Experimental Implementation of Time-varying Input Shaping on UR Robots*

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Abstract: Lightweight design leads to the unwanted vibration of industrial robot manipulators. Input Shaping (IS) has been proven to be an effective vibration suppression method. However, applying IS to suppress the vibration of industrial robots faces a challenging problem: time-varying dynamics. To address the time-varying dynamics of robot manipulators, this paper presents a novel and practical solution to vibration suppression based on Time-Varying Input Shaping Technology (TVIST). Our focus in this paper is to develop a practical implementation strategy that can be applied in discrete time. A Fractional Delay Finite Impulse Response filter is employed to design and implement TVIST. This solution makes TVIST more useful in practice because it can be combined with online and discrete-time trajectory generation. It can also be implemented in combination with position control using feed-forward velocity and torque. The performance of the new approach is validated through experimental implementation on a lightweight robot from Universal Robots A/S. Experimental results are analyzed to demonstrate significant vibration suppression and increased productivity of the robot with the proposed solution. The proposed method can be extended to the vibration suppression of other types of industrial robotic manipulators with serial links as well as other time-varying dynamic systems.

1 INTRODUCTION

In order to meet the requirements of increased productivity, safety and energy efficiency, manufacturers tend to develop robots with light weight design compared to traditional robots. Light weight design leads to mechanical flexibility of the robotic system due to reduced stiffness and damping. A visualization of primary mechanical flexibility in a light weight collaborative robot from Universal Robots A/S (UR) is presented in Figure 1.

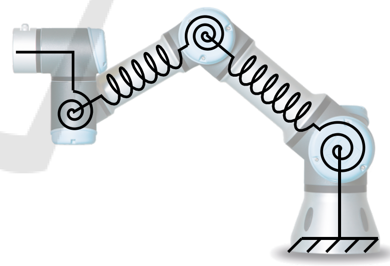

Figure 1: Mechanical flexibility visualized in a UR3 robot.

As shown in the Figure 1, mechanical flexibility comes primarily from gear flexibility in the joints (strain wave gears) and link flexibility in the two long links. In addition to mechanical flexibility, reduced impedance resulting from control algorithms and electrodynamics decreases the total system stiffness. The mechanical and the electrical flexibility cause the robot manipulator to be subject to unwanted mechanical vibrations during motions with high acceleration. These mechanical vibrations are unwanted, because they affect robot precision, accuracy, wear, power consumption and productivity in a negative way.

In the recent decades, many different strategies have been investigated to reduce the unwanted mechanical vibrations in light weight robotic systems. Generally, the different strategies can be divided into hardware design, trajectory optimization, feedback control, and feed-forward control methods.

One type of feed-forward vibration suppression is Input Shaping (IS) (Singer and Seering, 1990). IS has gained a lot of attention for its simplicity and efficiency.

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The basic principle of IS is to convolve a reference signal with a well-designed impulse train to generate a modified (shaped) reference signal, that introduces a reduced amount of unwanted mechanical vibrations in the robotic system.

The conventional IS assumes that the system is time invariant, i.e. the system frequency and damping do not change with time. Applying IS to an industrial robot manipulator faces a significant challenge as industrial robots have configuration dependent dynamics (time-varying dynamics), i.e. the natural frequency and damping of an industrial robot often vary with configuration and payload. This behavior arises mainly from time-varying mass distribution, i.e. inertia, as illustrated in Figure 2. Here, the actuator of the illustrated 1DOF robot will experience a position dependent mass moment of inertia, which will result in position dependent natural frequency and damping ratio of the system.

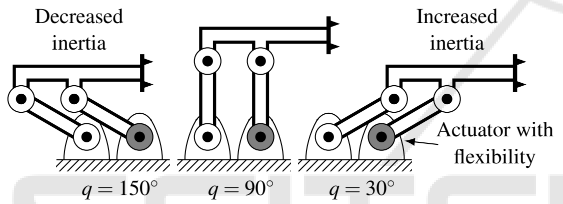

Figure 2: 1DOF manipulator with configuration dependent inertia.

Taking a UR5e robot as an example, the damped natural frequency varies as much as from 6Hz to 15Hz with a constant 5kg payload. The Robust IS method was developed to accommodate slight deviations in system frequencies and damping (Singh and Vadali, 1993; Kim and Croft, 2018), but it is not capable of handling the large deviation of the frequencies and damping in industrial robot manipulators (Thomsen et al., 2018). The Time-Varying Input Shaping Technology (TVIST) is a promising method for handling the time-varying dynamics and providing efficient vibration suppression throughout the workspace of the robot for any desired motion (Cho and Park, 1995; Chang and Park, 2005; Kivila, 2017). However, TVIST methods in existing literature on are not directly applicable in commercialized industrial robots, since the reported research is limited to very flexible robot manipulators, or have no practical implementation strategies.

A new type of TVIST, which utilizes Fractional Delay FIR filtering has been suggested for industrial robots (Thomsen et al., 2019). While simulations have been published to support the new principles, practical implementation and experimental validation have not yet been presented.

The main contribution of this paper is to develop and validate the practical and effective implementation strategy of TVIST on typical industrial robots with six joints. The detailed principles and procedures of implementing TVIST on a UR robot are presented together with preliminary experimental results. A set of test motions are performed, and the experimental results are analyzed. The experimental results validate the efficiency of the proposed experimental implementation strategy.

