Variation minimization in tele-sandblasting system: the effect of human-arm movement error

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Abstract. In tele-sandblasting task, human arm movement is a critical source of producing variation in position of sandblasting nozzle resulting in high operating cost and low productivity. Each operator behaves differently leading to unpredictable movements. Skilled operators are able to reduce the variation; however, developing skills requires a training period. In this paper, we proposed a new approach which is the use of a novel operator's arm movement pattern incorporated with a Kalman filter to reduce the effect of human-arm movement error. A virtual tele-sandblasting system is used to validate our approach. The experimental results verify that our proposed approach is able to significantly reduce the effect of human arm movement error. The approach helps operators to perform the task more comfortably and takes short training time.

1 Introduction

Teleoperation system has been an active research area and used in diverse applications as it provides several benefits such as preventing operators from hazardous environment and accident, enabling small-scale or large-scale tasks, reaching inaccessible spots. Specifically, a tele-sandblasting system employs teleoperation system for complex structure maintenance and cleaning purpose [1].

Despite many benefits, teleoperation system inherently associates with problems causing variation in the system. The system consists of master controller stage and slave device stage. Recently, much research has contributed on variation occurred at the slave device which is caused by robot movement error and time delay [2][3]. However, the study of the variation occurred at the master controller which is mainly caused by human arm movement has been rarely found [4]. To the best of our knowledge, we realized that variation in master controller position in two-dimensional space caused by human arm movement has not been studied. This problem affects total variation of sandblasting nozzle position which is explained by system's accuracy and precision which eventually results in higher operating cost and lower productivity [5]. Skilled operators are able to reduce the variation; however, developing skills generally requires training period.

In this paper, we describe tele-sandblasting as two-stage system and we propose a novel arm movement pattern incorporated with Kalman filter to withstand human skill differences so that the system total variation is reduced. We then validate our approach by an experiment.

2 System Description

Tele-sandblasting system mainly consists of two stages, master controller and slave device as shown in Fig. 1. Master controller is the part where the operator interacts with the system to create a command for the slave device. Generally, master controller is a passive manipulator. Its movement is controlled by the operator. The slave device is an active manipulator which is sent into a working environment. It moves following the command received from the master controller. A sandblasting nozzle is mounted at the end-effector. At the working area, a camera is placed to capture the movement of the slave device for the operator.

Fig. 1: Tele-sandblasting system

The preferable outcomes of the task is to ensure that the surface is completely clean as fast as possible. To do so, the width of the blasting path is set to be equivalent to or slightly smaller than the blasting spot size to achieve optimal operating time and cost [6], shown in Fig. 2. With this setup, navigating the nozzle inaccurately and imprecisely will result in poor surface quality. Therefore,

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pathwidth was frequently set to be much smaller than the blasting spot size to cover variation caused by human-arm movement error resulting in the longer time required to complete the task as the total traveling distance increases. Note that, the output of interest is the variation in Y axis of the sandblasting nozzle position.

Recently, many variation reduction approaches were proposed to minimize robot movement error [3]. Liu and Zhang, (2014), proposed an adaptive ANFIS model to control human arm movement velocity in gas tungsten arc welding task [5]. Popp et al.,(2016) pointed out the problem of physical interface between human and computer which requires an approach to assist human operator in performing a hand-movement task more comfortable [7]. However, the aforementioned research did not consider the variation in the position caused by human.

Fig. 2: A surface having tele-sandblasting operation where the sandblasting spot is controlled to blasting along target line to blast the path.

Variation caused by human-arm movement error can be divided into two portions: accuracy and precision. A blasting line created by human contains both of them which produce multiple types of possible variation behaviors. Also, for an operator, the behavior was not consistent. Therefore, it is difficult to define a model to estimate the variation for a specific person. Therefore, we proposed a new approach to cope with the problem.

3 Our Proposed Approach

There are two steps in our approach as described in Fig. 3: 1) navigating arm movement pattern and 2) using a linear estimation with Kalman filter

Fig. 3 : diagram describing our proposed approach

3.1 Proposed a navigating arm movement pattern

This step is motivated by noise filtering in electrical signal processing which uses linear estimators or filtering techniques to smooth out the jitter signal. We employ this

concept to solve the variation in position of the master controller in tele-sandblasting application.

The existing approach requires highly skilled operator and takes very long time to train to move along the target line. The reason is that, in the existing approach, a specific guidance is not given to operator. They are allowed to move freely leading to a high variation. Therefore a certain movement must be specified in advance. Following electrical noise filtering, existing arm movement pattern is changed from “straight line following the target” to “jitter line across the target” to imitates the noise in electrical signal, depicted in Fig. 4. After this step, we have a jitter line ready for Kalman filter. Then, Kalman filter is applied to the line to filter the jitter line into a straight line.

