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Short Communication

A practically efficient method for motion control based on asymmetric velocity profile ☆

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ABSTRACT

In this paper, a practically efficient method to achieve the desirable motion behaviors is proposed and validated by introducing the asymmetricity to the conventional *S*-curve velocity profile. The proposed asymmetric *S*-curve profile allows the manipulation of jerk magnitude at the deceleration period by a single parameter so that the residual vibration or the maximum acceleration can be easily managed. The prospective of the proposed method will be demonstrated by the experiments.

1. Introduction

The generation of motion profiles has been one of the important issues in the motion control area for automated manufacturing machinery or robots. For example, the equipments for semi-conductor manufacturing require the motion highly accurate, fast and smooth for high productivity and quality production. Unfortunately, however, the fast motion generically conflicts to the smoothness of motion due to the residual vibration. To make the motion fast, it is necessary to control rapid increment or decrement of acceleration, which would cause high jerks and, so thus, the residual vibration. Therefore, the trade-off between the speed of motion and the vibration reduction has been one of the difficult tasks in motion planning.

One of the easiest ways in view of practical implementation is to use the trapezoidal velocity profile. However, it has been known that the profile may show higher residual vibration after the completion of motion than the symmetric *S*-curve does. The symmetric *S*-curve profile has been widely investigated and adopted for motion control in literature and in practice as well [5,6]. Chen and Lee [1] proposed a smooth profile using digital FIR filter and applied the algorithm to enhance the accuracy of an $X-Y$ table. Erkokmaz and Altintas [2] developed a trajectory generation algorithm to satisfy the additional jerk limitation based on the quintic spline interpolation for fast CNC systems. Hong and Chang [4] proposed an algorithm using the buffered digital differential analyzer and applied it to an electrical discharge machining (EDM) device for machining parametric curvature. Meckl and Arestides [5] optimized the parameters of the *S*-curve profile to minimize the residual vibration. Also, Zanasi et al. [10] proposed a nonlinear filter satisfying the velocity and acceleration constraints for achieving the smooth motion. In addition, it is known that the residual vibration can be effectively reduced by combining the *input-shaping* technique with the predetermined velocity profile when the system is exactly identified [8].

Apart from most of the symmetric *S*-curve based approaches, the idea to use an asymmetric *S*-curve was presented by Tsay and Lin [9], and by Rew and Kim [7] to reduce the residual vibration. Motivated by [9,7], in this paper, a practical method for generating the asymmetric velocity profiles governed by a single design parameter is proposed, which allows the easy motion adjustment in practice. It is noted that the exact system identification or determining many of design parameters are not preferable in case of *actual* field applications. To resolve this, a scale parameter relevant to the jerk and the jerk period during the deceleration phase is introduced, which causes the asymmetricity as shown in

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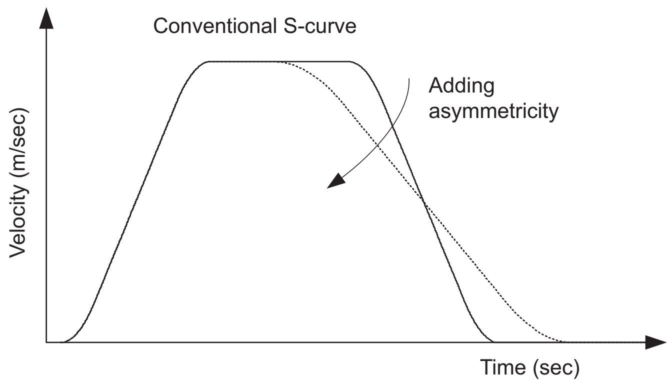

Fig. 1. A concept of asymmetric *S*-curve.

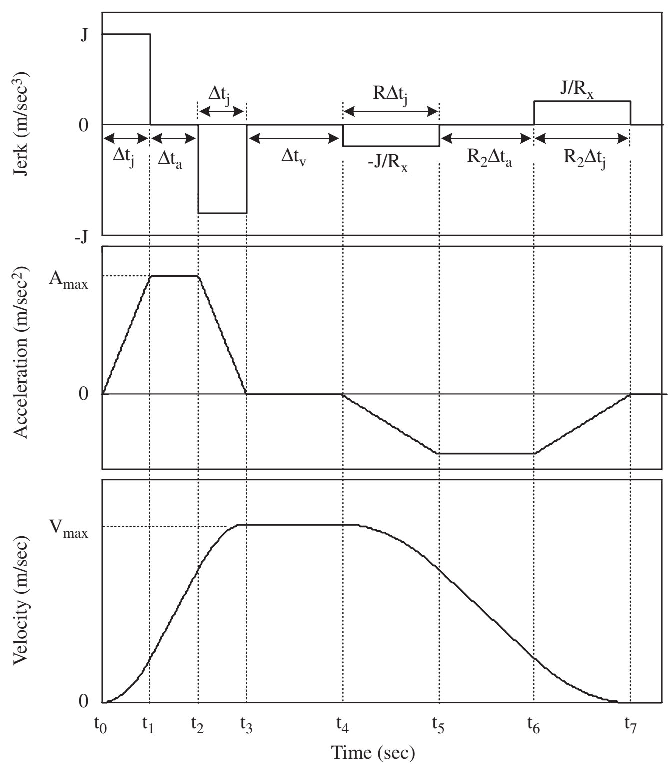

Fig. 2. Generation of asymmetric *S*-curve.

