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Preshaping input trajectories of industrial robots for vibration suppression

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ABSTRACT

This paper presents several novel methods that improve the current input shaping techniques for vibration suppression for multi-degree of freedom industrial robots. Three different techniques, namely, the optimal S-curve trajectory, the robust zero-vibration shaper, and the dynamic zero-vibration shaper, are proposed. These methods can suppress multiple vibration modes of a flexible joint robot under a computed torque control based on a rigid model. The time delays for each method are quantified and compared. The optimal S-curve trajectory finds the maximum jerk to obtain the minimum vibration. The robust zero-vibration shaper can suppress multiple modes without an accurate model. The delay of the dynamic zero-vibration shaper is smaller than the existing input shaping techniques. Our analysis is verified both by simulation and experiment with a six degrees-of-freedom commercial industrial robot.

1. Introduction

High speed motion for industrial robots is critical to efficiency in many applications, e.g., spot-welding in automotive industry and pick-and-place in the electronics industry. The trapezoidal velocity profile (TVP) is widely used for industrial robots as it simplifies the problem of online time-optimal trajectory planning [1,2]. However, the second order trajectory cannot be tracked accurately by a simple control scheme, e.g., PD (Proportional- Derivative) control, because the high frequency content in the generated trajectory can excite the unmodeled flexibility of the robot, especially, the modes associated with joint elasticity [3–6]. A number of research papers have addressed this issue and the work can be categorized in two separate groups. The first group focuses on improving the "trajectory" such that it does not excite the flexible modes, resulting in a good tracking performance even with a simple PD controller. The other group focuses on the "input" or the torque command in the control loop such that the robot can follow an arbitrary reference trajectory. In robotics research, in many cases these efforts are independent to each other due to the structure of industrial robot control systems, which are, in general, decomposed into "planning" and "control" components to maximize their utility over a range of robot platforms. In practice, combining the two components can lead to a high cost design for the motion control system for industrial robots since it will require the repeated solution of complex robot dynamics at each control cycle for both planning and control. In general, this is not feasible for a low-cost generic robot controller. By modularizing the design, planning can be done ahead of time and the dynamics can be solved only once at each control cycle, e.g., for feedforward control, gain-scheduling, visual-servoing, or force control [7,8]. In this document, we refer to the former group as *the planning approach* whereas the latter group is referred to *the control approach.*

In the planning approach, two research topics have received much attention, namely, the smooth trajectory planning and the input shaping technique (IST). In general, the former aims to generate a third order trajectory by limiting the jerk [9–14]. It has been shown that the jerk limitation can achieve smooth transitions at switching instances, resulting in a fast settling time and a better tracking performance compared with the TVP trajectories whose jerks are infinite [6]. The IST is a filtering technique that is originally proposed for an LTI (Linear-Time-Invariant) system [17]. Recently, it was shown that the IST can be applied for a time-varying system with multiple modes [18] such as industrial robots [15,19]. In [15], the IST is combined with the iterative learning scheme. However, this method requires additional sensor on the tip of the robot. In [16], a linear system identification method is utilized to design the outer-control law to suppress the vibration of the tip of the robot. It is known that the IST has a short time delay compared with other smoothing methods [20]. In general, the planning approach is much easier to implement compared with the control approach as it can be used with a generic controller. However, the methods are not robust against model uncertainty because it is purely a feedforward approach.

In the control approach, a nonlinear multivariable control based on the flexible joint dynamic model has received much interest. Some of well-known achievements in this group include feedforward control

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[21], feedback linearization [22], singular perturbation control [23], and passivity-based control [24]. In theory, the control approach is more appealing as it does not assume a specific type of robot trajectory. However, one significant challenge of the control approach is that it is often not possible to implement such advanced control algorithms in the existing controller due the limitation of achievable sampling rate, sensor requirements, and the control structures [25].

Although many important results have been achieved by both approaches, an important question that has not yet been addressed is "What is the best motion performance that can be achieved by the planning approach alone and how good the performance would be compared with the control approach for industrial robots?" This issue is important as the control approach requires a significant modification of the existing control hardware and software. However, it is difficult to find the answer in the literature as the two approaches have been pursued separately using different test platforms. In addition, the existing methods in the planning approach need to be improved as they are typically designed for systems that are much simpler than industrial robots, which are nonlinear and multivariable with position-dependent inertia. In particular, the followings are still open questions when the planning approach is applied to industrial robots.

- What is the optimal jerk of the S-curve trajectory such that the vibration is minimized?
- How can the IST address the time-varying multiple modes without an accurate dynamic model?
- Is it possible to further reduce the time delay of the IST?

