

LOW ENERGY CONTROL OF PERIODIC MOTIONS IN MANUFACTURING

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Summary This paper presents two methods for designing linear and nonlinear springs as local energy storage devices to improve the efficiency of nonlinear rheonomic systems such as assembly robots. Firstly, the shooting method is applied to find parameters of a mechanical system resulting in a conservative limit cycle close to the desired trajectory. The second method describes an alternative approach to design a system with low energy consumption by fitting the characteristics of a spring to an optimal force function calculated by inverse dynamics. With both methods, the fine tuning of the prescribed trajectory is achieved by some additional low energy control.

INTRODUCTION

Manufacturing processes require periodic motions which may be realized by an active robot. A well established robot control principle is inverse dynamics which is used to overcome high nonlinearities typical for mechanical systems undergoing large displacement motion. Based on an accurate model of the system under consideration, all the nonlinearities are compensated firstly by control action and then, the remaining double integrator is controlled by linear feedback. This approach is very attractive to control engineers since a broad variety of established tools can be applied successfully. However, this principle results in high energy demand, see e.g. WALDRON [1].

To improve the efficiency it is proposed to design the mechanical system in such a way that the desired trajectory is approximated by a passive limit cycle of a nonlinear conservative system and some additional low energy control, see SCHIEHLEN [2]. The design parameters case are the stiffness of linear springs or the characteristics of nonlinear springs, respectively, both of which serve as local energy storage.

Since, the parameters for the limit cycle of a system may be hard to find, it is proposed, too, to minimize the consumed energy by fitting the stiffness and characteristics of the springs to a force function resulting from inverse dynamics. In this case, the position/force function for meeting a certain trajectory has to be computed first.

These two methods are applied to a two degree of freedom assembly robot modelled as double pendulum as shown in Figure 1. The angles α_1 and α_2 are the degrees of freedom, u_1 and u_2 are the torques of two motor drives. The springs have the coefficients c_1 and c_2 , their zero position can be adjusted using the spring mounts α_{1N} and α_{2N} .

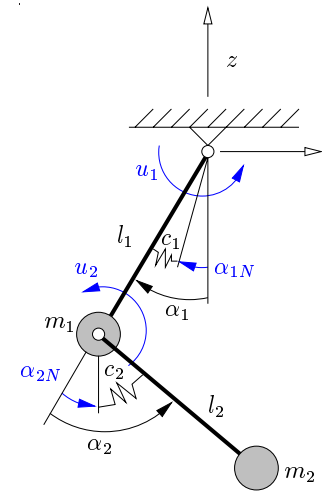


Figure 1: 2 DOF Robot

ENERGY OPTIMAL DESIGN USING LIMIT CYCLES

In this section, a properly designed nonlinear conservative oscillator is proposed to generate the required motion coarsely without energy dissipation and to adjust the motion finely by linear control with strongly reduced energy consumption. Thus, periodic trajectories are adapted as closely as possible to the limit cycle of the underlying mechanical system. The fundamentals of energy consumption and energy storage of mechanical systems with rheonomic constraints have been analyzed for a linear harmonic oscillator, see SCHIEHLEN [3]. It is shown how spring characteristics have to be chosen to reduce the energy consumption for arbitrary periodic trajectories of a robot arm.

The desired trajectory of the system, e.g. a sinusoidal straight motion as shown in Figure 2, defines the boundary conditions for the state of the motion. These conditions are the positions α_i and the velocities $\dot{\alpha}_i$ at the beginning and at the end of the motion, respectively. In particular, for a periodic motion, the state has to be the same after a full cycle. Thus, the boundary conditions read as

$$\left. \begin{aligned} F_i(s) &= \alpha_i(t_{end}, s) - \alpha_{i0} = 0, \\ F_i(s) &= \dot{\alpha}_i(t_{end}, s) - \dot{\alpha}_{i0} = 0, \end{aligned} \right\} i = 1, 2.$$

The goal is to design the mechanical system to meet the boundary conditions by adjusting its parameters. Therefore, the standard shooting method which is a helpful tool to solve boundary value problems is modified to obtain all these parameters. For the assembly robot the shooting parameters are the stiffness coefficients c_i and the spring fastening α_{Ni} .

