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Machine Learning Based Optimal Acceleration/Deceleration Design for a 3-UPU Type Parallel Kinematic Mechanism

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Since large acceleration and deceleration could undermine the machining accuracy and cause machinery damage, an interpolator that plans the motion of the system and a controller that maneuvers the motion are included in a CNC system. Many studies have been focusing on the effects of motion profile on machinestability, but few consider the physical limitation of the machine.In this study, a machine learning based interpolator that plans the motion profile of a pre-determined path of the end effector is proposed for a 3-UPU type Parallel Kinematic Mechanism (PKM). First, a trapezoidal motion profile is created to provide the velocity-ramps at two ends. A kinetostatic model that considers the external loadings exerted at the end-effector, the equivalent inertiaforces of the components, the specifications of motors and ball screws, as well as the gravitational effect, are employed to verify the maximum loadings of the joints and define the maximum allowable acceleration of the end-effector. The resulting maximum accelerations in the task space were mapped into the joint space to obtain the allowable jerk constraints of the individual length-varying links in the following optimization algorithm. Then, the interpolator labels the positions on the pre-determined path whose corresponding jerk of the length-varying links exceeds the user-defined limits. A Gaussian-shaped deceleration profile is added to each labeled position that serves as the basis of the path profile. Accordingly, a machinelearningmodel that optimizes the motion profiles by Adam algorithm with PyTorch is developed. The objective of the loss function is to search for the shortest processing time within the user-defined limit for the jerk of the length-varying limbs by adjusting the parameters of the Gaussian profiles. Three illustrative examples in different paths and with jerk limits between $1500\text{mm}/s^3$ *to* $5500\text{mm}/s^3$ *were studied to verify the proposed interpolator of a 3-UPU PKM.In conclusion, the proposed machine learning based interpolator that accounts for the constraints and the motions of both the end-effector and the actuatorsprovides a possible precursor for the development of a cyber-physical system.*

NOMENCLATURE

$\vec{r}(s)$ =parametric curve
A =jerk peak value
σ = width of jerk peak
k= number of jerk peaks
$g.a.p.$= Gaussian amplitude pre-factor
L = loss function
N =total number of line segments
w =weighting factor

1. Introduction

With the trend of Industry 4.0, the cooperation between software and hardware are emphasized to fully utilize the production capacity of a machine tool.Moreover, due to highly coupling between limbs in a parallel kinematic mechanism, interpolator that considers only the end-effector cannot function efficiently.In a CNC controller, the CAM processing code is translated into the format of controller through the interpreter, then the acceleration and deceleration planning and the motion command of each axis are generated through the interpolator. The machine tool is therefore actuated according to the transmitted command.The acceleration and deceleration planning has significantinfluence on the overall machining accuracy and machining time. An appropriate and smooth motion planning can effectively reduce machining errors, improve machining efficiency, and extend machine life.

Goldber [1] developed the Omative system with the concept of green machining, emphasizing that proper acceleration and deceleration planning can not only maintain/increase machining accuracy, but also effectively improve productivity and enhance energy efficiency. Common acceleration and deceleration plans can be divided into several types according to their speed curves, such astrapezoid, bell, S-shaped, etc. Different types of acceleration and deceleration will inducedifferent effects on the machines [2]. Martínez analyzed trapezoidal and S-shaped acceleration and deceleration curves [3].The resultsshowedthat the trapezoidal curve is suitable for rapid machining with low precision requirements; on the contrary, the S-shaped curve leads to longer processing time but less overall vibration.Meckl and Arestides conducted an optimization study on the S-shaped acceleration and deceleration curve to minimize machine vibration [4]. However, due to the large amount of calculation and complexity of the S-shaped curve, powerful hardware equipment is required. To solve this problem, Haoproposed an equivalent trapezoidal acceleration and deceleration control algorithm [5]. Zheng and Chengapplied the look-ahead method for pre-interpolation, as well as an adaptive S-curve that effectively improve the work efficiency and the dynamic performance of the machine [6].