Fig. 1. Fortunately, the idea leads to a closed form solution for the asymmetric velocity profile, which enables the immediate generation of motion profiles without involving complicated calculations. Through the experiments, the practical advantage of the proposed approach will be shown.

2. Deriving asymmetric *S*-curve profile

In this section, the velocity profile depicted in Fig. 2 is derived. Suppose that the total distance to move is given by $\delta(t_7) = \delta_{target}$, and, the jerk is chosen as follows:

$$J \triangleq \frac{A_{max}^2}{\beta V_{max}} \quad (0 < \beta \leqslant 1), \tag{1}$$

where V_{max} and A_{max} are the maximum velocity and the maximum acceleration limited by the motor specification. Note that the jerk magnitude can be arbitrarily selected by choosing a β within physical limitations. However, if $\beta > 1$, the motion cannot be achieved along with V_{max} since the jerk is too small, which will be clear later on.

Now, consider a design parameter for asymmetricity, R_2, which is the ratio of the arrival jerk time (i.e., $t_5 - t_4$) to the start jerk time (i.e., $\Delta t_j = t_1 - t_0$). Also, the scale factor R_x is introduced. If the *jerk period ratio* R_2 is greater than 1, then, the jerk during the deceleration period would be smaller than that of the acceleration period, which implies that the scales R_2 and R_x are not independent of each other. In the following, the asymmetric velocity profile in each of the time periods will be derived.

Period $[t_0, t_1]$: For the relative time variable $t \in [0, \Delta t_j]$, since $a(t) = (A_{max}/\Delta t_j)t$, it holds that

$$v(t) = \frac{A_{max}}{2\Delta t_j} t^2. \tag{2}$$

Period $[t_1, t_2]$: For $t \in [0, \Delta t_a]$, since $a(t) = A_{max}$ and $v(t_1) = \frac{1}{2} A_{max} \Delta t_j$, it can be seen that

$$v(t) = A_{max} t + \frac{A_{max}}{2} \Delta t_j. \tag{3}$$

Period $[t_2, t_3]$: For $t \in [0, \Delta t_j]$, one may show that

$$v(t) = A_{max}\left(-\frac{1}{2\Delta t_j} t^2 + t + \Delta t_a + \frac{\Delta t_j}{2}\right). \tag{4}$$

Period $[t_3, t_4]$: For $t \in [0, \Delta t_v]$, since $a(t) = 0$, it holds that

$$v(t) = v(t_3) = A_{max}(\Delta t_a + \Delta t_j). \tag{5}$$

Period $[t_4, t_5]$: For $t \in [0, R_2 \Delta t_j]$, since $a(t) = -(J/R_x)t = -(A_{max}/R_x \Delta t_j)t$, it follows that

$$v(t) = -\frac{A_{max}}{2R_x \Delta t_j} t^2 + A_{max}(\Delta t_a + \Delta t_j). \tag{6}$$

Period $[t_5, t_6]$: For $t \in [0, R_2 \Delta t_a]$, since $a(t) = a(t_5) = -R_2 A_{max}/R_x$, one may have

$$v(t) = A_{max}\left\{-\frac{R_2}{R_x} t + \Delta t_a + \left(1 - \frac{R_2^2}{2R_x}\right)\Delta t_j\right\}. \tag{7}$$

Period $[t_6, t_7]$: for $t \in [0, R_2 \Delta t_j]$, using that $v(t_6) = (1 - (R_2^2/R_x))\Delta t_a + (1 - (R_2^2/2R_x))\Delta t_j$, one may show that

$$v(t) = \frac{A_{max}}{2R_x \Delta t_j} t^2 - \frac{R_2 A_{max}}{R_x} t + v(t_6), \tag{8}$$

which gives

$$v(t_7) = A_{max}\left(1 - \frac{R_2^2}{R_x}\right)(\Delta t_a + \Delta t_j). \tag{9}$$

Then, it should hold that $R_x = R_2^2$ for $v(t_7) = 0$, which is the key result of the proposed approach. As a result, all the velocity profiles are summarized in Table 1.

Now, the motion parameters such as Δt_j, Δt_a and Δt_v should be determined. Since $A_{max} = J\Delta t_j$ from Fig. 2, it is obtained that

$$\Delta t_j = \frac{A_{max}}{J} = \beta \frac{V_{max}}{A_{max}}. \tag{10}$$

Also, since $V_{max} = A_{max}(\Delta t_a + \Delta t_j)$ from (5), it follows that

$$\Delta t_a = (1 - \beta)\frac{V_{max}}{A_{max}}. \tag{11}$$

It can be seen that β has the role to distribute the time periods between Δt_j and Δt_a. In addition, if $\beta > 1$, Eq. (11) does not hold, which implies that V_{max} cannot be achieved with the small jerk value.

With the parameters Δt_j and Δt_a, the total distance would be represented as follows:

$$\delta = \delta_p^* + V_{max} \Delta t_v$$