Using a set of starting parameters, values for stiffness and spring fastening can be found by iteration, such that the boundary conditions for finding a limit cycle are met. Figure 3 shows the trajectory of the system for some chosen starting parameters (dashed line) and the limit cycle using the starting parameters calculated by the shooting method (solid line). The limit cycle motion with two additional linear springs reduces the energy consumption by 52%. Other trajectories, e.g. a sinusoidal motion in z-direction, offer savings of up to 94%.

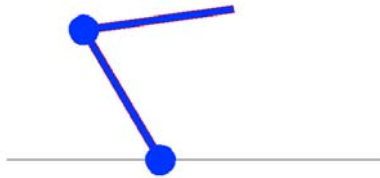


Figure 2: Desired trajectory.

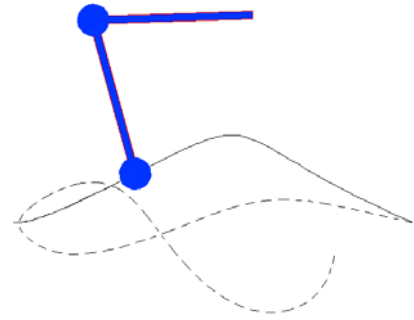
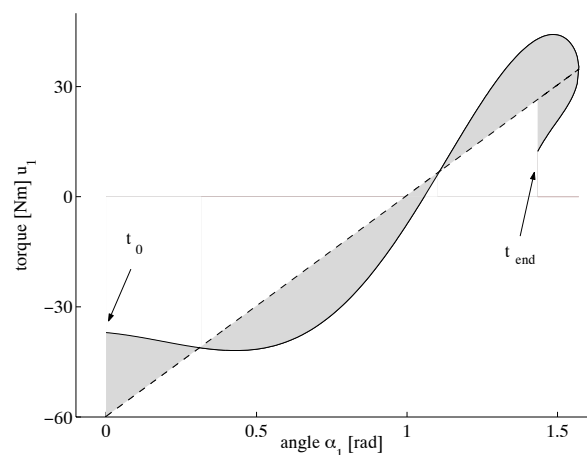


Figure 3: Trajectory using starting parameters (dashed line) and the limit cycle (solid line). Both motions are conservative.

ENERGY OPTIMAL DESIGN USING CURVE FITTING

A more engineering approach is to compute the required controlling force or torque as function of the position of the robot arm, and then to use a linear or cubic polynomial to fit this curve. The area between the linear or cubic fit and the required force represents the work that has to be applied by a secondary PD-control such that the robot trajectory meets its desired path, see also ACKERMANN et. al. [4].

Starting from the trajectory prescribed by the manufacturing process the required control signal, here the torque of the motor drive, is computed using inverse dynamics. Then, this torque is converted to a function of the position, as shown in Figure 4. The solid line shows the control force u_1 calculated by inverse dynamics with respect to angle α_1 for the time $t_0 < t < t_{end}$. A linear function is used as a curve fit (dashed line) representing a linear spring where the spring coefficient is the slope of this curve fit and the axis intercept being the spring fastening.

Figure 4: Torque u_1 calculated by inverse dynamics (solid line) and the fitting function, i.e. torque of a linear rotational spring.

The area between the required force function and the curve fit (grey area in figure 4) is equal to the work that has to be applied by the PD-controller to force the system on the desired trajectory. Therefore, this area has to be minimized by curve fitting. The amount of energy that can be saved is approximately the same as for the springs designed using a limit cycle. Savings of more than 50% were obtained for a linear rotational spring. For nonlinear springs, e.g. cubic progressive or cubic degressive springs, the stiffness and characteristics of can be found very easily, too. Same procedure has been successfully applied to the second robot arm.

CONCLUSIONS

Two methods were shown to design system parameters for reducing the energy consumption of rheonomic nonlinear mechanical systems. The first method uses that a limit cycle of a system generate a periodic motion close to the desired motion without energy dissipation. The second method reduces the work that has to be applied by fitting a spring characteristics to a position/force curve computed by inverse dynamics. For both methods only low energy control is needed to force the system on its desired trajectory. They both deliver approximately the same parameter values and the same amount of energy savings of easily more than 50%.

References

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