An experimental facility for nonlinear robot control

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An experimental facility for nonlinear robot control

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Abstract

An experimental facility for evaluating robot controllers is discussed. Highlighted are the motivation for the need of such a system, its design, modeling, construction, and general use. A recently proposed globally stable PID type controller and a passivity based computed torque controller were implemented and some preliminary experimental results are presented. They illustrate the usefulness of this facility.

Keywords: Robot control, nonlinear system, control system validation.

1. Introduction

1.1. Background and motivation

Many robot control schemes are based on a relatively straightforward model, assuming the number of degrees-of-freedom being equal to the number of independent control inputs. Variations on this model are common: flexible joints or links, motor dynamics, sensor dynamics, vision based sensing, etc. The standard model contains several nonlinear terms. The mass matrix is configuration dependent. Coriolis and centrifugal forces are present. It accounts for viscous and Coulomb friction. All those effects are considered in the control schemes and/or in their analysis.

Those nonlinear terms are not too easy to highlight in robots for industrial use. The configuration dependent inertia terms may be dominated by the central moment of inertia of the motors, when high geared drive lines are used. This has the effect of linearizing the system and of decoupling the degrees of freedom.

When using direct-drive motors, so without gear boxes, this linearizing effect is not present. In this case the main hindrance to get a sizeable effect of other nonlinear terms is the limited velocity that can be obtained (remember that the Coriolis and centrifugal forces contain terms with velocity squared). The velocity is limited because normally the operation

range of the robot is restricted. This may be due to limitations in the construction, or to avoid breaking cables that transport energy and information along the robot's chain, from base to end-effector and vice-versa.

Again, also this argument can be annulled, by providing a motor that can generate a high torque, so a speed profile can be imposed that has a high level, but does not lead to a large displacement or rotation. The argument against this is that it will be expensive, it will excite additional vibrational modes in the system, which in practice would be avoided by choosing a more sensible profile, and it combines high velocities with high accelerations. The last point prevents separation of the effects of configuration dependent inertia from Coriolis and centrifugal forces.

The conclusion is, that although the influences of nonlinear terms are certainly present in robotic systems, they do not always dominate, nor can their effects be studied individually. This makes it difficult to compare control schemes. Such a comparison is of interest, however. First, because the weight of robots is constantly reduced to achieve higher velocities, and by that smaller cycle times and increased productivity are obtained; and because the use of gear trains is hindered by friction, play, and backlash, so direct-drive motors are preferred, the nonlinear terms are becoming of more importance. Second, in the theoretical derivation of control schemes the main attention is paid to stability issues. Of course, this is of paramount importance. But one should not stop there. When stability is guaranteed, performance is the next target to aim at when conceptualizing and analyzing control schemes.

Besides the issues of nonlinear terms and performance, other points have to be addressed. Control for nonlinear rigid robots using joint coordinate and velocity measurements is relatively well established: several classes of controllers with guaranteed global stability are available [1-3]. The case when only joint

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position measurements are available has been given a fair treatment [4]. Control of non-rigid robots, with flexible joints or links, has been treated in the past as well [5]. Recently, work has concentrated on other areas, *i.e.*, the study of global stability of simple PID schemes and the use of other measurements than joint coordinates, *e.g.*, obtained by the use of vision systems. An experimental facility should be able to access the properties of this type of controllers also.

Verification of the practicability and performance of controllers, sensing schemes, and actuation setups for rigid and non-rigid robots cannot be carried out on paper only, but should involve experiments. This has been done in the past by several researchers [6, 7]. In [7] the nonlinearities were dominated by Coulomb friction and the performance was limited by unmodeled flexibilities. To address some of the issues raised, a new experimental facility was needed. The description of the design considerations, the design itself, its realization and preliminary use are the main contributions.

1.2. Robot properties

To be able to test robot control schemes for those cases where Coriolis and centrifugal forces dominate, to gain experience with the use of new forms of actuation and sensing - and their integration in the closed loop - an experimental facility has been designed and build. Highlights of this facility are

- unconstrained rotation of the rotary joints
- direct-drive motors without gear-boxes
- modular setup with exchangeable joint and link
- 3D optical end-effector position measurements
- graphical based control system implementation
- automated real-time code generation
- use of industry standard equipment.

The graphical user interface makes it possible to test a large number of controllers in a short time frame. The unconstrained rotation and direct-drive motors allow analyzing the controller's ability to handle relatively large Coriolis and centrifugal forces with good performance, *i.e.*, without large tracking errors, making use of the possibility to prescribe trajectories with high velocities and small accelerations at the same time. The modular setup enables changing the last joint and link, so both rigid and flexible joints and links are possible. The vision system provides high accuracy measurements with high update rates, allows to test non co-located actuator/sensor setups, and gives access to the end-effector position independently from the computed position with the joint coordinates. It also provides the possibility for sensor fusion with joint position measurements.

