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Vibration Measurement, Analysis and Dynamic Parameter Optimization for Delta Robot

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Abstract— **Delta robots have been widely used in many manufacturing applications because of their high velocity and acceleration. Vibrations are one of the obstacles blocking them from further releasing all of their performance. Existing solutions include inserting a wait time between cycles, programming with smoother trajectory, introducing damp and limiting the jerk, even integrating compensation mechanisms. However, due to the lack of accurate robot-environment vibration model, typically those dynamic parameters are set empirically. Furthermore, the vibration of robot base/frame is not considered in the current literature. In this paper, an optimization procedure is proposed to solve the dynamic parameter tuning problem. An overlap based pick and place door shape trajectory generation method and jerk limited acceleration profile are used to generate smooth motion. By directly executing the pick and place motion with candidate parameters and measuring the vibration a comprehensive analysis and grid based constraint optimization can be performed to find the optimal dynamic parameters. The whole tuning technique is performed without modifying the existing hardware and software and it can be implemented with different smooth motion generation methods. The experimental results show the effectiveness of the proposed methodology.**

I. Introduction

Industrial robots are usually designed with very high stiffness, speed and repeatability. Consequently, when the robot moves with high speed and acceleration, a big reaction force will be imposed on the mounting base/frame, i.e., the base/frame will be forced to vibrate. Vibrations are undesired phenomena existed in mechanical system with structural elasticity. The primary reason for vibration is the robot moves along a trajectory with discontinuous acceleration profile. Because the robot is tight to the base/frame, the vibration can also be transmitted to the robot itself. When the robot moves cyclicly, the vibration may superimposed together and cause undesired effect such as noise, position error, mechanical failure, shorter lifetime.

As shown in Figure 1, Delta robot is a 3/4 Degree-of-Freedoms(DOFs) lightweight parallel robot built using parallelogram mechanisms [1]. It has three kinematic chains and can move swiftly in three dimensional space(Clavel, 1988) [2], [3]. Because the moving mechanisms are usually made by light weight materials such as aluminum or carbon fiber, the Delta robot has very small moment of inertia and can moves very fast and execute the picking cycles at up to 300 cycles per minute.

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Although they are specifically designed for the pick-and-place task, they are more and more involved in new applications within domains such as assembly, material handling, machining, packaging and screening. Usually it is mounted on a frame or a cantilever to operate workpiece from top to bottom. Although lightweight in mass and small in inertia, it can still generate huge reaction force because of its excellent acceleration performance. Moreover, center of mass of the frame is typically higher than base of the serial robots, therefore, Delta robot also suffers from the vibrations that can decrease the accuracy and performance considerably.

The position accuracy of end-effector is an important index for evaluating the performance of parallel robot. Most of the existing research works focuses on how to improve the end effector accuracy in the robot base coordinate frame [4].

Zhang [5] and Wang [6] studied the trajectory planning and optimization method to obtain smoother and more efficient trajectories for Delta robot. Smoother motion can reduce the vibration and improve the reliability and stability [7]. Kuo built dynamic model for Delta robot with flexible links and performed natural frequency analysis and convergence analysis. Link flexibility is a major reason for delta robot vibration, therefore, two smooth paths were specifically designed for circular motion and pick-to-place motion.

van der Wijk proposed to use additional mechanisms to balance the vibration. A specific architecture is designed, hence the Delta robot can be force balanced with only three counter-masses and two additional links. Moment balancing can be achieved by active actuation of three additional rotating inertias [8]. Courteille [9] proposed a method for the design optimization of a Delta-like robot manipulator with respect to multiple global stiffness objectives. This can reduce the structural elastic deformation and improve both accuracy and payload performances. Li [10] studied optimization technique for the robot manipulator parameter identification problem to overcome the parameter uncertainties brought by manufacturing and assembly process. Besides the trajectory, damping, acceleration profile and jerk profile are also very important factors causing vibration. [11], [12], [13] studied trajectory generation problem with jerk constraints.