2 OVERVIEW ON INPUT SHAPING

Input Shaping (IS) is a vibration suppression method, which aims to avoid introducing vibrations in a dynamic system by convolving the reference signal with a set of vibration free impulses in order to obtain a modified (shaped) reference signal. The shaped reference signal will solve the desired task without introducing vibrations in the system.

The fundamental principle of input shaping is illustrated in Figure 3. Here it is shown how an impulse, A_1, will cause a dynamic response in the system, and how the response of a second impulse, A_2, will cancel out this response if applied with the correct timing and amplitude.

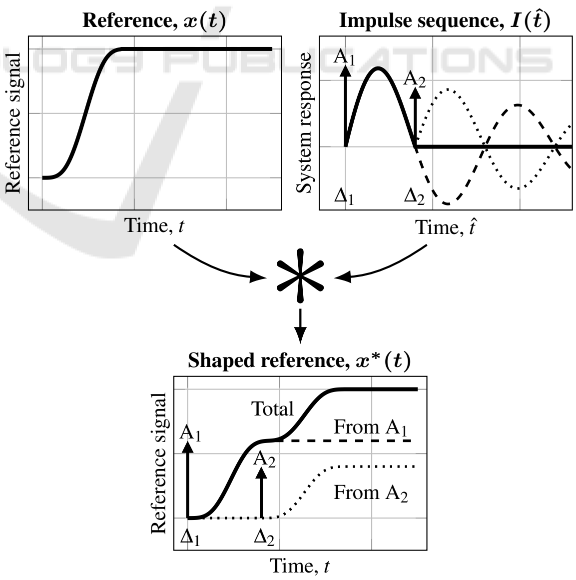

Figure 3: Convolution of Zero Vibration (ZV) shaper.

In general, the impulse sequence, $I(\hat{t})$, can be expressed as shown in (1)-(3), where $\hat{t}$ is internal filter time, $\vec{A}$ is impulse amplitudes, and $\vec{\Delta}$ is impulse timings for a shaper with N impulses.

$$\vec{\mathrm{A}} = \{\mathrm{A}_1 \quad \mathrm{A}_2 \quad \cdots \quad \mathrm{A}_N\} \tag{1}$$

$$\vec{\Delta} = \{\Delta_1 \quad \Delta_2 \quad \cdots \quad \Delta_N\} \tag{2}$$

$$I(\hat{t}) = \begin{cases} \mathrm{A}_j & \text{if } \hat{t} = \Delta_j \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

For the Zero Vibration (ZV) shaper, $\vec{\mathrm{A}}$ and $\vec{\Delta}$ can be determined as described by (4)-(7), where K is a helping constant, ζ is damping ratio, ω_n is natural frequency in rad/s, and f_d is damped frequency in Hz (Singer and Seering, 1990).

$$K = e^{\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \tag{4}$$

$$f_d = \frac{\omega_n}{2\pi}\sqrt{1-\zeta^2} \tag{5}$$

$$\vec{\mathrm{A}} = \left\{\frac{1}{1+K} \quad \frac{K}{1+K}\right\} \tag{6}$$

$$\vec{\Delta} = \{0 \quad 0.5/f_d\} \tag{7}$$

Once all parameters of $I(\hat{t})$ are known, the shaped reference command, $x^*(t)$, can be obtained by convolving the reference command, $x(t)$, and $I(\hat{t})$ as presented in (8). This operation is called *shaping*.

$$x^*(t) = (x * I)(t) \equiv \sum_{j=1}^{N} (\mathrm{A}_j \cdot x(t - \Delta_j)) \tag{8}$$

The shaping can be performed on any reference signal for the controlled system, such as a position, velocity, acceleration, torque, or current reference signal. The convolution of a position reference is also illustrated in Figure 3. Here it is seen that convolving $x(t)$ with $I(\hat{t})$ corresponds to splitting $x(t)$ into two parts, which are scaled by A_1 and A_2 and delayed by Δ_1 and Δ_2, respectively, before being added together as $x^*(t)$. If $x^*(t)$ is given to the system as reference, this will result in zero vibration in the system.

3 TIME-VARYING INPUT SHAPING

While IS has proved efficient for suppressing vibrations system with time-invariant dynamics, it is not robust enough to variations in f_d and ζ to provide acceptable vibration suppression for time-varying dynamic systems such as serial link robots. This is clearly seen, by inspecting a sensitivity curve for the Zero Vibration Derivative (ZVD) and Extra Insensitive (EI) shapers as presented in Figure 4. It is seen, that an EI shaper can not guarantee vibration suppression to a level of less than 36% for the span of f_d from 6 to 15Hz, which is seen in a UR5e robot. This is even without taking damping variations into account.

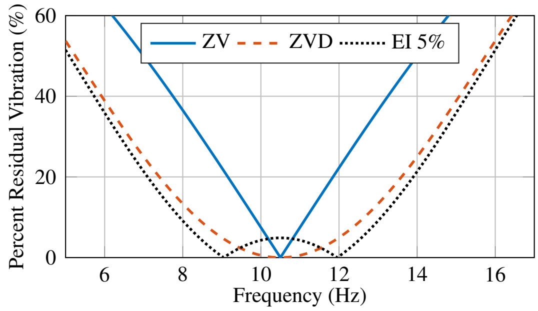

Figure 4: Sensitivity plot of ZV, ZVD, and EI shapers.

It is possible to increase robustness, but this comes at the expense of increased shaper delay, which is undesirable. It is desired to increase vibration suppression capabilities and decrease shaper delay for systems with time-varying dynamics. Thus, a demand for taking time-varying dynamics into account exists for light weight robots. This section elaborates on how to extend the IS methods to TVIST.