1.3. Overview

This paper discusses the design of the robot, Section 2, it sketches the simulation program that has been used to aid in the design of the system and to validate the control software, Section 3, it reports on the implementation of two control schemes, Section 4, and gives some provisional experimental results, Section 5. The main conclusions are in Section 6.

2. Robot design

The project started with a conceptual design of a compact and lean robot, see Fig. 1, with three unconstrained rotational degrees of freedom, mimicking typical robots in industrial use with an anthropomorphic kinematic chain. The joints are all "one-sided," so they can be replaced easily.

Figure 1: Robot concept

It was expected that by using unconstrained rotary degrees-of-freedom large velocities could be generated, where the largest part of the torque generated by the motor would be needed to compensate Coriolis and centrifugal forces. A lean design was preferred to make it easier for a vision system to acquire the position of the end-effector, that should be kept in sight. A small construction volume would make it less likely that the end-effector would be obscured from view. Later it became apparent that direct-drive motors were more bulky than expected, so the final design was more voluminous, as can be seen in Fig. 2.

Power and information has to be transported along the robot's chain. Cables crossing the joints were not acceptable, because even with a large spare length of cable, ultimately it would constrain the rotation. Several options were investigated to solve this problem

- radio frequency transmission of information
- optical joints connecting fiber glass channels

Figure 2: Robot final design

- conductive information and power transfer
- slip rings.

Although initially slip rings were placed at the bottom of the short list, being seen as a standard and not a high-tech solution, at the end they appeared to be the only option that was feasible. Figure 3 gives an approximate impression of the layout of a single robot joint and link. The signal transfer block in this scheme represents the slip rings. In reality, three joints and links are present, with the three motor drives (power supply, power amplifier, and other drive electronics) at the base joint. All signals for the other joints and for all the links flow through the slip rings.

To determine the motor capabilities and link dimensions, an iterative design procedure was followed, where simulation results were used to predict the ratio of Coriolis and centrifugal forces against motor torque. To be more precise, for the standard rigid robot model

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q, \dot{q}) = \tau$$

with q the degrees of freedom, M the inertia matrix,

Figure 3: Joint layout

$C\dot{q}$ the Coriolis and centrifugal forces, g gravity and friction forces, and τ the motor torque, the ratio

$$\frac{\int |(C\dot{q})_j| dt}{\int |\tau_j| dt}$$

was required to exceed 0.5 for at least one of the joints j and for a trajectory that was within the physical possibilities of the system, i.e., that did not saturate the motors. Results for such a case are in Fig. 4. More details can be found in [8].

Figure 4: Size of Coriolis and centrifugal forces

A choice was made to use direct-drive motors, without gear boxes, with built-in high resolution encoders. A velocity signal is generated from the position measurement by the motor drives. The motor control unit can perform several task, the only relevant one in our case being the possibility to dictate the motor torque. Most of the drive electronics are therefore not really useful. A 2-dimensional blue print drawing of the robot itself, showing the joints,

with motors and slip rings, and the links, is presented in Fig. 5.

Figure 5: Blue print of the robot

Data acquisition and control is done with a low cost PC solution and a powerful data acquisition plug-in board, providing encoder input signal channels, together with analog input/output and digital input/output channels.

Supporting software allows the board to be used in a Windows environment. The control software is tightly integrated with Matlab/Simulink. It is therefore easy to use, simulation and experiment can both be performed using the same controller block scheme due to real time code generation options. Signal traces from the experiment can be displayed real time. Some controller parameter changes are possible while running the controller and take effect immediately. This all makes it easy to carry out experiments and to evaluate several control parameter setting, without bringing the experiment to a halt and without regenerating real time code.

The real time code runs on the PC itself. Despite the lack of real time facilities under Windows, this solution was preferred over the use of a dedicated control processor or over a nonstandard operating system. Main arguments were performance, costs, and the preference for standard solutions, together with integration of design and experimental development environment. Some of these arguments are also reported in [9], but in our case led to a different choice. A table listing the main components of the experimental facility appears in the Appendix.

3. Simulations

To get insight in the behavior of the robot, a simulation model was used, both in the design phase (see Section 2), and in the software verification phase, before the controller was used on the real system.

The model was setup using a general purpose symbolic computation platform. Efficiency was not of primary concern, so standard Lagrangian dynamics were used to derive the model, the kinematics being described by the Denavit-Hartenberg notational convention. This set-up does not excel in speed, so is not well suited for applications with hard real time constraints, but has the advantage of easy programming and flexibility in use.

Some wire frame animations of the robot performing a tracking maneuver are in Fig. 6.