In fact, motion profiles such as trapezoidal and S-curve are unable to limit the jerk of each limbs for parallel kinematic mechanisms.Besides, complex algorithms that demands for additional computing time andspaceshould be avoid. In this paper, the notion of Gaussian-shaped profiles is introduced to achieve a compromise between the confining values of the jerk in the joint space and the reduction in the moving time for the whole task path. Moreover, the capability of the driving system, as well as the payload limitation of the mechanism joints, are considered. A machine learning based interpolator is then simulated by taking a 3-UPU type PKM as an illustrative example. The proposed approach is verified to effectively suppress the jerk of the actuator output and shorten the moving time of the end-effector.

2. Interpolator Design

Fig. 1 illustrates the design procedure of the proposed interpolator. First, to provide optimal motion profile for a 3-UPU type parallel mechanism, a properly up-sampled parametric curve$\vec{r}(s)$that contains the end effector position information is introduced.Next, the trapezoidal motion profile for $\vec{r}(s)$ as the data preprocessing before optimizing the acceleration and deceleration are planned. Then, themovingtime corresponding to the assigned path is given by the trapezoidal motion profile where the speed at the beginning and the end of the motion is zero. The motion profile must conform to the limit acceleration of the machine and the acceleration/deceleration-terminal speed time ratio set by the user. In this paper,akinetostatic model that considers the external loadings exerted at the end-effector, the equivalent inertia forces of the components, the specifications of motors and ball screws, and the gravitational effect, are applied to define the maximum allowable acceleration of the end-effector.The resulting maximum accelerations in the task space were mapped into the joint space to obtain the allowable jerk constraints for each limb. The peaks of the limbs' jerk that exceeded the user-defined jerk limit (assuming there are k peaks) are then labeledfor adoptingGaussian-shaped deceleration profile, the center of each gaussian deceleration profile is the accumulative time up to the center of each peak. The analytical form of the gaussian deceleration profiles and the initial guesses of the parameters are as follows:

$$dt_i{}'^{(n)} = t_{scale}{}^{(n)} dt_i \prod_{k=1}^{K} \left\{ 1 + A_k{}^{(n)} e^{\frac{-\left[\left(\sum_{j=1}^{i} dt_j\right) - \hat{t}_k\right]^2}{2\left[\sigma_k{}^{(n)}\right]^2}} \right\} \tag{1}$$

$$A_k{}^{(0)} = \frac{\log_{jerk\_limit}(1 + |jerk_k|)}{3} \times g.a.p. \tag{2}$$

$$\sigma_k{}^{(0)} = (dt_{i,k\_width}) \times 200 \tag{3}$$

where $t_{scale}{}^{(n)}$ is a parameter that scales the overall motion profile. It is set to 1 initially. The profile is then optimized by adjusting A_k and σ_k in the Gaussian function. The initial guess of each $A_k$scales with the logarithm of the peak value with a base of the jerk limit; the initial guess of each σ_k scales with the width of each peak.The superscript (n) indicates the n-th iteration. $dt_i$is the i-th time segment for the trapezoid motion profile after pre-processing. $dt_i{}'^{(n)}$ is the i-th segment after gaussian deceleration. $A_k{}^{(0)}$ is the initial guess for A_k; the scaling factor 1/3 results from an observation that the 3 limbs usually have peaks of jerk at the same time index; Gaussian amplitude pre-factor $(g.a.p.)$ is a hyperparameter that scales the initial depth of the each gaussian profile;$\sigma_k{}^{(0)}$ is the initial guess of the standard deviation of each gaussian profile. dt_{i,k_width} is the width of the peak that exceeded the jerk limit. A scaling factor was empirically set to 200.