For a system with time-varying dynamics, i.e. time-varying damping ratio, $\zeta(t)$, and damped frequency, $f_d(t)$, the impulse train can be updated as presented in (9), which is an expansion of (3). Here $I(\hat{t}, f_d(t), \zeta(t))$ is updated continuously as $f_d(t)$ and $\zeta(t)$ varies with time.

$$I(\hat{t}, f_d(t), \zeta(t)) = \begin{cases} \mathrm{A}_j(\zeta(t)) & \text{if } \hat{t} = \Delta_j(f_d(t)) \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

When introducing the impulse sequence as $I(\hat{t}, f_d(t), \zeta(t))$, it is necessary to expand (8) as presented in (10).

$$x^*(t) = \sum_{j=1}^{N} (\mathrm{A}_j(\zeta(t)) \cdot x(t - \Delta_j(f_d(t)))) \tag{10}$$

The formulation of TVIST in (10) is the idealized principle, which can be used in systems, where: 1) The analytical description of the reference signal is known, and 2) The system does not have multiple reference signals, which are dependent on each other, such as position and velocity signals. The next section elaborates on the shortcomings of this formulation, and propose a way to overcome them in the implementation in UR robots.

3.1 Implementation of TVIST

This section elaborates on the implementation of TVIST in the control structure of a UR robot. The original control structure is illustrated in Figure 5. As illustrated, a trajectory generator provides reference joint positions, $\vec{q}$, reference joint velocities, $\dot{\vec{q}}$, and reference joint accelerations, $\ddot{\vec{q}}$, to an inverse dynamic model, which computes reference joint torques, $\vec{\tau}$. Then $\vec{q}$, $\dot{\vec{q}}$ and $\vec{\tau}$ are provided to the joint controllers, which also utilize sensor feedback about actual joint positions, $\vec{q}_a$, and actual joint velocities, $\dot{\vec{q}}_a$, to generate actual motor voltages, $\vec{u}_a$, which are applied in the joints. Thus each joint controller should be seen as a feedforward-feedback controller with 3 reference inputs, 2 feedback measurements and 1 controller output.

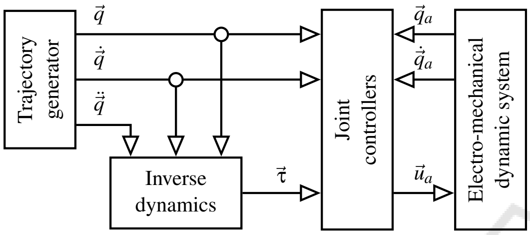

Figure 5: Control structure of a UR robot.

By shaping $\vec{q}$, $\dot{\vec{q}}$, and $\ddot{\vec{q}}$ simultaneously, it would be possible to handle the multiple reference inputs in the classic time-invariant shaper presented in (8). However, once introducing time-varying shaping, as presented in (10), the relation between $\vec{q}$ and its derivatives becomes non-linear.

Thus it is not an option to shape $\vec{q}$, $\dot{\vec{q}}$, and $\ddot{\vec{q}}$ simultaneously using identical shapers. Others (Beazel, 2004; Chatlatanagulchai et al., 2006) suggest averaging the non-linear dynamics of the robot over the motion and treat them like linear dynamics. Then $\vec{\tau}$ is shaped, and weighted to fit the linearized dynamics. Then $\ddot{\vec{q}}$ is determined and integrated twice to obtain $\dot{\vec{q}}$ and $\vec{q}$. This process requires that the analytic description of the whole motion is known in advance, and that the motion is completed before starting a new motion. Hence this method does not suit a system with online trajectory generation. Also, the method is computationally expensive because complex dynamic models need to be evaluated.

Instead it is proposed to implement the method in discrete time and to shape $\vec{q}$ while performing numerical differentiation in order to obtain $\dot{\vec{q}}$ and $\ddot{\vec{q}}$, like illustrated in Figure 6.

By implementing the TVIST filter as a discrete time filter, the robot will be able to perform filtering on any trajectory, which can be generated online or even provided by a 3rd party PC or software, which sends discrete reference commands to the robot.

3.2 TVIST in Discrete Time

When IS is implemented in discrete time, it is necessary to use a discrete time impulse sequence, $I[i]$, i.e. to discretize $I(\hat{t})$ from continuous time to discrete time domain (Rappole, 1992; Murphy and Watanabe, 1992; Cole, 2011). The traditional method of implementing IS in discrete time is to use a Finite Impulse Response (FIR) filter to convolve the discrete time reference signal $x[i]$ with $I[i]$ (Singer, 1989). However, a major challenge in Discrete Time Time-Varying Input Shaping Technology (DT-TVIST) is that the FIR convolution operation results in significant defects in x^*, when f_d is varying such that the position of an impulse is moving from one discrete time step to another (Magee and Book, 1992; Magee, 1996).

The discretization problem is illustrated in Figure 7. Here it is seen how a change in f_d results in a time shift of the second impulse. When the time shift becomes large enough, the impulse will jump from one discrete time step to the next, and this will cause defects in the convolved signal (Murphy and Watanabe, 1992; Magee, 1996).

