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Digital twin of dynamic error of a collaborative robot

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Abstract

This paper proposed a new digital twin method to effectively, accurately and in real-time in-situ track machine dynamic error using accelerometer data. The digital twin tracked the positioning data measured by its built-in encoders and superimposes it with displacement data obtained from the accelerometers for more accurate positioning, resulting in micrometre level improvements. In this paper, the digital twin dynamic error tracking approach was implemented on a collaborative robot. Ball-bar tests were conducted to evaluate the effectiveness of the proposed digital twin dynamic error tracking approach. The results show a significantly improved position tracking accuracy of up to 75%, compared with using the collaborative robot's built-in encoders. The digital twin provides a cost-effective solution to track machine dynamic errors. This method could also be expanded to work on other CNC machines and robots, making it a universal solution for improving machine dynamic m easurement accuracy.

Digital twin, dynamic error, COBOT, accelerometer

1. Introduction

Machine dynamic error is defined as the deviation of the actual displacement at the effector end of the motional axis relative to the reference (setpoints) displacement in the feed motion achievable [1]. It is proportional to the increase in feed rate, as acceleration increases during rapid machining causing larger inertia forces. These larger forces cause greater elastic deformation of the machine affecting the end effector/tool positioning. Elastic deformation can happen due to the forces deflecting the beam/support, gears or shafts of the machine. This elastic deformation cannot be directly measured as it is outside of the control loop [2]. Elastic deformation can also lead to vibration within the structure of the machine, resulting in a greater positioning error of the end effector [3][4]. For these reasons, the dynamic error becomes the dominant error source when machining at high speeds [1].

Most modern CNC machines use encoders which are built along the motional axes to track their positioning errors for feedback control. However, these encoders are unable to detect the defection of the machine and dynamic error at the machine end effector which is away from the location of the encoders. In-situ measurement of machine dynamic error in real-time presents a significant knowledge gap and becomes a bottleneck in achieving high machining accuracy when the machine is operating at high speed.

This paper proposes a novel digital twin approach that can effectively and accurately track the dynamic errors of any machines in-situ and in real time. This approach allows more accurate tracking of errors outside the servo loop caused by elastic deformation and vibration of the system using accelerometers. The digital twin dynamic error tracking approach is implemented on a collaborative Robot (COBOT) as its 6 degrees of freedom movement makes position tracking at a high level of accuracy challenging. The effectiveness of the approach is evaluated through a ball-bar test.

This paper is split into four sections. First is the introduction, followed by methodology, which explains how the digital twin is established and works, and the experimental conditions. The third section covers the results and discussions of the study. The fourth section provides key conclusions from the experiment and the effectiveness of this new method of error tracking.

2. Methodology

2.1 Operation of System

In the proposed digital twin tracking approach, accelerometers are used to measure errors that cannot be detected by machine encoders although accelerometers are traditionally used for vibration/chatter [5-7], tool/machine vibration [8, 9], cutting force measurement [10, 11] and fault detection [12]. The accelerometers and positioning data from the encoder are utilized to build a real-time digital twin which can be used to determine the dynamic error which is its deviation from the command position value.

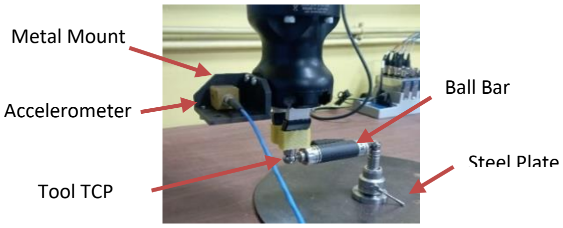

Figure 1 COBOT End Effector Setup

The setup of digital twin tracking system on a collaborative robot (COBOT, UR10e) is shown in Figure 1. Two triaxial accelerometers (PCB model 356B18) having bandwidth of 0.5 to 3000 Hz (±5%) are used in this paper.

One accelerometer was located at the wrist of the COBOT to measure the elastic deformation and vibration, and the second one was placed at the base of the COBOT on the frame. Differentiation of the readings from these two accelerometers allow the influence of background noise to be removed. The accelerometer readings are collected through a data logger (National Instruments cDAQ-9174) to a data card (NI-9234). All readings from the accelerometers are filtered using FFT (Fast Fourier Transformation). The filtered data from the wrist is subtracted by the base to eliminate the effects of external factors. Double integration using cumulative trapezoidal numerical integration is performed to convert the readings into displacement at the TCP (Tool Centre Point) as X, Y and Z deflections. The displacement is then combined with the real-time positioning data to generate a more accurate TCP location. This more accurate location is then fed back to the operator. This allows for vibration and elastic deflection of the arm to be measured and accounted for while in operation with real-time data.

This method uses cartesian positioning data as encoders on COBOT's provided joint angle. The use of a cartesian position allows the system to be universal as the configuration of the machine is irrelevant. The only requirement is that the accelerometer is positioned on the same section as the Tool TCP to minimise errors.

MATLAB was used for data handling and communications and RoboDK software was used for COBOT control. The system connection and data flow are illustrated in Figure 2.