Figure 6: Wire frame animation of simulation

4. Control schemes

Two control schemes of the ones that have been applied are highlighted. Both are using the rigid robot model. One is based on a recent result establishing global stability of setpoint control with a linear PID type controller for rigid robots when gravity forces are uncertain [10]. The other one is a relatively standard passivity based computed torque controller.

The PID controller with provable global stability is based on a two step procedure. The controller starts as a PD one, and when the target point is sufficiently close, the integral action is switched on. Sufficiently close can be quantified using an approximating approach that gives the switching time.

The passivity based computed torque controller is of the form

$$\tau = M(q)\ddot{q}_d + C(\dot{q}, q)\dot{q}_d + g(\dot{q}, q) + K_d\dot{e} + K_p e$$

with $e = q_d - q$ the tracking errors and q_d the desired joint coordinates.

The control parameter matrices K_p and K_d should be positive definite and, in theory, can be chosen arbitrarily within this restriction. In practice their value is bounded from above, because large values correspond with high bandwidth, and then the rigid robot modeling assumption is no longer valid. In practice this means there are values for K_p and K_d that, when they exceed the upper bounds, lead to an unstable closed loop.

Coding of the controller takes place in the Matlab/Simulink environment, with graphics based block diagram manipulation. With a modular setup of the control schemes, large parts of the block diagram can be re-used. Switching from simulation to real time control can be performed with a click of the mouse to select the control scheme to be executed, to generate the real time code, and to start the execution of the controller.

A block diagram of the computed torque controller is in Fig. 7. This diagram also displays the trajectory generation, the blocks for the data acquisition board, and the feedback loop signal flow.

5. Experiments

Experiments were carried out with the two control schemes presented in the previous section. Both controllers use the joint velocities. These signals are delivered by the motor drive electronics, but they did not have a very good quality. The approach taken at the moment is to numerically differentiate joint position and filter this with a low pass Butterworth filter. The resulting signal was of better quality than that delivered by the motor drives, and was therefore used in the experiments. Other options are investigated.

It appeared that the advantage claimed for the globally stable PID controller could not be assessed on this system. As stated, this scheme is based on a two stage or composite procedure, first use a PD type controller to bring the system in the vicinity of the target point, and then switch on the integral action. In our system this vicinity of the target point was so large that starting the controller with integral action enabled was enough to reach the target point and stabilize the system in that point. So the virtues of this control scheme could not be showcased. Perhaps it is possible to choose the control parameters in such a way that the stability range of the PID controller does

not encompass all possible configurations of the robot, while it stabilizes near the target point, making it possible to demonstrate the advantage of switching on the integral action. This has not been carried out, because the practical relevance of this idea seems null.

The passivity based computed torque control law has been successfully used on the experimental system. The control parameters K_p and K_d were chosen using rules of thumb to estimate the achievable closed loop bandwidth, and were tuned by trial and error to get an acceptable (stable) response. No effort was spent in trying to achieve an "optimal" response.

Figure 8 shows a comparison of experimental and simulation results for the computed torque controller. The simulation was for the same desired trajectory, with large rotations and rotational speeds, and almost the same initial conditions as used in the experiment.

Figure 8: Simulation and experiment for computed torque controller

These results still show appreciable differences between experiment and simulation, probably due to incorrect values for several model parameters, especially those related to the motor drives. It is expected that this can be overcome by a careful analysis of the system parameters and their experimental identification. Comparing theoretical and experimental values can also give an indication which terms in the model are important and which effects are missing and need to be included. Perhaps, it may be necessary to use a better model of the motor drives, that are now only represented by a simple constant parameter, relating control input level to delivered motor torque.

Figure 7: Block scheme of computed torque controller

6. Conclusions

An experimental facility is made available that offers flexibility in use and has a proven ability to test, and to experiment with, robotic control schemes. Not only schemes for rigid robot control can be handled, schemes for robots with a flexible joint and/or link, with non co-located actuation/sensing, with vision feedback, etc., also fall within the range of possibilities.

Experiments with two rigid robot controllers implemented on the facility show the robot to achieve its intended goal. In the future the other possibilities of the robot need to be explored: using vision based feedback, employing a flexible joint and link, and the ability to implement and test many controllers in a short time frame.

To facilitate controller testing, a systematic procedure has to be developed that tunes the controller parameters, only using rules of thumb and trial and error is not that convenient and takes a lot of time.

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Appendix

Table 1: List of main system components

Component	Source	Type
Motors	Litton Precision Prod	Dynaserv
Slip rings	Litton Precision Prod	
Vision system	Schäfter + Kirchhoff or other	Line scan cameras
DA board	Quanser Consulting	MultiQ
Control SW	Quanser Consulting Mathworks	WinCon Matlab Simulink