In the proposed implementation, the described challenges are handled by maintaining a buffer of previous filter inputs and perform an interpolation in order the obtain an estimate of $x(t)$, as illustrated in Figure 8. The figure illustrates that at time step i, the reference command, x_i, is stored in a buffer of length M . An estimate of $x(t)$ is established through interpolation of the buffered reference commands. Then $x(t)$ is convolved with the impulse sequence of current time step, $I^i(\hat{t})$, to compute the shaped reference command, x_i^*. $I^i(\hat{t})$ is established based on an estimate of f_d and ζ based on the shaped reference command of the previous time step, x_{i-1}^*, as described in section 3.3.

This type of convolution filter, which includes interpolation of discrete reference commands, is called a Fractional Delay Finite Impulse Response (FD-FIR) filter (Laakso et al., 1996). The option to utilize FD-FIR filters in IS has recently been presented and analyzed (Thomsen et al., 2019).

3.3 Estimating Time-varying Dynamics

In order to validate the effect of the proposed TVIST design, it is required to have a method of estimating the robot dynamics, i.e. $f_d(t)$ and $\zeta(t)$. This can be achieved using different types of dynamic modeling (Book, 1993; Chang and Park, 2005; Sayahkarajy et al., 2016; Kivila, 2017), system identification (Pham et al., 2002; Khalil and Dombre, 2004), or lookup tables (Hearne, 2009).

The most accurate estimate seems to be achieved

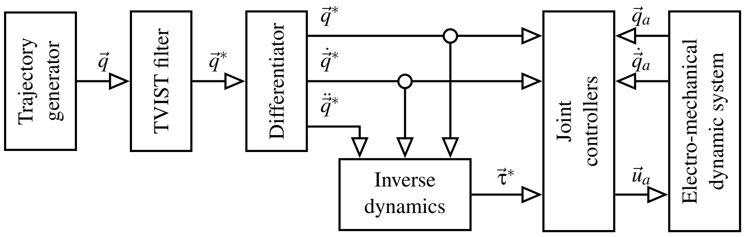

Figure 6: Control structure of a UR robot with TVIST.

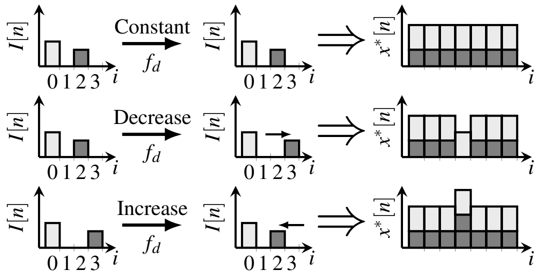

Figure 7: The discretization problem of TVIST.

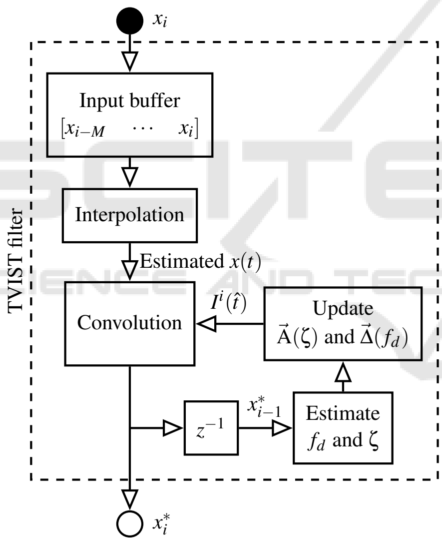

Figure 8: UR TVIST filter design.

from a combination of dynamic modeling and systems identification. However, a representative dynamic model would need to include a large number of parameters in describing mechanical, electrical and software non-linear dynamics.

Before engaging in developing such a complex and computationally intensive estimator, it seems reasonable to try a simple method and see, if this can provide a useful estimate for the given application.

Thus, for this work it was decided to make a lookup table based on measurements in multiple different configurations over the workspace of the robot. This lookup table was fitted to two multi-variable polynomials, which are evaluated to estimate $f_d(\vec{q}(t))$ and $\zeta(\vec{q}(t))$.

4 EXPERIMENT

To validate the performance of the proposed TVIST implementation in UR robots, experiments are performed on a UR5e robot. Section 4.1 presents the experimental setup, section 4.2 presents the results of the experiment together with the performance parameters of interest, and section 4.3 presents a discussion on the results.

4.1 Experimental Setup

In the experimental setup, a UR5e robot is mounted on a steel stand, which is deemed very rigid compared to the flexibility of the robot itself. A rigid steel payload of 5kg is installed on the robot tool flange. This corresponds to the rated payload of the robot. The test setup is illustrated in Figure 9.

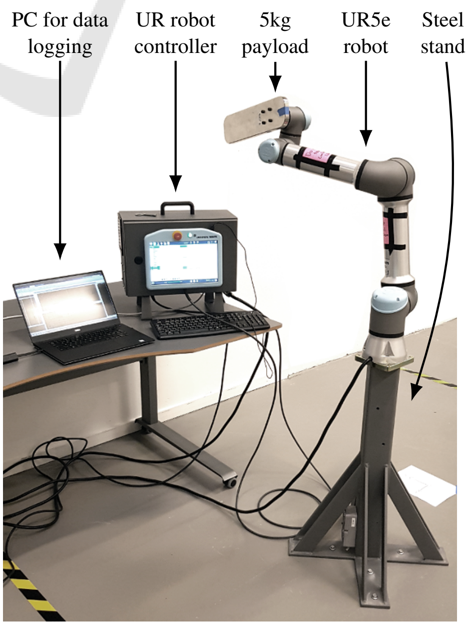

Figure 9: Test setup with UR5e robot on stand.