Other research works focues on the kinematic calibration problem [14]–[16] and control problem [17].

The Delta robot's static base is connected to the ground through robot frame. When the robot performs high speed cyclic motion, the inertial force applies impulse to the robot frame and causes significant vibration. However, this external vibration was not considered in the current literature. Frame

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vibration only affects the dynamic performance in cyclic motion situation. Although including a mount of waiting time can reduce the vibration, it will affect the efficiency.

Our main objective is to find feasible solutions to reduce vibration, keeping efficient and without modifying the hardware design and existing software architecture.

The remaining paper is organized as follows. The dynamic parameter tuning problem for Delta robot pick and place motion is introduced and formulated in Section II. The proposed solution, including the vibration measurement platform, signal acquisition and processing is presented in Section III. The experimental platform, results and discussion are given in Section IV.

II. Problem Formulation

A. The Delta Robot

Different from the serial robot manipulator, a parallel robot usually have multiple kinematic chains connecting the robot base and the end effector. Different chain mechanisms and configurations can generate different parallel robots.

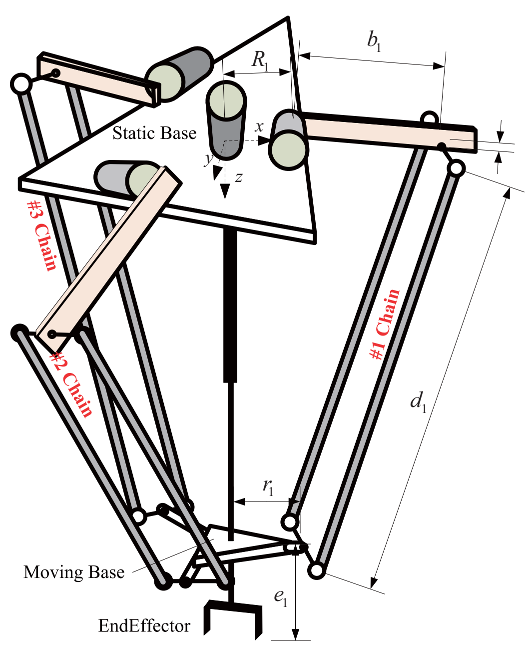

Fig. 1. Diagram of the Delta Robot with additional Rotation DOF

The Delta parallel robot was firstly invented by Prof. Reymond Clavel in 1980s. The main concept is using parallelogram mechanism for each kinematic chain. The upper end of parallelogram mechanism is connected to the drive link and then the motor through revolute joints. The lower end is connected to a small moving platform. Three of this chains are integrated together symmetrically (120° interval) to form a stable mechanism. Because of the parallelogram mechanisms, the base and the end effector are always parallel with each other and can only generate pure translational movement in x-, y-, and z-direction. Usually 1-3 additional rotation DOFs are integrated to standard Delta structure to make it more useful in different applications. The structure of Delta parallel robot with one rotation DOF is shown in Figure 1.

All the actuators and gearboxes can be mounted on the fixed base and all the moving parts can be made with light weight materials such as aluminum and carbon fiber. Therefore, the Delta robot can achieve very high speed and accelerations. Typical commercial Delta robot can complete the Pick-and-Place Tasks 120 times per minute and even 300.

Key parameters of the Delta robot are marked in Figure 1. They are the static platform radius(R_i), input link length(b_i), shaft offset(c_i), output link length(d_i), moving platform radius(r_i) and end effector offset e_i, where $i = 1,2,3$ refers to the chain numbers.

B. Pick and Place Motion

Figure 2 shows a typical pick-and-place trajectory for delta robot. It is a door shape trajectory consisted of one horizontal movement and two up-down movements. The Z_{max} is a preset vertical height value and Z_{trig} is predefined position for waiting for the next task.