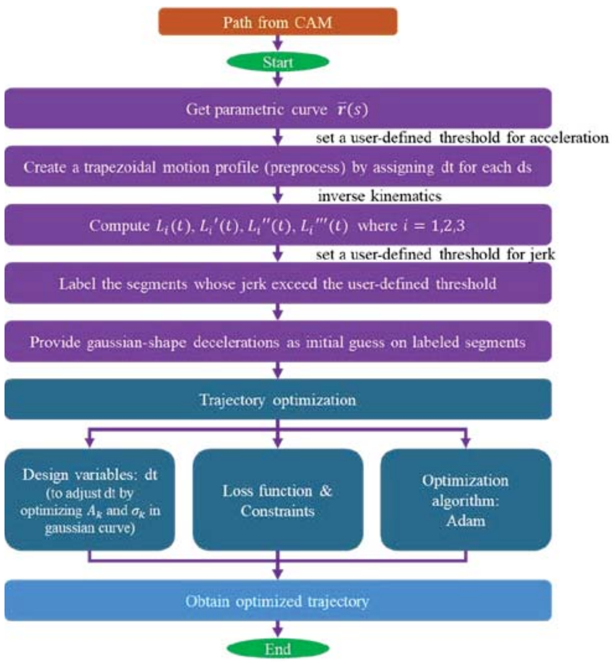

Fig. 1 Motion Profile Optimization Flowchart

The machine-learningmodel willcalculate iteratively according to the Adam algorithm with PyTorchuntil loss function converges, outputs the optimized motion profile for each limb.The optimization flowchart is shown in Fig. 1. The designed loss function is considered as

$$L = w \times \frac{\sum_{i=1}^{N} {jerk_i^{(n)}}^2}{\sum_{i=1}^{N} {jerk_i^{(0)}}^2} + (1 - w) \times {t_{scale}}^2 \qquad (4)$$

$$w = \frac{1}{1 + e^{-(max\_jerk^{(n)} - 0.95 * jerk\_limit)}} \qquad (5)$$

where N is the total number of line segments (ds);${jerk_i^{(n)}}^2$is the square of the jerk of three limbs in the *i*-th time periodof the *n*-th iteration; w is the weighting factor.

3. Simulation Results

Different from traditional pre-interpolation and post-interpolation, this study considers the motion behavior of the end effector and actuators at the same time when planning the acceleration and deceleration of the system, so that the optimized motion profile of the end effector can be smooth and continuous. Furthermore, the maximum jerk generated by the drive end does not exceed the limit set by the user.To verify the proposed interpolator, three illustrative examples in different test paths are shown in Fig. 2, with jerk limits between $1500 \mathrm{mm}/s^3$to $5500 \mathrm{mm}/s^3$. Note that path A refers to the test path of the Omative systemon the y=0 plane; path B is a curve with large turning angle on the z=50 mm plane; path C is a closed curve inclined in the workspace.

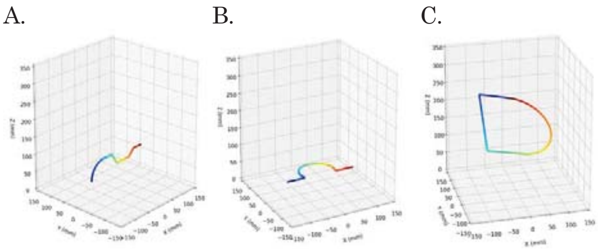

Fig. 2Test paths A, B, and C adopted in the illustrative examples.

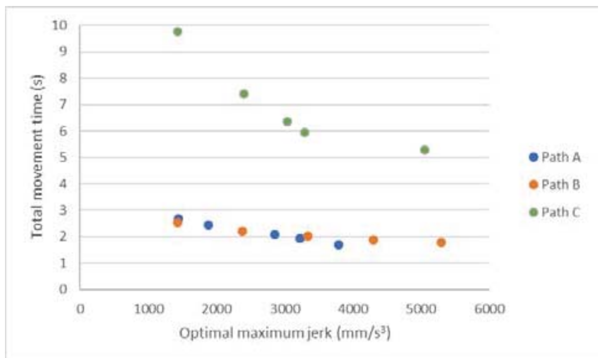

Fig. 3 Optimal Maximum Jerk and Total Movement Time with jerk limits between $1500 \mathrm{mm}/s^3$to $5500 \mathrm{mm}/s^3$of A, B, C test paths

As shownin Fig. 3, optimal solutions with jerk value between $1500 \mathrm{mm}/s^3$to $5500 \mathrm{mm}/s^3$are found. As the jerk limit value given by the user increases, the total movement time of test path A can be reduced from 3.08 seconds to 1.69 seconds; the total movement time of test path B can be reduced from 2.53 seconds to 1.79 seconds; The total movement time can be reduced from 9.77 seconds to 5.28 seconds. In jerk limit $5500 \mathrm{mm}/s^3$,the optimal motion profiles for 3-UPU type parallel mechanism in three paths are shown in Figs. 4-6.