All test data is logged from the robot's Real Time Client (Universal Robots A/S Support, 2018) at 500Hz. This includes reference joint positions, $\vec{q}$, reference joint accelerations, $\ddot{\vec{q}}$, actual joint positions, $\vec{q}_a$, and tool accelerometer readings, $\vec{\alpha}$.

It has been chosen to use a ZV shaper for evaluating the performance of the proposed TVIST implementation. There are two reasons for this choice, 1) The ZV shaper has a short time-delay, 2) The ZV is sensitive, i.e. not robust, to errors in estimated f_d and ζ. Both of these characteristics are seen as strengths, when it is sought to validate the performance and applicability of the method. In practice, it would probably make sense to implement a Zero Vibration Derivative (ZVD) shaper for increased robustness, but this depends on the application.

Test motions are performed with and without shaping for evaluating the TVIST method. Motions are performed between configurations Q_1, Q_2, and Q_3, which are listed in Table 1.

Between these configurations, three different joint space motions are used for evaluation, namely $Q_1 \rightarrow Q_2$, $Q_1 \rightarrow Q_3$, and $Q_3 \rightarrow Q_1$. Visualizations of these motions are presented in Figure 10 and Figure 11. The configurations and motions are chosen such that the $Q_1 \rightarrow Q_2$ motion will have non-varying dynamic properties, while $Q_1 \rightarrow Q_3$ and $Q_3 \rightarrow Q_1$ motions will have varying dynamic properties.

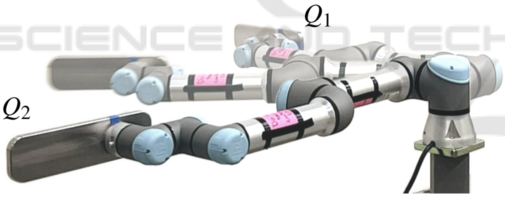

Figure 10: $Q_1 \rightarrow Q_2$ motion.

By varying dynamic properties, it is understood that $Q_1 \rightarrow Q_3$ yields increasing f_d and decreasing ζ, while $Q_3 \rightarrow Q_1$ goes in the opposite direction and yields decreasing f_d and increasing ζ. In the test motions, the kinematic limitations of the double S velocity profile trajectory (Biagiotti and Melchiorri, 2008), is set as $\max(\dot{\vec{q}}) = 1.5$rad/s, $\max(\ddot{\vec{q}}) = 2.0$rad/s^2, and a jerk time, i.e. acceleration ramp up time, of 20ms.

4.2 Experimental Results

The results of performing the three different motions are presented in Figures 12-14. Here it has been chosen to present shaped reference accelerations ($\ddot{\vec{q}}^*(t)$), Cartesian distance to attained position (E), tool accelerometer amplitude ($|\vec{\alpha}|$), estimated damped frequency in Hz (f_d), and estimated damping ratio (ζ).

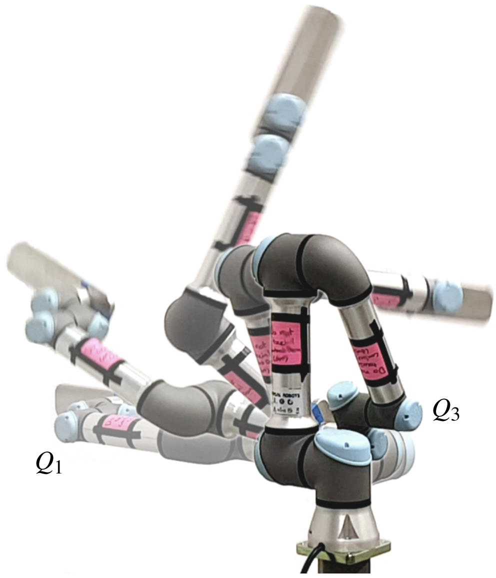

Figure 11: $Q_1 \rightarrow Q_3$ motion.

E is interesting because it is used to determine a set of key performance parameters in (ISO 9283, 1998), such as stabilization time (t_{stb}) and overshoot (e_{os}). The attained position is the actual Tool Center Point (TCP) position after the motion has finished, and after the position has been stabilized. E is defined as the Cartesian distance from actual TCP position to the attained position. Actual TCP position should ideally be measured by external 3D tracking equipment. However, for the scope of this paper, which is to determine the relative impact of TVIST on mechanical vibrations, it has been chosen to use $\vec{q}_a$ and perform a calibrated forward kinematics to determine actual TCP position. This makes it possible to obtain all data from the robot itself.

In this work, three performance parameters are established based on E, namely t_{stb}, e_{os}, and t_{cycle}. The definition of these parameters will be given here.

In this work, cycle time, t_{cycle}, denotes the time span from when the reference motion starts, until the last time, where E takes value higher than the repeatability of the robot. For the UR5e robot, the repeatability is specified as 0.03mm. The stabilization time, t_{stb}, is the time span from the first time, where E takes value lower then the repeatability of the robot (t_{enter}), until t_{cycle} (ISO 9283, 1998). The overshoot, e_{os}, is the maximum value of E after t_{enter} (ISO 9283, 1998). If this value is lower than the repeatability, the overshoot is 0. Another metric of interest is the shaper delay (Δ_n). Δ_n, t_{stb}, e_{os}, t_{enter}, and t_{cycle} are all illustrated in Figure 15, and the actual values for the test motions are listed in Table 2. Here the listed values are average values from 10 runs of the test motions.

Table 1: Listed test configurations.