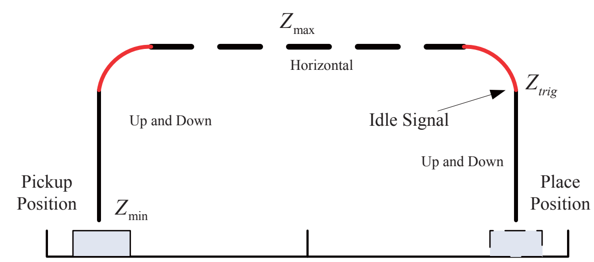

Fig. 2. The robot door shape pick and place motion trajectory. trajectory

There are a lot of methods to generate such door shape trajectory. The commonly used are lamé curve, polynomial curve or 5-Segments curve(as shown in Figure 2) [18], [19]. In most applications, the pick-place trajectory varies in each cycle because of the randomly place workpieces. Therefore, different methods may have quite different trajectory planning complexity. In this paper, we use the overlap method to generate the smooth pick and place curve and study the vibration optimization problem.

The concept of overlap is to overlapping the adjacent two linear motions and generating a new smooth transition trajectory. Figure 3 show the overlaping process and the controlling parameter OVL:α.

If $\alpha = 0$, those two linear motion from P0 $\longrightarrow$ P1 and P1 $\longrightarrow$ P2 are separated with their own accelerating and decelerating stages. There will be a complete stop during this movement. If $\alpha > 0$, in the first linear motion, the speed will not decrease to zero. Those two motions have an overlap which makes the transition smoother. If $\alpha = 100$, during the movement, there will be no decelerating and the velocity will remain maximum.

The overlap parameter α has two advantages: smooth the motion and improve the efficiency with the cost of losing trajectory tracking accuracy. However, it is not a problem for pick-and-place tasks because what care most is the accuracy of positions P0 and P3.

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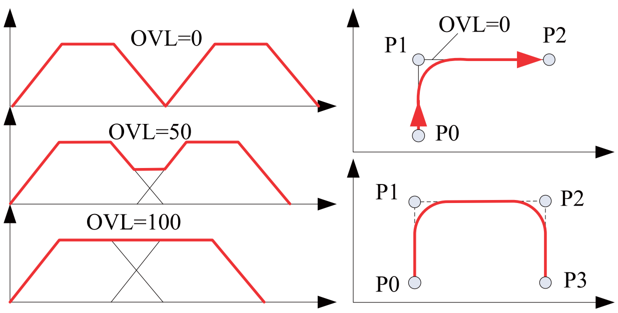

Fig. 3. The trajectory overlapping principle and example

The overlap method reduces the programming difficulty and number of varying parameters. In this paper, it is adopted as the curve generation method. As shown in Figure 3, a complete door-shape trajectory is decided by (P0,P1,P2,P3,α). P1 and P2 are intermediate positions associate with P0 and P3. By selecting appropriate α, the smoothness of the curve can be adjusted.

It is worth to mentioned that the following motion optimization method is not restricted to the overlapping trajectory generation method. it can also applied to other methods such as lamé and polynomial.

C. Acceleration Profile

Beside the pick and place trajectory, another factor affecting the vibration is the acceleration profile, which refers to how the velocity and acceleration changes in the trajectory tracking control process.

The jerk-limited profile is a widespread smooth command pattern used by modern motion systems such as machine-tools and industrial robots. Jerk is time derivative of acceleration. The introduce of jerk can eliminate the discontinuities of acceleration and reduce the residual vibration.

Figure 4 shows an example plot of jerk limited profile. By using the bang-bang control law, a time optimal accelerating trajectory is achieved. The jerk limitation (J_{max}) is the smoothness parameter and empirically selected for reducing vibrations.

As shown in Figure 4, a jerk-limited profile equals to a trapezoidal or a triangular acceleration profile. Such a trajectory can be easily implemented. Because the profile is symmetrical, there are only three time parameters:T_j, T_a, T_v. T_j is the maximum jerk period. T_a is the maximum acceleration period. T_v is the maximum velocity period.

