Sensorless force control with a Disturbance Observer for a compliant manipulator

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Abstract

Force or torque control can be implemented using a dedicated force or torque sensor that measures the actual interaction of a manipulator with its environment. Although this approach can be very successful and reliable there can be various reasons to avoid the extra sensor such as costs, implementation issues or control bandwidth limitations. These considerations have stimulated research on sensorless control where basically the interaction forces are estimated from known driving forces or torques [3]. Needles to point out that the dynamic behaviour of the manipulator needs to be known sufficiently accurately to be able to establish the dynamic relation between drives and interaction with the environment.

Compliant manipulators may then offer advantages. In these manipulators elastic deformations of flexible elements in so-called flexure joints enable motion which low amount of friction and hysteresis [2]. Moreover, no contributions from Coulomb friction or other hard to predict effects are expected which should result in very deterministic system dynamics. This paper addresses the feasibility of a known force control concept [3] for such a compliant manipulator.

For this purpose the two degree-of-freedom (DOF) manipulator shown in Figure 1 is considered. This system is driven by two base mounted actuators. Seven links are connected to each other, to the base and to the end-effector with eleven flexure joints such that the end-effector only moves in two translational directions denoted x and y [1]. The dynamic behaviour of this system is dominated by the inertia properties of the links and the finite compliances of the flexure joints. In addition wires connected to moving parts of the actuators and sensors give rise to damping which is to a large extend linear, but some non-linear sticking behaviour can be observed near the neutral, i.e. not actuated, configuration. In this paper we consider force control in one DOF being the y direction, while in the other DOF the x position is controlled with a standard PD-controller.

The force control makes use of two observers as shown in Figure 2 [3]. The disturbance observer (DOB) estimates external disturbances and system uncertainties, which are fed back to the system input in an inner loop. The reaction torque observer (RTOB) is quite similar and its output is an estimate of the

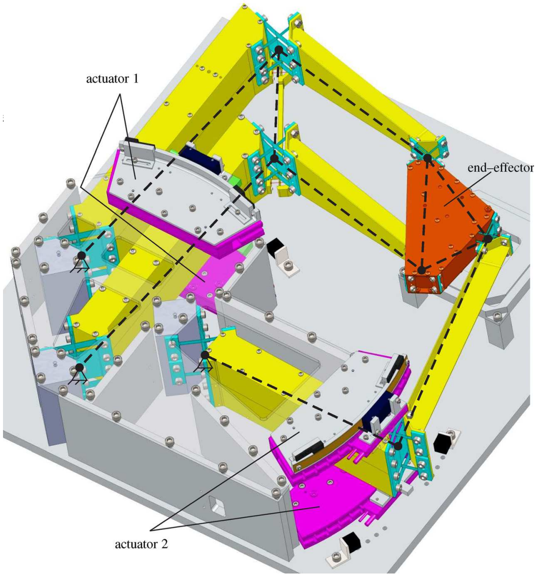


Figure 1: Two-DOF mechanism with two base mounted actuators and eleven cross-flexure hinges allowing motion of the end-effector in two translational directions (from [1]).