Conf.	q_0 (rad)	q_1 (rad)	q_2 (rad)	q_3 (rad)	q_4 (rad)	q_5 (rad)	f_d (Hz)	ζ (-)
Q_1	0	$-\pi$	0	$-\pi/2$	0	0	6.7	0.34
Q_2	$\pi/2$	$-\pi$	0	$-\pi/2$	0	0	6.7	0.34
Q_3	$\pi/2$	$-\pi/2$	$5\pi/6$	$-\pi/2$	0	0	15.0	0.14

Table 2: Performance evaluation of TVIST, average of 10 repetitions.

	Delay (ms) Δ_n	Stabil. Time (ms) t_{stb}	Cycle Time (ms) t_{cycle}	Overshoot (m) e_{os}	Res. Vibration (m/s^2) RV
$Q_1 \rightarrow Q_2$					
Unshaped	0	548.8	2368.9	5.5E-04	1.11
Shaped	74.1	167.0	2229.5	3.1E-05	0.13
Impact	-	-69.6%	-5.9%	-94.3%	-88.6%
$Q_1 \rightarrow Q_3$					
Unshaped	0	70.8	2821.4	3.7E-05	0.80
Shaped	33.6	7.2	2820.4	1.0E-05	0.17
Impact	-	-89.8%	0.0%	-72.4%	-78.5%
$Q_3 \rightarrow Q_1$					
Unshaped	0	1049.2	3707.8	1.3E-04	1.14
Shaped	74.2	816.7	3596.0	6.4E-05	0.22
Impact	-	-22.2%	-3.0%	-50.3%	-80.8%

The UR5e robot has an accelerometer in the tool flange. Analyzing the measured accelerations is considered the most reliable way of quantifying the amount of residual vibrations in of the motion without using external 3D tracking equipment. When determining the amount of residual vibration, the amplitude of the total acceleration $|\vec{\alpha}|$ with gravity compensation is considered. Then the amount of Residual Vibration (RV) is found by identifying the peaks of the acceleration signal and fitting them to an exponential decay. RV is the amplitude of the fitted curve at the time, where the reference motion stops (Kozak et al., 2006). RV is also listed in Table 2. Figure 16 is introduced for easy comparison of $|\vec{\alpha}|$ with and without IS.

4.3 Discussion on Results

From the $Q_1 \rightarrow Q_2$ motion presented in Figure 12 it is seen that the estimated dynamics are constant at $f_d = 6.7$Hz and $\zeta = 0.34$ during the motion. It is seen from $|\vec{\alpha}|$ that mechanical vibrations are present during and after the unshaped motion. When comparing with the shaped motion, it is seen, how oscillations are clearly reduced during the motion, while residual vibrations are practically eliminated. It appears that IS is performing well, but there are other contributions to mechanical vibrations, which can not be eliminated by IS. This is believed to be a result of mechanical imperfections, such as kinematic error in the gears (Tuttle, 1992) and bearing imperfections.

The same tendency for residual vibration is seen for E. When comparing the shaped and unshaped motions, it may be noticed how the introduced delay seems to pay off well, as the TCP comes to rest faster than originally. The promising results for the $Q_1 \rightarrow Q_2$ motion tells us that IS can provide effective vibration suppression in the system, when dynamics are invariant.

By inspecting the $Q_1 \rightarrow Q_3$ motion in Figure 13 and $Q_3 \rightarrow Q_1$ in Figure 14. It is found that effective vibration suppression is also possible, when f_d and ζ vary over time. These are really good results, especially since the TVIST is implemented with the simple ZV shaper. Achieving good vibration suppression using a time-invariant robust shaper would require two or three times more delay and would not give as good results. f_d is varying between 15Hz and 6.7Hz, while ζ varies between 0.14 and 0.34. This huge span would not be possible to cover appropriately with one robust shaper.

Table 2 lists the performance metrics for the shaped and unshaped motions, as well as the relative impact from shaping. Here, it is seen that t_{stb}, e_{os}, and residual vibration are reduced for all three test motions. This was also expected from introducing IS. However, it