In this paper, we attempt to answer the above questions. To this end, we propose several methods to improve the planning approach. The proposed methods are then compared with the control approach. Our particular attention is given to preshaping a trapezoidal velocity profile as it is widely used for industrial robots. In Fig. 1, the six degrees-of-freedom (DOF) articulated robot considered in this paper is shown. As typical with industrial robots it exhibits highly nonlinear dynamics and the joint elasticity is significant due to the non-rigid gearboxes mounted on the joints [26]. We assume that the robot is controlled by an industrial controller with the control loop designed with a

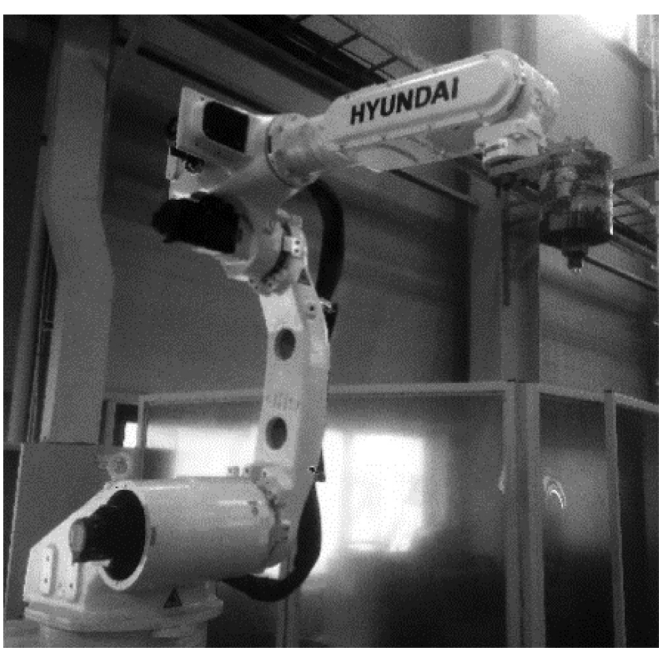
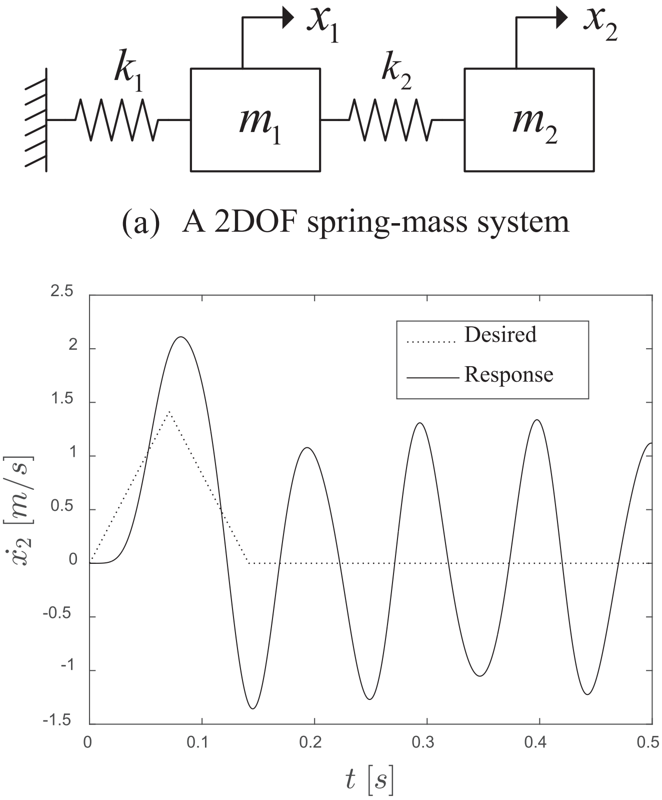


Fig. 1. HA006B (Hyundai industrial robot, DOF: 6, maximum payload: 6 kg, gearboxes of main axes: Nabtesco™ RV series, http://www.hyundai-robotics.com/robot/robot01.asp).



(a) A 2DOF spring-mass system

(b) Response to a TVP trajectory

Fig. 2. Illustrative simulation result for a 2DOF robot ($m_1 = 53.188\,kg$ $m_2 = 12\,kg$, $k_1 = 300\,kNm/m$, $k_2 = 100\,kN/m$, natural frequency: 10 Hz, 17.366 Hz, initial position: $x_1 = 0$, $x_2 = 0$, final position: $x_1 = 0.1\,m$, $x_2 = 0.1\,m$).

computed torque control (PD control and feedforward control based on a rigid model). In Fig. 2, the problem that we address in this paper is described in an illustrative example for a simplified robot modeled as a 2DOF spring-mass (lightly damped) system. As shown in the figure, the robot generates a significant vibration when the TVP trajectory is applied. The main goal of this paper is to develop methods that preshape the TVP trajectory such that a 6DOF robot (Fig. 1) generates minimum vibrations at trajectory endpoints.

The main contributions of the paper are as follows. The proposed smoothing technique finds the optimal jerk that can be used to generate a 3rd order trajectory from the original TVP trajectory (*optimal S-curve trajectory*). We show that the jerk period must be selected as the largest natural period of the robot to generate minimum vibrations. By applying this technique, one no longer needs to find some "optimal" jerk by trial-and-error, as previously described in the literature [6,10–13]. This result is similar to the work presented in [14], which arrived the same conclusion on the jerk selection. However, the work in [14] is derived from a single DOF mass-spring system, whereas a multiple DOF nonlinear dynamics that is more suitable for representing a typical industrial robot is considered in this paper. The second method is developed based on the traditional zero-vibration (ZV) shaper. The ZV shaper requires that all natural frequencies of a robot be known precisely, which is difficult to achieve in reality due to the complexity of robot dynamics and model uncertainty. The proposed filter, referred to as *the robust zero-vibration (rZV) shaper*, combines the ZV shaper and the simple moving average (SMA) filter. This simple combination results in a very robust filter that can suppress a wide range of frequencies, effectively addressing all vibration modes without an accurate model. The last method is referred to as *the dynamic zero-vibration (dZV) shaper*, which is derived from the work in the control approach [21]. The