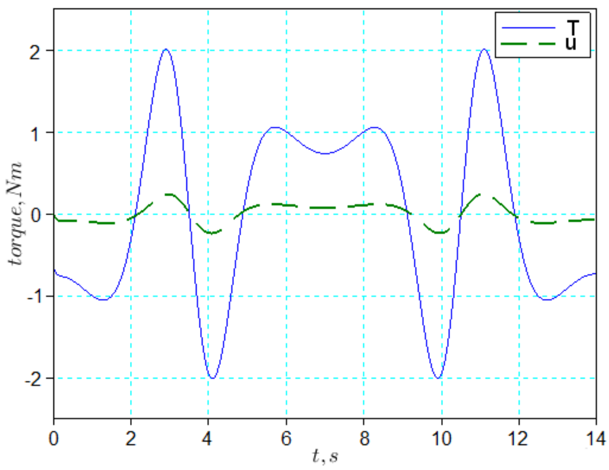

Figure 2: Driving torques at selected joint.

Model-based controller

Equations of motion of a serial articulated manipulator consisting of n rigid links can be written in a matrix form [1]:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{G}(\mathbf{q}) + \mathbf{Q}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{T}(\mathbf{q},\dot{\mathbf{q}}), \tag{1}$$

where $\mathbf{q} \in \mathbb{R}^{n\times 1}$ is a vector of joint coordinates, $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{n\times n}$ is the inertia matrix of the manipulator, $\mathbf{C}(\mathbf{q},\dot{\mathbf{q}}) \in \mathbb{R}^{n\times n}$ is the Coriolis/centrifugal matrix, $\mathbf{G}(\mathbf{q}) \in \mathbb{R}^{n\times 1}$ is the gravity vector, $\mathbf{Q}(\mathbf{q},\dot{\mathbf{q}}) \in \mathbb{R}^{n\times 1}$ is a vector of external forces acting on links and vector $\mathbf{T}(\mathbf{q},\dot{\mathbf{q}}) \in \mathbb{R}^{n\times 1}$ contains driving torques at joints.
For motion control an implementation of PD control law plus feedforward can be used. Equations describing control system shown in Fig. 1 are [1]:

$$\begin{cases} \mathbf{T} &= \hat{\mathbf{M}}(\mathbf{q}_d)\ddot{\mathbf{q}}_d + \hat{\mathbf{C}}(\mathbf{q}_d,\dot{\mathbf{q}}_d)\dot{\mathbf{q}}_d + \hat{\mathbf{G}}(\mathbf{q}_d) + \hat{\mathbf{Q}}(\mathbf{q}_d,\dot{\mathbf{q}}_d) - \mathbf{u} \\ \mathbf{u} &= -\mathbf{K}_p\mathbf{e} - \mathbf{K}_v\dot{\mathbf{e}} \end{cases} \tag{2}$$

where $\mathbf{q}_d$ is a vector of instantaneous desired joint coordinates, $\mathbf{e} = \mathbf{q}_d - \mathbf{q}$ is the tracking error and $(\hat{\bullet})$ are estimates of corresponding matrices. Finally, $\mathbf{K}_p$, $\mathbf{K}_v \in \mathbb{R}^{n\times n}$ are proportional and derivative gains. Since FRI allows the user to specify desired torques, Eq. (2) can be used directly wihout accounting for dynamics of motor and computing voltage inputs.
To obtain an inverse dynamics model, a recursive algorithm based on spatial operator algebra [3] is used. The algorithm is desribed in detail in [4].

In the computational model the robot is treated as a multibody system and described in joint coordinates, as evidenced in Eqs. (1) and (2). Equations of motion are expressed in a compact matrix form which is convenient for control purposes. Currently, for simplicity, neither actuator dynamics, nor joint elasticity are considered, but they can be included at the price of greater complexity of the equations.
Formulation of the equations begins with link velocities and accelerations propagating from the base to the tip. Forces acting between links propagate backwards – from the tip to the base – and are stacked in a vector. Projecting that vector of internal forces onto the joint space leads to the matrix-form equation of motion (1). The inertia and Coriolis matrices as well as the vectors of gravitational and external forces are expressed as products and sums of several known submatrices [3]. These submatrices, in turn, are calculated recursively using an algorithm described in [4].

Numerical results

Simulations of the control system were conducted in the Scilab environment. Kinematic data for the model were obtained from the official KUKA documentation. Several research groups have published partial results of identification of LWR4+ dynamic parameters, however, in this study only roughly estimated parameters were used. Both forward and inverse dynamics models were created with the use of aforementioned recursive algorithm, however, in the latter case parameters were slighlty altered to account for uncertainties in the control system.
The duration of the simulation was set to 14 seconds and the same desired relative motion was prescribed for all joints:

$$q_{d\,j}(t) = \frac{\pi}{2} cos\left(\frac{\pi}{7}t\right) \quad j = 1,\ldots,7. \tag{3}$$

After some tests, gain matrices were chosen to be constant in time and equal:
$\mathbf{K}_p = diag[225,400,400,625,100,100,25]$ and $\mathbf{K}_v = diag[30,40,40,50,20,20,10]$.
The final simulation resulted in satisfactory position and velocity tracking. Fig. 2 presents the driving torques at the first joint. It shows the total torque and the PD component u. It is worth noting that only a fraction of the generated torque is the output from the PD controller.

Conclusions

In the paper an algorithmic approach to solve efficiently the LWR4+ robot inverse dynamics, as required by the model-based control scheme, is investigated. The results of the control system simulations are presented. The algorithm can be extended to account for actuator dynamics, joint elasticity, friction, etc. The author is currently implementing the algorithm on LWR4+ robot and plans to verify it experimentally. The author hopes to further improve the model-based control system and to present experimental results at the conference.

Acknowledgements

This research was supported by the National Science Centre (Poland) grant no. DEC-2012/07/B/ST8/03993.

References

[1] R. Kelly, V. Santibáñez Davila, A. Loría Perez. Control of Robot Manipulators in Joint Space. Springer London, 2005.

[2] G. Schreiber, A. Stemmer, R. Bischoff. The Fast Research Interface for the KUKA Lightweight Robot. In Proceedings of the IEEE ICRA 2010 Workshop on ICRA 2010 Workshop on Innovative Robot Control Architectures for Demanding (Research) Applications – How to Modify and Enhance Commercial Controllers, pp. 15–21, Anchorage, May 2010.

[3] G. Rodriguez, K. Kreutz-Delgado, A. Jain. A Spatial Operator Algebra for Manipulator Modeling and Control. International Journal of Robotics Research, vol. 10, pp. 371–381, Aug. 1991.

[4] Ł. Woliński. Modeling and control of articulated-body robot manipulators in joint space *(in Polish)*. Master's thesis, Warsaw University of Technology, 2013.