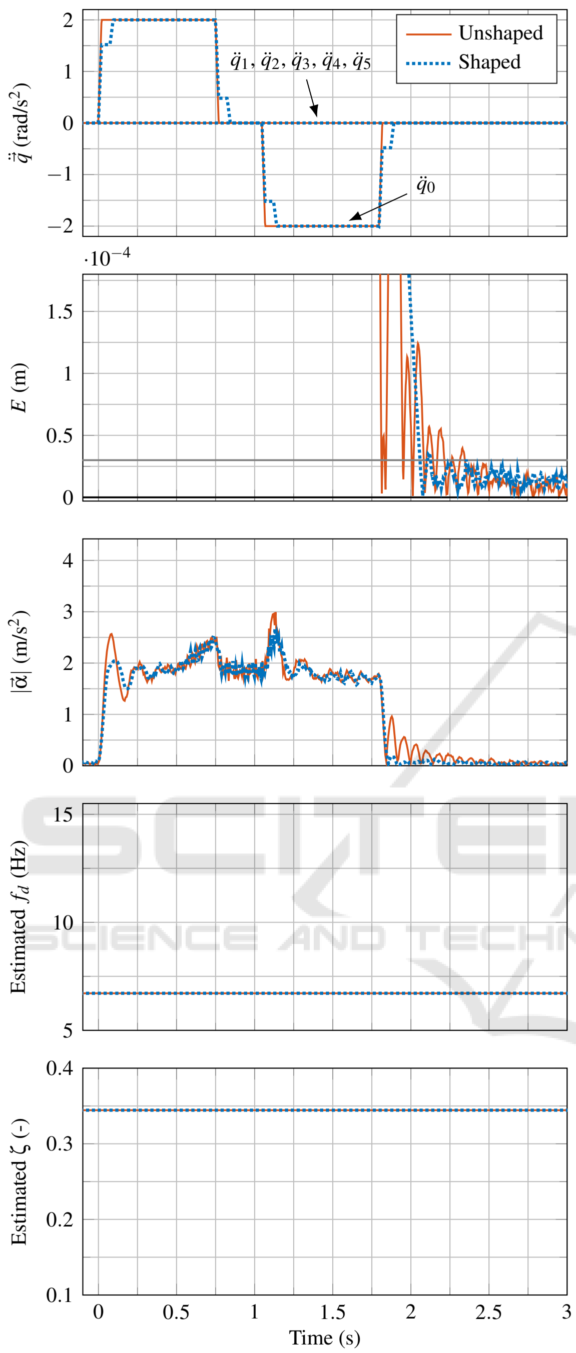

Figure 12: Recorded data from $Q_1 \rightarrow Q_2$ motion.

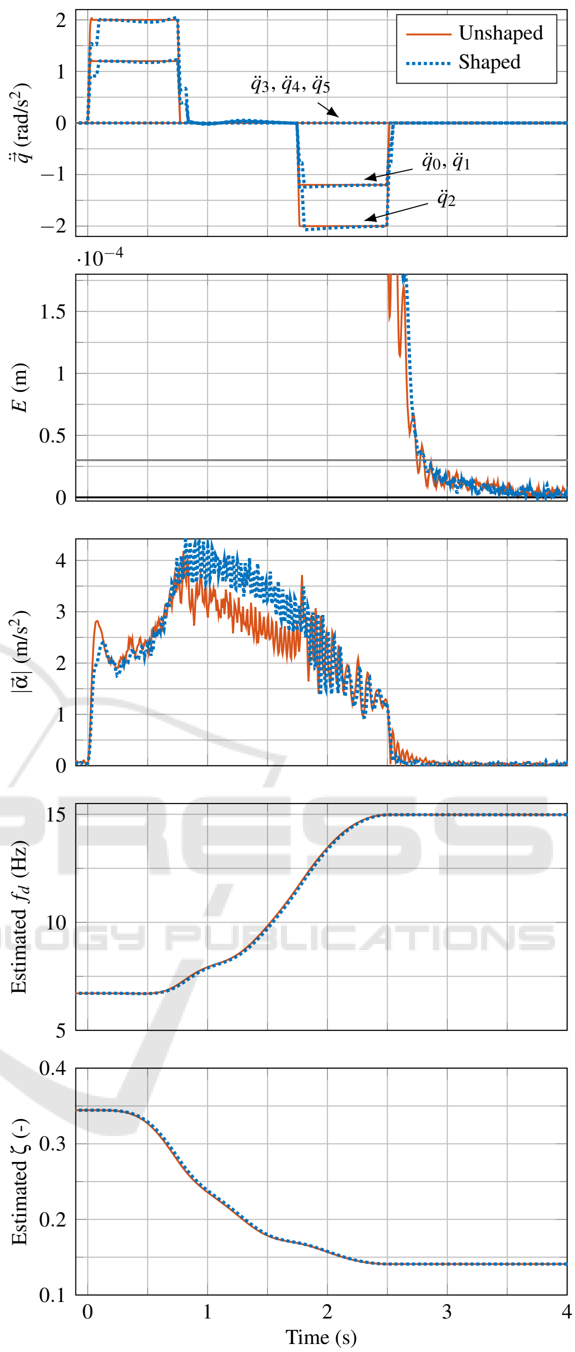

Figure 13: Recorded data from $Q_1 \rightarrow Q_3$ motion.

is impressive to see, that the absolute reduction in stabilization time is larger, than the introduced time delay, meaning that the total cycle time can be reduced by up to 5.9%. In other words, the productivity of the robot can be increased by up to 6.3%.

5 CONCLUSIONS

In this paper, a need for efficient vibration reduction methods in light weight robots has been identified. It was found that Input Shaping (IS) had great potential, but lacked on the ability to handle the time-varying dynamics of industrial robots with the serial