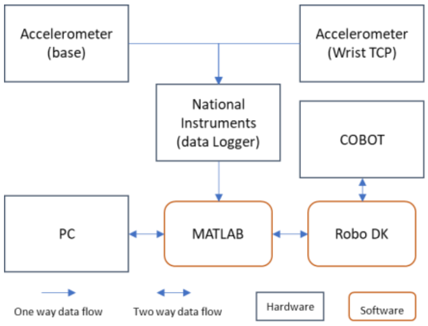

Figure 2 System Connection and Data Flow

When the system is in operation, it will load the necessary toolpath programs and repeat the following process until the program is complete:

- Real-time positioning data is collected, along with acceleration values from wrist TCP and base, with offsets for each applied.
- Wrist TCP and base accelerometer data are filtered using FFT to remove noise.
- Vibrations measured from the base accelerometer are subtracted from the wrist to remove background noise.
- Acceleration values at Tool TCP are converted to mm/s^2.
- Double integration is carried out using cumulative trapezoidal numerical integration to convert acceleration to displacement in X, Y and Z axis.

- Homogeneous transformation is conducted to convert from accelerometer TCP to Wrist TCP, then again to convert accelerometer/wrist TCP to Tool TCP.
- COBOT positioning data and digital twin data are both saved.

While the program is running, real-time data will be shown to the user as well as a visual representation.

Fast Fourier Transformation was used as the filtering method as it allows for real-time signal processing [13]. The right selection of cut-off frequency is critical as it separates useful data from the noise. Here, the cut-off point of the FFT was set using historical data from tests and a swarm-based intelligent search algorithm called particle swarm optimization (PSO). This automatic filter cut-off selection minimizes the difference between the known value and the attached value from the raw data.

The digital twin dynamic error tracking system was designed to seamlessly work with most of the modern CNCs, robot arms, COBOTs and machine controllers which can export data to external devices. The system works as a supervisory digital twin[14]. MATLAB was used to explore and display its current XYZ position and RoboDK was used to visualise the system in a computer in real-time.

2.2 Evaluation experiment

Ball bars are measurement tools that can provide error readings for quasistatic and dynamic measurements. The ball bar test is widely used as a globally accepted standard approach to test the accuracy of machines, especially in machining applications. In this paper ball bar test was, therefore, used to evaluate the effectiveness of the digital twin tracking approach, in which the ball bar data is regarded as standard to evaluate superimposed position data obtained from the digital twin and the data directly read from the COBOT. A Renishaw system (QC20-W) was used in this study. It has a measurement accuracy of 0.1 µm [15]. The setup of the ball bar in the COBOT is shown in Figure 3. The ball bar measured the linear distance from two endpoints using a transducer. This allowed for the radius to be known from the centre as the ball bar moved around the centre. The measured data was used to determine the accuracy of the machine as well as the quasistatic and dynamic properties of the machine [4, 16].

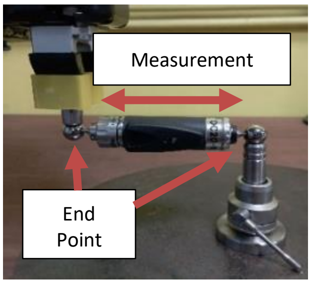

Figure 3 Ball Bar Set Up

The following assumptions were made in the ball bar test:

- The temperature of the room was assumed to be constant as the experiment was conducted in a basement room.
- The basement location with concrete floors allows for the assumption that no vibrations from external sources affected the test.
- The ball bar readings are assumed to be error-free. For this, the ball bar was recalibrated between changes of feed rate.

The experiment was conducted in the following steps:

- Conducted 100 mm radius ball bar test in XY plane at different feed rates starting from 2000 mm/min to 6000 mm/min at increments of 1000 mm/min.
- Each feed rate test would be conducted three times so the results can be averaged.
- Real-time positioning data of the COBOT from the controller and acceleration data were collected at the same time.
- Acceleration data is filtered and double-integrated to compute the displacement.
- Displacement is taken as the dynamic error and is superimposed onto the COBOT positioning data from COBOT TCP.
- Superimposed data and COBOT positioning data are compared to ball-bar results to check for their relative accuracy concerning actual TCP position.

The limitations of the current experiment are:

- Though the COBOT supports the 6-axis motion, the current scope of dynamic error tracking is limited to three axes as the system needs further adjustments to accommodate the rotational movements of the accelerometer and COBOT.
- In this study, the ball bar tests are conducted only on the XY axis. The Z axis was not considered to reduce the number of experiments for each feed rate, this is because ball bars can only measure two axes at a time making each result require three tests.
- At present, the sampling rate of the system is restricted to an average of 4.6 Hz. This is a limitation of the RoboDK and MATLAB API. A faster method of communication is being investigated to improve the sampling rate of the systems.
- The accelerometers have a bandwidth between 0.5 to 3000 Hz at ±5% and +10% up to 5000 Hz. This may limit what vibrations are being measured and processed by the system.

3. Results and discussions

The experimental results were averaged for each feed rate and are shown in Figure 4 and Table 1.