The acceleration profile parameters $J_{max}, A_{max}, V_{max}$ greatly affect the robot motion efficiency and smoothness, i.e. the vibration amplitude and frequency. Therefore, instead of empirically setting those parameters, it is necessary to find an optimal solution for fast and vibration free motion.

D. The Vibration and Error

As shown in Figure 5, a Delta Robot is mostly mounted on a big heavy frame which provide a relatively static basis. A typical frame is 2 meters high and 1.5 meters wide

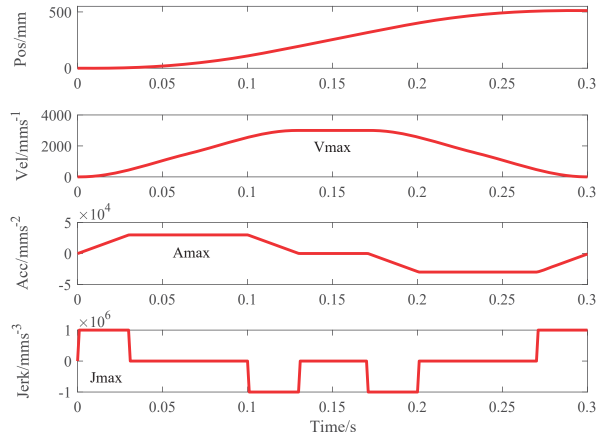

Fig. 4. The Trapezoidal Acceleration Profile

which covers work range of the Delta robot and size of the conveyor. Thick square steels are welded together which make it more than 500 kg.

However, even it is very heavy, when the robot is moving, inertial force and shocks can still cause significant vibration of the robot frame. This vibration cause two problems: Reducing the lifetime of mechanical parts and accuracy of the robot end effector. Because the robot static platform and sometime the industrial camera are mounted on the frame, vibration of frame introduces errors in the transformation matrix of robot base frame and world frame, hence lower the pick or place accuracy.

For economic consideration, it is better to use lighter steels. For precision consideration, it is better to minimize the vibration. As previously mentioned, smoothness of the door shape trajectory and acceleration profile affect the robot and frame vibration, hence, the following sections will discuss methods to solve this problem.

III. Proposed Solution

Since the robot motion and frame vibration are related implicitly, it is hardly possible to find analytical solution. A feasible way is to directly test parameter combinations and evaluate the corresponding vibrations.

A. Vibration Measurement Platform

Vibrations can be measured by several kinds of devices, such as laser tracker, IMU, strain sensor and even radio signals [20]. In this paper, a nine axis IMU module is used to measure the frame vibration. It is an easy to use and low cost IMU device with acceptable speed and precision. The used module is based on the InvenSense MPU9250 chip which consisted of a 3-Axis gyroscope, a 3-Axis accelerometer and a 3-Axis magnetometer. It can be programmed to measure acceleration range from ±2g, ±4g, ±8g, and ±16g.

The vibration measurement platform is shown in Figure 5. Two IMU modules are integrated. #1 is mounted on the robot frame to detect the frame vibration signals and #2 is

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mounted on the moving platform to measure the desired driving acceleration signals. Both sensors transfer the data at 200Hz back to computer through USB-UART interfaces.