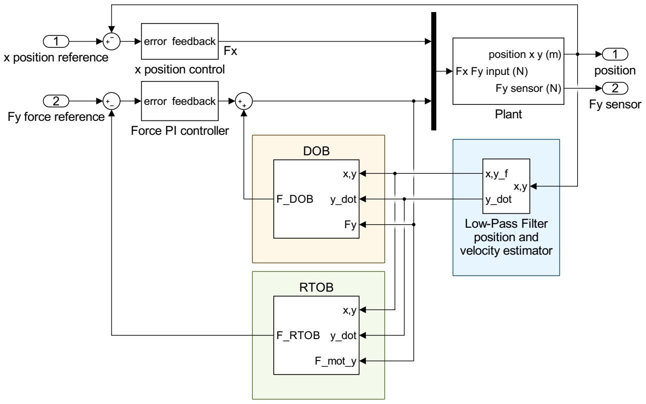
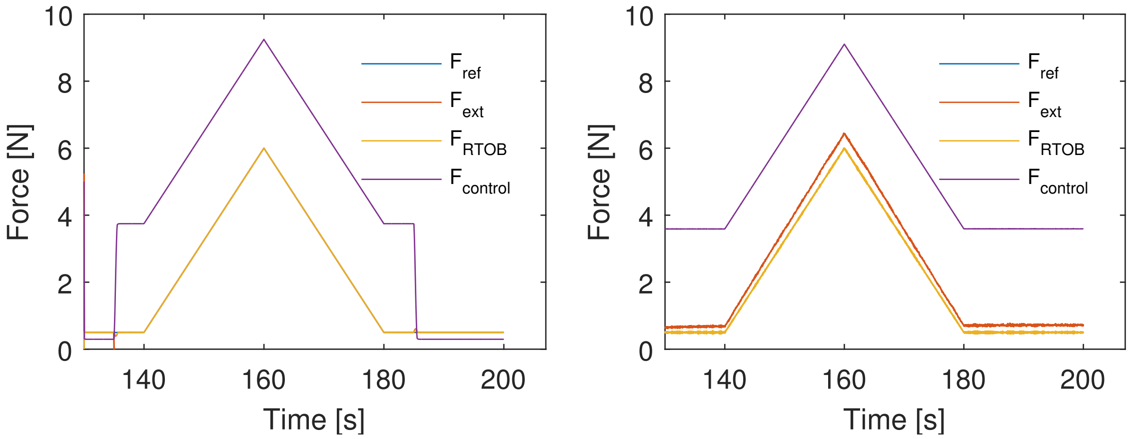


Figure 2: Block diagram of 1D force control with disturbance observer (DOB) and reaction torque observer (RTOB) both using the low-pass filtered manipulator position and estimated velocity (adapted from [3]).

interaction with the environment. The action of the force controller depends on the error between this estimate and the reference force that should be applied by the manipulator. Both observers need a velocity input signal which is estimated from the measured position signal (encoder) with a combined low-pass filter and velocity estimator.

Compared to the original control scheme [3] some changes are proposed when using it for a compliant manipulator. Next to inertia properties the finite stiffness has to be included in the manipulator model that is used in the observers. The damping contribution is small but to a large extend known and can be added similarly. Finally, the finite stiffness implies that a pure proportional action for force control as in [3] will lead to a steady-state error for the external force in case the manipulator is not in the neutral configuration. Hence a PI-controller is used for this purpose in Figure 2.



(a) (b)

Figure 3: (a) Simulation and (b) experimental data of the force control. In both cases the interaction force with the environment F_{ext} should track a reference force F_{ref} that varies linearly from 140 s to 180 s. In the experiments the end-effector position is stationary at about 20 mm from the neutral position whereas in the simulation a displacement of 20 mm in 0.5 s is applied at 135 s and 185 s moving back and forth.[1]

As the force controller depends heavily on an adequate model of the manipulator, its 2×2 mass, damping and stiffness matrices have been computed from an experimental identification of the inverse plant model, i.e. from observed displacements to driving torques, using a multi-sine excitation. Figure 3 shows the performance of the force controller both in simulations and experiments. In the simulations the external torque F_{ext} is perfectly estimated by the observer F_{RTOB} and hence the varying reference F_{ref} can be tracked almost perfectly. Only when a displacement of the end-effector is simulated some dynamic effects of the observers can be noticed. It can be seen clearly that the controller output force F_{control} has an offset relative to the other forces as such force is needed to deform the flexure joints statically. In the experiments an external sensor measures the actually applied force on the environment F_{ext} although this measurement is not used in the control loop. It can be seen that this force closely resembles the reference apart from a small offset and a small difference in the calibration. Nevertheless, these initial results demonstrate the feasibility of the DOB/RTOB force control concept, which will studied in more detail in the future by investigating the closed-loop stability as well as incorporating the manipulator kinematics in the control scheme, e.g. for 2-DOF force control.

References

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[1] Note that the experimental work for this paper has been affected by the COVID-19 outbreak. Figure 3(b) shows some preliminary experimental data which however has been obtained with an “older” controller different from the PI-controller mentioned in the paper. Unfortunately, the “newer” controller can’t be tested as the lab facilities are inaccessible. We expect to include the correct data in the final version of this abstract/paper.