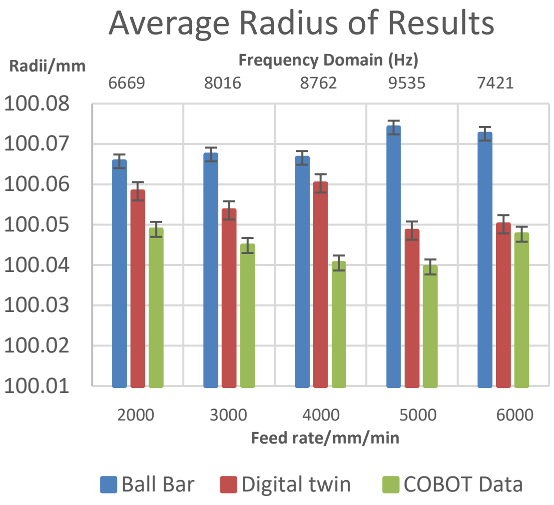

Figure 4 Average Radius of Results

The ball bar readings can be assumed to reflect the real positioning values of the TCP since the ball bar testing is a standard calibration approach for precision machines. The Renishaw ball bar system operated at a sampling rate of 1000 Hz, and its measurement accuracy is 0.1 µm. The deviation between the ball bar results shown in Figure 4 and the nominal values will be the real dynamic errors of the COBOT during the test. As the radius of the ball bar test was set as 100 mm, the average dynamic error is 69.2 µm. The dynamic error results and error reductions are shown in Table 1. The accuracy of the digital twin and the COBOT positioning can be assessed by comparing them with the ball-bar results.

As shown in Figure 4 and Table 1, the digital twin data is closer to the ball-bar results than the positioning data displayed by COBOT, thus confirming the improved accuracy of this method. The measurement error of the digital twin varies from 2 to 19.7 µm as shown in Table 1, depending on the feed rate. A significant enhancement in position tracking accuracy (up to 75%) was achieved by the digital twin dynamic error tracking approach. When the error reduction is averaged across all feed rates, the digital twin is 9.872 µm more accurate than that measured by COBOT's build in encoders. The value of 9.872 µm presents a 41.3% measurement error reduction. From a frequency perspective, it can be seen that the frequency domain increases as the feed rate increases for all the feed rates except 6000 mm/min shown in Figure 4 and Table 1. The mean frequency has a trend of decreasing with feed rate until 6000 mm/min as shown in Table 1. This out-of-trend behavior at 6000 feed rate will be further analysed in future studies.

The variation of measurement error of the digital twin under different feed rates is believed to be due to the real-time communication capability of the data logger. The sampling rate of the data logger is 4.6 Hz on average. As the feed rate increases, the number of samples collected will decrease. This will significantly reduce the accuracy of the data due to the limitation of available data. Currently, the issue is believed to be from the RoboDK and MATLAB API and a method to overcome this is being investigated. Nevertheless, the advantage of the digital twin dynamic error tracking approach compared to the ball bar is apparent.

The digital twin allows in-situ even in-line real-time measurement of machine dynamic error in a 3D space, and this is not possible by the ball bar system which is an off-line measurement approach and being limited to measuring in two axes.

Table 1 Experiment Results

Dynamic Error from 100mm Radius Ball Bar Test					
mm/Min	**2000**	**3000**	**4000**	**5000**	**6000**
Ball Bar (µm)	65.7	67.4	66.5	74.1	72.5
Digital twin (µm)	58.3	53.5	60.2	48.5	50.1
COBOT Data (µm)	48.8	44.8	40.5	39.5	47.6
Difference Between Digital twin and COBOT Data (µm)	9.5	8.7	19.7	9	2.5
Error Reduction (%)	56.2	38.5	75.8	26	10
Frequency Domain (Hz)	6669	8016	8762	9535	7421
Mean Frequency (Hz)	59.17	54.58	49.51	49.60	101.28

4. Conclusion

This paper has presented a new digital twin method to track dynamic errors on a COBOT. This method uses triaxial accelerometers to double integrate X, Y, and Z axis reading to determine the displacement of the arm due to elastic deflection and vibration. The calculated displacement is superimposed onto the encoder values in real-time to more accurately determine its position in 3D space. The effectiveness of the system has been tested using a ball bar test in the XY axis and comparing the tracking results between the superimposed results by the digital twin and the positioning data displayed by the COBOT. The results show the proposed digital twin tracking approach can significantly enhance tracking accuracy (up to 75%). The effectiveness of this method is limited by its sample rate as higher feed rates reduce the time of the test thereby reducing the amount of data available. This in turn has resulted in reduced error reduction at higher feed rates. The out-of-trend respounce in frencucy mean and domain at 6000 mm/Min will need further investorgation. The proposed method of tracking dynamic errors is more accurate and, in theory, is transferable to other systems. It could provide a universal increase in machining accuracy without compromising the machining speed.

Future research will be focused on the following aspects:

- Further increasing the sampling rate of the system to improve the accuracy at higher speeds.
- Testing the system on other machines to validate its robustness and development of automated corrective actions based on the real-time tracking results.
- Refining the test method to include the Z axis for validating its effectiveness in 3D space.

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