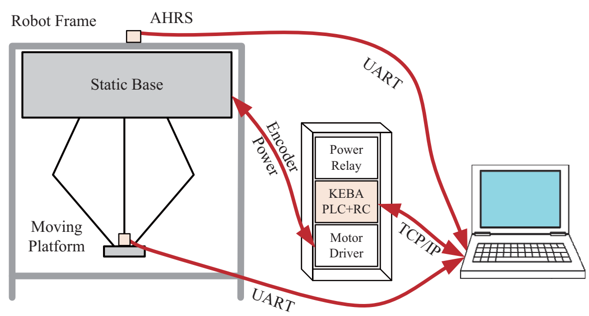

Fig. 5. The Vibration Measurement Platform

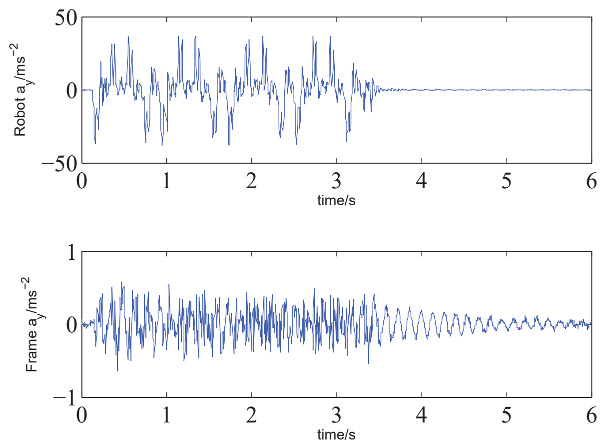

Fig. 7. Typical vibration signals recorded by the IMU sensors. Top: Acceleration of moving platform along Y-axis; Bottom: Frame vibration along Y-axis.

The robot is controlled by a KEBA Motion Controller(CP 263). It is preprogrammed to repeat a pick and place motion with different dynamic parameters, which are sent from the computer through Ethernet interface. In each experiment, the parameters and the corresponding vibration signals are recorded. Figure 6 gives an overall flowchart of the signal acquisition process.

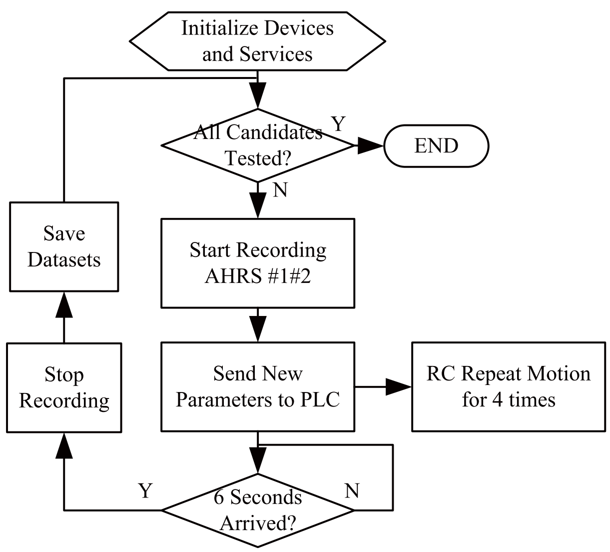

Fig. 6. Flowchart of the vibration signal acquisition process

Figure 7 shows some of the recorded vibration datasets. Each sample lasts for 6 seconds. The top curve is the acceleration profile of the robot's moving platform. The bottom curve is the frame vibration signal. Both signals are in Y-axis, i.e., the main direction of the pick and place motion. From this figure, it is able to identify that the robots perform the pick and place motion for four times. During the motion process, the frame is forced to vibrate and even the robot stops at 3.5s, the frame still vibrate for nearly 3 seconds.

Based on the platform, different dynamic parameter candidates are tested and the vibrations are recorded. The obtained datasets can be used to build the model for optimization. The overall modeling and optimization process is shown in Figure 8.

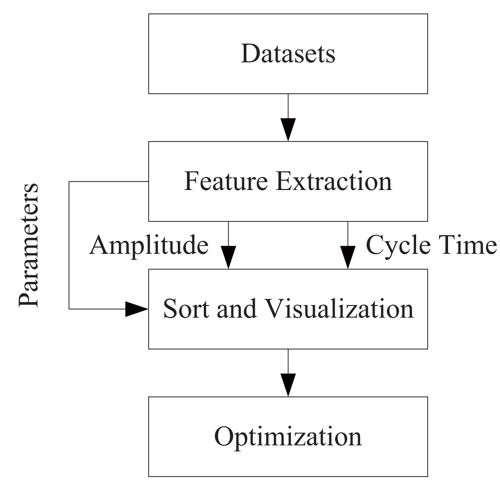

Fig. 8. Flowchart of the signal processing, modeling and optimization process.