To perform the task with our proposed arm movement pattern, during training the operators will be trained by moving the cursor along the guideline to be familiar with the new arm movement pattern before operating the task. Mathematical model to construct the guideline in two dimensional space is expressed in (1). The guideline is shown in Fig. 4(a).

$$\begin{bmatrix} x_t^G \\ y_t^G \end{bmatrix} = \begin{bmatrix} v_x \cdot i \cdot t \\ v_y \cdot i \cdot t \end{bmatrix} + \begin{bmatrix} \frac{v_y}{v_x + v_y} \\ \frac{v_x}{v_x + v_y} \end{bmatrix} (-1)^k \cdot \left(\frac{H}{2} + \frac{H}{k} \cdot (t \bmod j) \right) \quad (1)$$

Where, x_t^G and y_t^G are the positions in x axis and y axis, respectively, at time t . v_x and v_y are the desired blasting velocities of the sandblasting nozzle in x and y directions, respectively (mm./sec.). H is the amplitude (height of the wave). i is the amount of time per interval (second). j is the number of time interval in a half wavelength, depicted in Fig. 4(b). W is the wavelength which can be calculated by using (2).

$$W = 2 \cdot j \cdot t \cdot (\|v_x + v_y\|) \quad (2)$$

(a)

(b)

Fig. 4: (a) An example of a guideline (dash) with a human-made line (solid). (b) The guideline is design to have 10 mm. of amplitude ($Y = -5:5$), 4 mm. of wavelength. Time interval is 0.2 second. The generated guideline truncated by time interval lines, t_n 's.

The shape of the guideline is a connection of multiple waves with equivalent size of amplitude. As human

operated the task, the effect of human-arm movement error caused the difference in the sizes of amplitudes and wavelengths so that the positions form a bell-shape histogram which imitates the random noise behavior in electrical signal.

3.2 Using linear estimation with Kalman filter

Kalman filter is an approach used to minimize output variation by predicting the output based on previous values. Then, update the output based on the error between measured output and predicted output. Practically, Kalman filter works by predicting the current state first. The predicting equation is given in (3).

$$\hat{\mathbf{y}}_t^- = \mathbf{D}_t \hat{\mathbf{y}}_{t-1} + \mathbf{E}_t \mathbf{s}_t \quad (3)$$

Where $\hat{\mathbf{y}}_t^-$ is the predicted current state. $\hat{\mathbf{y}}_{t-1}$ is the state vector containing the sandblasting nozzle positions at time t . $\mathbf{D}_t$ is the state transition matrix which applies the effect of system state parameter(s) at time $t-1$ on the system state at time t . $\mathbf{E}_t$ is the control input matrix which applies the effect of control input parameter(s) in the vector $\mathbf{s}_t$ on the state vector. Then, the confidence of the prediction, $\mathbf{P}_t^-$, is estimated by (4).

$$\mathbf{P}_t^- = \mathbf{D}_t \mathbf{P}_{t-1} \mathbf{D}_t^T + \mathbf{Q} \quad (4)$$

Where $\mathbf{Q}$ is the covariance of the process noise which is assumed to normally distribute with zero mean. After the current state has been predicted by (3) and (4), we then check how good the prediction is using updating equations as follows:

$$\mathbf{K}_t = \mathbf{P}_t^- \mathbf{F}_t^T (\mathbf{F}_t \mathbf{P}_t^- \mathbf{F}_t^T + \mathbf{R})^{-1} \quad (5)$$

$$\hat{\mathbf{y}}_t = \hat{\mathbf{y}}_t^- + \mathbf{K}_t (\mathbf{z}_t - \mathbf{F}_t \hat{\mathbf{y}}_t^-) \quad (6)$$

$$\mathbf{P}_t = (\mathbf{I} - \mathbf{K}_t \mathbf{F}_t) \mathbf{P}_t^- \quad (7)$$

Where $\mathbf{K}_t$ is Kalman gain used in the updating process. $\mathbf{F}_t$ is the observation matrix used to map the true state space into the observed space (unit of measurement). $\mathbf{z}_t$ is the observed state matrix of $\hat{\mathbf{y}}_t$ which is the updated state. The measurement noise is assumed to normally distribute with zero mean and covariance $\mathbf{R}$.

According to Fig. 3, we define that $\mathbf{y}_t^1 = \mathbf{z}_t$ in (6) and $\mathbf{y}_t^1 = \hat{\mathbf{y}}_t$ in (6).