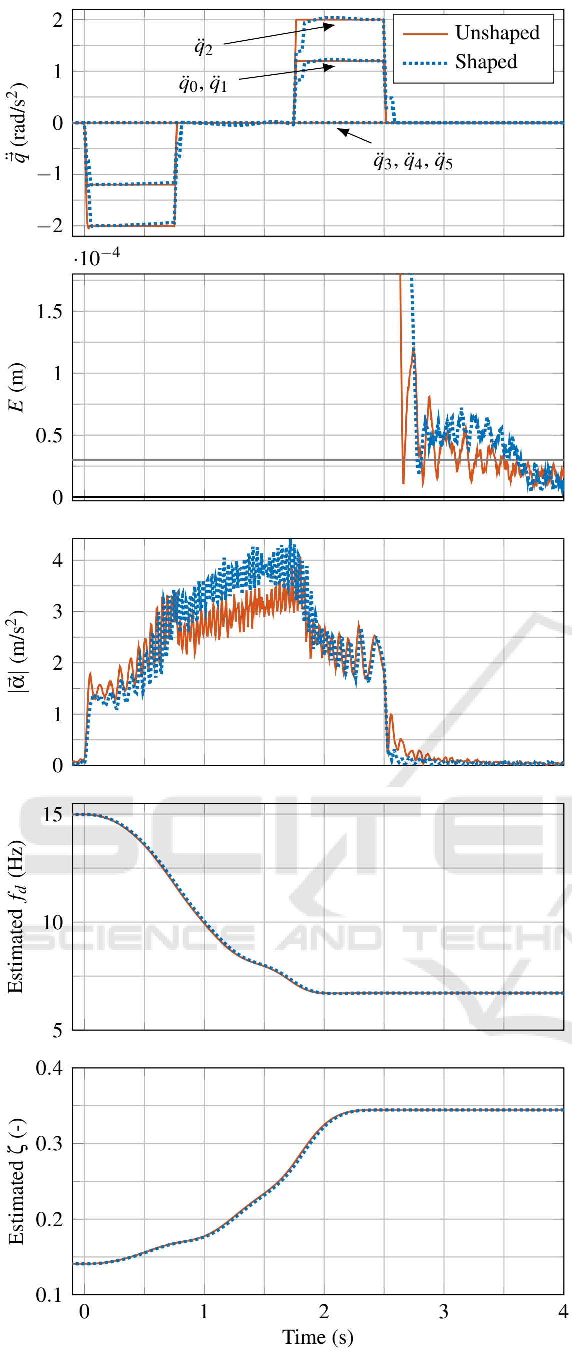

Figure 14: Recorded data from $Q_3 \rightarrow Q_1$ motion.

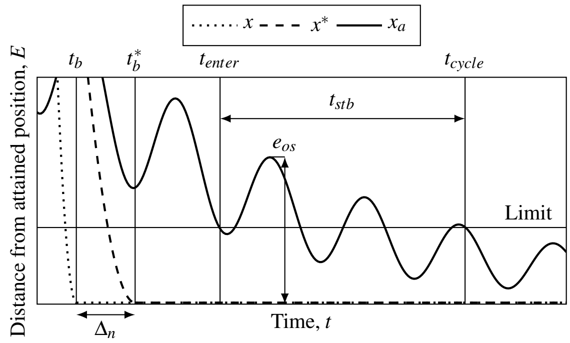

Figure 15: Visualization of delay (Δ_n), stabilization time (t_{stb}), cycle time (t_{cycle}), and overshoot (e_{os}).

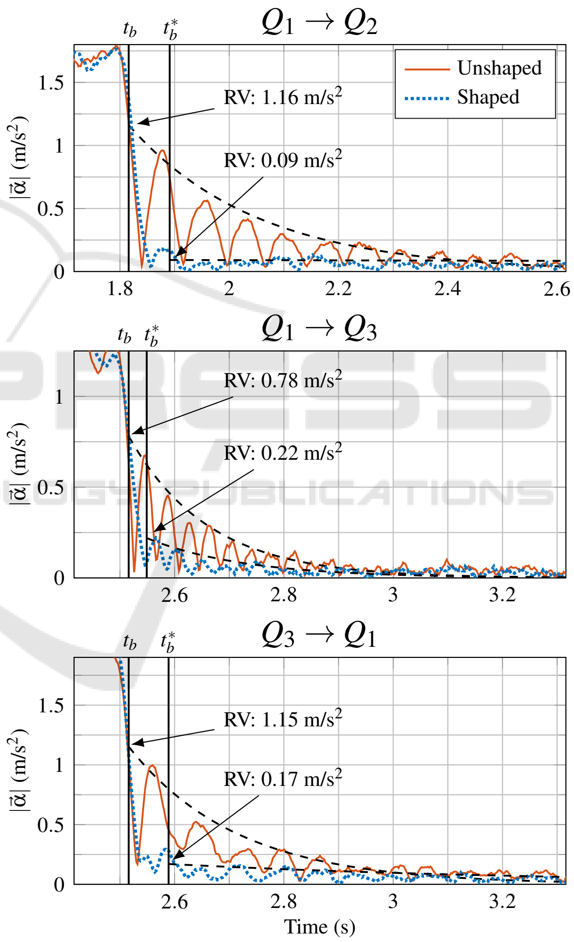

Figure 16: Tool accelerometer amplitude.

link configuration. IS has previously been extended to Time-Varying Input Shaping Technology (TVIST), for dealing with time varying dynamics. This paper focuses on the strategy of implementing TVIST on a UR5e robot from Universal Robots A/S (UR). It was found that it is necessary to change its present formulation to implement TVIST on an industrial robot manipulator.

We proposed a new and practical implementation strategy of TVIST on a UR robot. The new implementation of TVIST is a discrete time filter that performs IS in a reference position signal and numerically differentiates the shaped position reference in order to obtain shaped reference velocity and acceleration before performing inverse dynamics to compute shaped reference torques. Experiments are conducted on a UR5e robot with the proposed TVIST implementation to validate its effectiveness.

Preliminary experimental results demonstrate that the new TVIST implementation yields effective vibration suppression in the UR5e robot, and reduces the residual vibrations by 78.5-88.6% in the tested cases. In addition, experimental results show that it is possible to increase the productivity of the robot by up to 6.3% because the stabilization time is significantly reduced through the proposed TVIST implementation strategy.

We can conclude that the proposed method facilitates practical implementation of TVIST for vibration suppression on commercial industrial robots that has online trajectory generation and position control with feed-forward velocity and torque.

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