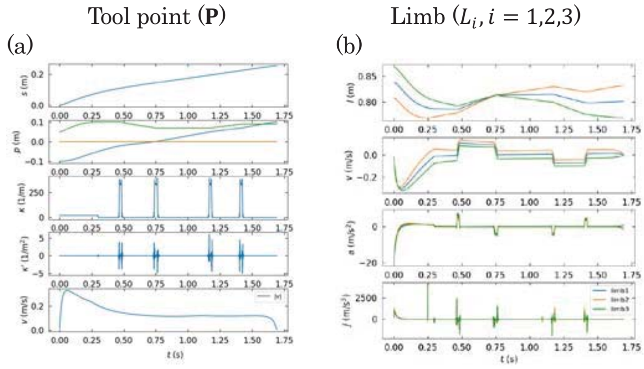

Fig. 4Optimized motion profile for path A in jerk limit $5500 \mathrm{mm}/s^3$

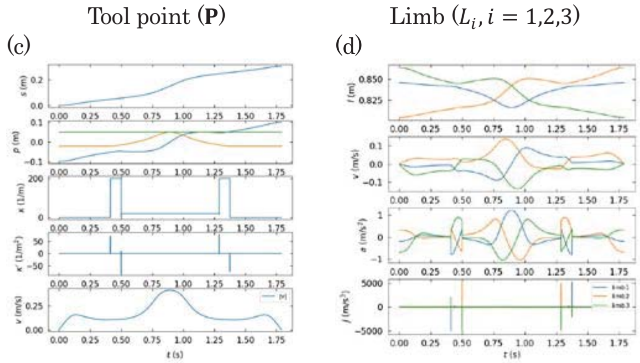

Fig. 5Optimized motion profile for path B in jerk limit $5500 \mathrm{mm}/s^3$

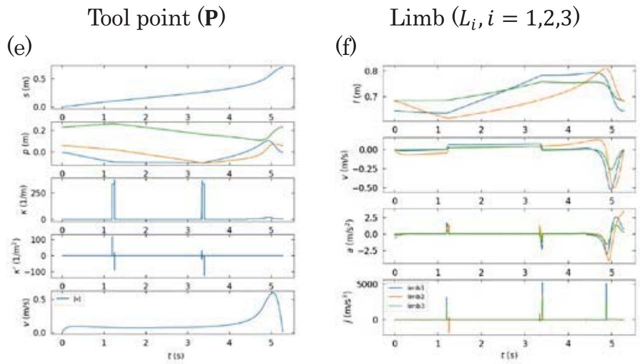

Fig. 6Optimized motion profile for path C in jerk limit $5500 \mathrm{mm}/s^3$

4. Conclusions

An interpolatorfor a 3-UPU PKM is proposed to fully utilize the production capacity of this machine tool. Akineostatic model is employedin this paper to provide the maximum acceleration of the end-effector that serves as the constraints of the optimal design.In the pre-processing of optimization, a trapezoidal motion profile is planned so that the speed at the beginning and the end of the path are both zero, and the jerk spike caused by the acceleration change are labeled and decelerated by a Gaussian curve, by adjusting A_k and $\sigma_k$in the Gaussian function to maintain the continuity of the motion profile.The results shown that if this mechanism enables to withstand larger acceleration and deceleration, the overall movement time can be greatly accelerated. Furthermore, this proposed approach is verified to effectively suppress the jerk of the actuator output and shorten the moving time of the end-effector.

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