4 Validation of Our Approach

In this section, an experiment is set up to validate our proposed. Then, the results are shown and discussed.

4.1 Experiment Setup

Fig. 5: A virtual tele-sandblasting workstation.

The experiment is conducted on a virtual tele-sandblasting system, depicted in Fig. 5, [8]. The surface for blasting is virtually created with a size of 350 mm. x 25 mm. placed horizontally along the X axis. Pathwidth is

10 mm. wide. The target line is at the middle of the path. The blasting operation is illustrated in Fig. 6.

Fig. 6: A surface to be blasted in the experiment.

Fig. 7: A guideline for the experiment.

The guideline for training is designed to have the amplitude, H , of 10 mm. The wavelength, W , is 6 mm. The amplitude and wavelength are set according to the numbers obtained from our sub experiment to find values that the participant was comfortable with in the movements of wrist and finger during the operation. The proper operating time for our virtual tele-sandblasting system is expected to be in a range of 35-40 seconds. The guideline is shown in Fig. 7.

4.2 Experimental Results and Discussion

In this section, the results obtained from the experiment are discussed. First, the collected data is plotted to see how the proposed arm movement pattern reforms the variation in the output. The plots of the master controller positions over time and the histograms of its position in Y axis of the existing approach and our proposed approach from a participant are shown in Fig. 8.

Fig. 8: An example of the master controller positions over time and the histograms of its position in Y axis. (a) the existing approach and (b) its corresponding histogram. (c) our proposed approach and (d) its corresponding histograms of the positions before filtering.

In Fig. 8 (a), with existing approach, we can see both inaccuracy and imprecision throughout the blasting line. The lack of accuracy was caused by the lack of an ability to guess the target accurately, while with the proper

velocity, the participants struggled to maintain the precision due to the ability in arm control which resulted in high variance in the line. In Fig. 8 (b), a histogram clearly shows low accuracy (the peaks are far away from zero) and imprecision (multiple high frequency bins), suggesting that the existing approach (straight movement) is not consistent and difficult to manage to achieve low variation in the output.

Considering our proposed approach, the plots of master controller positions and the filtered output, shown in Fig. 8(c), are represented by red lines and black lines, respectively. It can be seen that when the participant tried to imitate the guideline under a constraint i.e., proper velocity, the effect of human-arm movement error exists as variation in wavelengths and amplitudes. Focusing on the upper and lower boundaries, it can be seen that the participant failed to navigate the master controller to touch the guideline which is the nature of human. However, this characteristic of the line is suitable with Kalman filter because the error causes the data to form a bell-shape histogram (imitating random noise in electrical signal), shown in Fig. 8(d), which centers closer to zero comparing to that of the existing approach suggesting that the accuracy is reduced. The reason is that although the operator does not know the target position exactly, when he moves the cursor to approximately touch both side of the path alternately, there is a great chance that the cursor frequently crosses the target line so that the frequency of the positions will be high at the value close to zero. Consequently, the filtered output, represented by the black line is straighter and closer to zero than that of the existing approach resulting in lower total variation.

It can be seen that our proposed arm movement pattern incorporating with Kalman filter significantly improves precision and accuracy in the output. This is because moving the master controller across instead of parallel to the target line helps reduce the chance of missing the target line so that the accuracy is maintained. Therefore, the error in accuracy is minimized (close to target). Then, Kalman filter improves the precision (straightness). An example of the results can be seen in Fig. 8(c). The filtered blasting line provides better precision and accuracy which is as impressive as other Kalman applications, [9][10].

We have demonstrated how our proposed approach helps reduce variation due to human-arm movement error in the output of the master-controller stage. During training period, short training time was taken for training each participant with our proposed arm movement pattern. The given feedback from the participant can be concluded that they feel more comfortable and relax with our proposed arm movement pattern and it yet provided better system output as a result.

5. Conclusion

We have demonstrated a new approach which is composed of two steps: navigating arm movement pattern and using a linear estimation with Kalman filter. Our suggested jitter pattern minimizes the error in accuracy while Kalman filter helps improving the precision. Consequently, the total variation is significantly reduced.

The approach is then validated by a virtual tele-sandblasting system. However, in the future, an experiment will be conducted with more number of participants (with different ages and genders) to prove that our approach is applicable for multiple ranges of users.

Our approach can be an efficient alternative for tele-sandblasting task and other similar tasks to assist operators especially for those who prone to make high variation sandblasting nozzle position. Additionally, all participants stated that our proposed approach is more comfortable to perform than the existing approach leading to less stress and fatigue during the operation. We strongly believe that our approach can be applied to other similar applications.

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