Set-Point Regulation of Flexible Joint Robots: A Comparative Study[*]

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1 Extended Abstract

In virtually all present day robotic applications the basic point-to-point regulation problem is solved using proportional plus derivative (PD) controllers with gravity compensation. To insure, via total stability arguments, good behavior when tracking (slow) link trajectories it is desirable that the closed-loop be globally asymptotically stable (GAS), a property which was established in the seminal paper [8]. A drawback of these controllers is that they require the measurement of joint *velocities*, which is often contaminated with noise. Since, in practice, the values of the controller gains are limited by the noise level the achievable performance is usually below par. In order to avoid the noise measurement problem an *ad-hoc* solution is to

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numerically differentiate the position. Indeed, this solution is frequently employed in robotic applications today. However, besides the fact that there is no theoretical justification to this solution, this reconstruction of velocity may be inadequate for low and high speeds [2].

Another factor that hampers the behavior of robot controllers is the presence of *joint flexibilities* caused by harmonic drives, shaft windup, bearing deformation, and compressibility of the fluid in hydraulic robots. It is well known [7] that, in the absence of gravity forces, PD control around the motor side still achieves GAS in point-to-point regulation tasks in spite of the presence of joint flexibility. In the important paper [9] it is shown that to compensate for the gravitational effects it suffices to add a constant compensation term (the gravity force at the desired link position) to the PD controller above. GAS is still preserved, for some suitably chosen gains, provided the joint stiffness dominates the gravity forces, a condition that is very likely to be met in industrial robots. This is a significant contribution since it shows that the problem can be solved with a *linear* controller, and further obviate the need of additional sensors on the link side.

Very recently [1], [3] the authors presented two different solutions to the problem of designing GAS controllers for point-to-point regulation of flexible joint robot manipulators. Even though both controllers are *linear* and require *motor position measurements only*, they are essentially different, and are derived proceeding from different design philosophies. In both schemes we assume the joint stiffness dominates the gravity forces. Also, knowledge of the gravity forces is the only robot prior information required. Furthermore, if the joint stiffness coefficients are known, then we can tune the controller gains so that the equilibrium point coincides with the desired position. Besides the theoretical relevance of the results, the fact that the problem can be solved with a simple linear controller, without knowledge of the dynamic part of the robot model, and with only measurement of the motor position makes the result very attractive in practical applications

In [1] we follow the seminal paper [8], where the underlying rationale of the design is to *"shape" the total energy* of the closed loop system, so that it has an absolute minimum at the desired equilibrium, and add the required *damping* to achieve asymptotic stability. The main difficulty to attain these objectives is that the damping, provided by the derivative term when velocity is measured, has now to be injected to the system through an "observer". To design the latter we propose a second order observer, which does not aim at convergence to the *actual* motor velocity, but instead insures the observer position converges to some *a priori determined* value. This position coincides with the desired link position when gravity forces are absent, and is chosen to compensate for the latter in general. Then, we choose a control law and a correction term to the observer so that the effect of "adding a spring" between them is achieved. In this way, the actual motor angle is "pulled" by the observer position. The observer gains, the stiffness of the added spring and the joint stiffness must be such that we can insure the potential energy of the closed loop system has an absolute minimum at the desired equilibrium.

On the other hand, in [3] motivated by [4] we have used a classical analysis technique to show that motor shaft velocity measurement in the PD scheme of [9] can be replaced by an approximate differentiation of its position preserving GAS. This result provides a solid theoretical justification to the common practice of approximate differentiation in robot set-point control. Furthermore, the GAS property holds for all (positive) choices of the filter dynamics. However, the tracking performance will depend on its frequency response characteristic.

The purpose of this paper is twofold, first to present side-by-side both controllers to underscore their analytical similarities and differences. Second, to carry out a comprehensive simulation study that reveals further practical issues of the schemes, which are not captured by the analysis. Namely, comissioning problems, transient performance, sensitivity to unkown parameters, etc. As point of comparison, it is interesting to note that the controller of [1] contains n second order relative degree zero filters with inputs the motor shaft position and the gravity compensating constant term and output the generated torques. In contrast with this, the controller proposed in [3] consists only of n first order relative degree zero filters. On the other hand, as mentionned above, the design procedure followed in [1] is based on energy shaping ideas which exploit the natural structure of the system in a more transparent way. In particular, the Lyapunov function used for the analysis is the systems total energy. Although for the design of [3] we have a nice interpretation in terms of a feedback interconnection of passive subsystems a clearer physical understanding of the Lyapunov function is as yet unavailable. Other simulation studies comparing these schemes are reported in [5].

References

[1] A. Ailon, and R. Ortega, "An observer-based set-point controller for robot manipulators with flexible joints", *Systems and Control Letters*, (to appear). (See also Université de Technologie de Compiègne, France, Tech. Report, November, 1992.)

[2] P. R. Belanger, Estimation of angular velocity and acceleration from shaft encoder measurements, *Proc. IEEE Conf. Rob. and Automation*, Nice, France, pp.585-592, 1992.

[3] R. Kelly, R. Ortega, A. Ailon and A. Loria, Global regulation of flexible joint robots using approximate differentiation, *IEEE trans. Aut. Cont.*, (to be published).

[4] R. Kelly, A Simple Set-Point Controller by Using Only Position Measurements, *Proc. 12th IFAC World Congress*, (to be published), 1993.

[5] A. Loria, "Set point control of robots with flexible joints: A comparative study" *M. of Sc. Thesis*, Université de Technologie de Compiègne, France, June 1993.).

[6] M. Spong and M. Vidyasagar, *Robot Dynamics and Control*, J. Wiley, NY, 1989.

[7] Takegaki, M. and S. Arimoto, A new feedback method for dynamic control of manipulators, *ASME J. Dyn Syst. Meas. Cont.*, Vol. 102, 1981.

[8] Tomei, P., A simple PD controller for robots with elastic joints, *IEEE Trans Aut. Cont.*, Vol.36, no.10, pp.1208-1213, 1991.