B. Signal Processing and Feature Extraction

Performances of the dynamic parameters are evaluated from two aspects: robot motion efficiency and frame vibration amplitude. To formulate an optimization problem, these two aspects should be represented using some measures. In this paper, efficiency is defined using cycle time T. Vibration is defined using maximum acceleration $\hat{a}$ and energy E. All of these indices can be calculated from the datasets.

1) Cycle time: Cycle time T can be measured using to methods. The first one is using $T = 1/f_b$, where f_b can be found by FFT transformation and "findpeaks()" function.

The second one is based on the recorded time series $a(k)$. $a(k)$ is sliced into multiple small segments with a length of

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20(0.1s). By calculating energy level of each segment, it is able to identify whether the robot is moving or staying still. According to the prior knowledge, the robot stays still before new parameters are received. we can find the start time t_s of each movement with the accuracy of ± 0.05s.

Same operation can be used to find the stop time t_e. Cycle time can be calculated by

$$T = t_e - t_s \quad (1)$$

2) Maximum acceleration: This index is used to measure the instantaneous amplitude, it is calculated using $\hat{a} = \max(a(k))$.

IV. Experiments

A. Experimental Platform and Configuration

The experiments are performed on a Delta robot built in our laboratory. The robot is shown in Figure 9. It has three translational DOFs along the XYZ axis. Its physical parameters are listed in TABLE I. The work range is 1000mm. The robot can run at 5m/s with maximum acceleration of 100m/s^2.

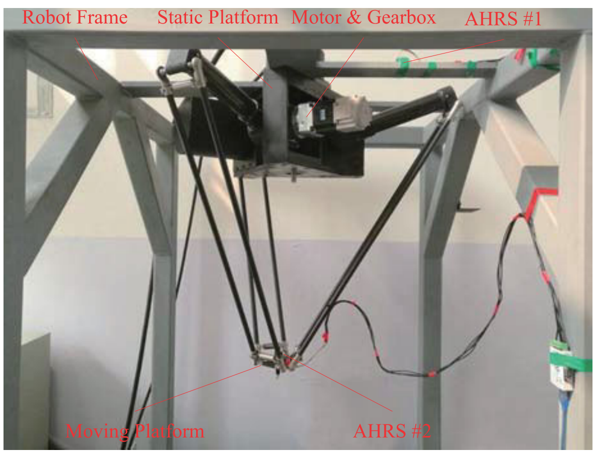

Fig. 9. The robot pick and place motion trajectory

TABLE I
Physical Parameters of the Delta Robot

R_i	b_i	c_i	d_i	e_i	r_i
146mm	343mm	37	953mm	10	47.93mm

The #1 IMU sensor is mounted on the robot frame as shown in Figure 9. It is located between the frame center and the frame boundary. The location is rough because what really matters is the relative amplitude of the vibration. The #2 IMU sensor is attached on the moving platform. Y axis of both sensors are aligned to the Y axis of the robot, which is the primary direction of the pick and place motion.

Dynamic parameters that may affect the motion smoothness and frame vibration are listed in TABLE II. The maximum, minimum and interval of each variable are presented.

TABLE II
Motion related Parameters

	V_{max} (mm/s)	A_{max} (mm/s^2)	J_{max} (mm/s^3)
Min	1000	10000	1000000
Max	5000	90000	25000000
Interval	500	20000	250000

Totally $9 \times 5 \times 7 = 315$ experiments were conducted.

The robot is preprogrammed with a pick and place motion defined by four points P0-P3 as shown in Figure 3. Their coordinates are P0=[0,-150,-960],P0=[0,-150,-860],P0=[0,150,-860],P0=[0,150,-900]. The experiments were performed according to the flowchart shown in Figure 6. In each experiment, the motion is repeated for four times. Each experiment lasts for 6 seconds. Therefore, the overall time is 1890s.

B. Experimental Results

After signal processing, performance indices of all the 315 data sets are extracted. Cycle time T and vibration amplitude a_y are plotted in Figure 10.

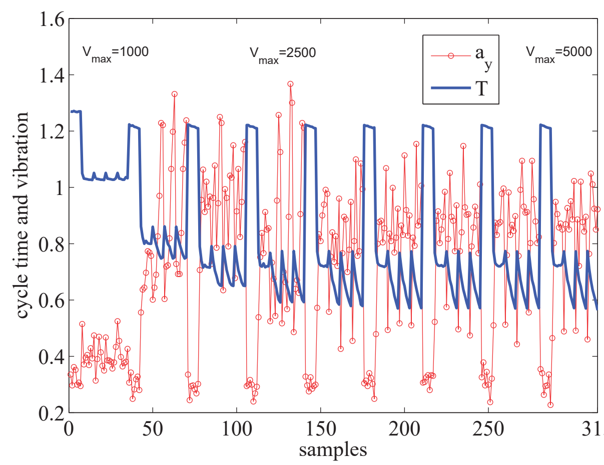

Fig. 10. The processed datasets, including 315 dynamic parameter combinations.

The blue thick line is the cycle time T and the thin line with circle marker is the maximum vibration. According to the experiments order, V_{max} splits all samples into 9 groups and each group contains 35 samples. Then A_{max} splits each group into 5 subgroups. From left to right, all parameters are in ascending order.

Because the designed pick and place trajectory is only 500mm(longer than typical value), the robot has no time to reach the maximum speed before decelerating. From Figure 10, one can find this saturation phenomenon clearly. When $V_{max} \leq 2500$, cycle time decrease when V_{max} increases. When $V_{max} \geq 2500$, the cycle time tends to independent with V_{max}. Same phenomenon also exists on A_{max}.

When both of V_{max} and A_{max} are saturated, only J_{max} influences the system performance. T is inversely proportional to J_{max}, while the vibration is proportional to J_{max}.

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C. Optimal Dynamic Parameters

The goal is to find optimal dynamic parameters that satisfy the efficiency condition and minimize the vibration. Given certain cycle time condition T_d, it is able to split the data set into two subsets(SA:T$\leq T_d$,SB:T¡T_d). Sorting SB according to a_y, one can find the optimal dynamic parameters. The optimal parameters and the corresponding performance indices are listed in Table III.

TABLE III
THE OPTIMIZED DYNAMIC PARAMETERS

T_d/s	V_{max}	A_{max}	J_{max}	T/s	a_y
0.6	3000	50000	2250000	0.59	0.72
0.7	2500	50000	1750000	0.66	0.54
0.8	3000	70000	1000000	0.77	0.43

From the above results, it is able to find that the robot frame vibration indeed can be optimized by choosing proper dynamic parameters, i.e., without redesigning the robot frame and the changing the software architecture. Meanwhile, the proposed vibration measurement method is easy to integrated and the recorded information is adequate to capture all the needed feature.

V. Conclusion

Vibrations are one of the obstacles blocking Delta robot from further releasing all of their performance. This paper discussed the dynamic parameter tuning problem for high speed Delta robots to reduce the frame vibration and improve the efficiency. The frame vibration reduction problem is divided into several aspects: smoothing the trajectory, modifying the acceleration profile, optimizing the dynamic parameters. In this paper, an overlap based door shape pick and place trajectory generation method is used where a parameter α controls the smoothness. A jerk limited trapezoidal acceleration profile is adopted to refine the dynamics where J_{max}, A_{max} and V_{max} are the related dynamic parameters. An IMU vibration measurement platform is developed to record the acceleration when robot execute the pick and place motion with candidate parameters. Cycle time and vibration indices are extracted from each recorded data set. A multiple goal optimization is take out to find the optimal dynamic parameter. The whole tuning technique is performed without modifying the existing hardware and software and it can be implemented with different smooth motion generation methods. The experiments are performed on a commercial Delta robot platform.The experimental results show the effectiveness of the proposed methodology.

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