The optimization of an autonomous real-time process using curve fitting signature signal

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Abstract—The thread fastening operations have been used for decades with the purpose of joining one component to another. Its tasks are popular because they permit easy to disassembly for maintenance, relocation and recycling. The threaded fastening process is typically carried out manually since it is very difficult problem to automate. As a result, there is very little published research on automating threaded fastenings. This paper investigates the problem of automated monitoring on the screw insertion process. The monitoring problem deals with predicting integrity of a threaded insertion, based on the torque vs. insertion depth curve generated during the insertions. The authors have developed an analytical model to predict the torque signature signals during self-tapping screw fastening. The proposed strategy is integrated with the automating threaded assembly system. The monitoring task needs to be identified and fitted the required signal from the online and optimization process. Its results are shown with up-to five insertion stages can be identified over three different fasteners.

Keywords—Threaded Fastenings, Screw fastening, Screw Insertion, Curve Fitting, Autonomous Threaded Assembly, Optimization.

I. INTRODUCTION

Screw fastenings are a common joining process and are especially popular in assemblies that need to be disassembled for maintenance, repairing, or relocation. A human performing, screw insertion will be typically used for four stages as Alignment, Positioning, Orientation, and Turning of the screw fastening process. Its process is start from the alignment hole, pressing at the position, and turning screw until screw fastening has been achieved[1], [8], [9].

In manual screw fastenings, human operators are particularly good at manual operation. As the torque exerted by the screwdriver depends mainly on the applied operator force. However, with power tools, the increased insertion speed reduces the human ability to monitor the on-line insertion process. Thus on-line automated monitoring strategies for the screw fastening process are highly desirable. One such approach is based on the “Torque signature signal vs. Insertion Depth signal” curve measured in real-time process; if this curve has been within a pre-defined bound of the correct insertion signal, then the insertion is considered to be satisfactory [6], [7]. An automated thread fastening process can be implemented and applied in several forms in different objectives.

With the development of electrically powered screwdrivers the attempts at the threaded fastening process with emphasis on the torque signature vs. Insertion deep signal. In 1997, by Ngemoh had proposed the analytical mathematical model for screw insertion process and implemented later [2].

The Neural Network techniques have been applied by using the ability of Weightless to monitor the screw insertion processes in difference insertion cases [3]. In 2000, Bruno had distinguished between successful and unsuccessful insertion based on Radial Basic function [4]. These monitoring performs are to apply Artificial Neural Network in view points of classifications.

“A distinction without a difference has been introduced by certain writers who distinguish ‘Point estimation’, meaning some process of arriving at an estimate without regard to its precision, from ‘Interval estimation’ in which the precision of the estimate is to some extent taken into account” [13]. Fisher founded the Probability theory as logic agree, which gives us automatically both point and interval estimates from a calculation. The distinction commonly made between hypothesis testing and parameter estimations are considerably greater than that which concerned Fisher. The screw fastening processes have carried out insertion on eight different materials and the self-tapping screws with using mainly screw sizes AB No. 4, 6, and 8. These screw sizes are the most common sizes in manufacturing. The corresponding theoretical profiles of a curve of the torque signature signal and rotation angle have been also generated to compare with the online process in this test.

II. THE EXPERIMENTAL TEST RIG SETUP

The Implementation of Screw Insertion System model has been integrated with three main factors. The first one is the screwdriver with the pilot materials for attempt to insertion screw. The second one is the instruments and sensor controller. This controller consists of the Rotary transducer or Torque sensor for capture a torque signature signal and the Optical Encoder for measurement the rotation angle during the real-time process. This controller is including the torque meter and manipulator equipment. The third one is the optimization system based-on the parameter estimation has employed for monitoring of the required parameters of the threaded fastening process. These factors have implemented and interfaced with Graphical User Interfaces (GUIs) technique.
A. Tools and manipulations

The tools and manipulations are necessary as input devices, which brought the input signal into the process. An electrically powered screwdriver has used with a torque range varying as 3.2 Nm to drive the screw into the hole. An illustration this screwdriver is presented in Figure 1.

B. The instrument and sensor controller

The controller is main function to control the sensors for the on-line operation. The integrated fastening system has been employed and interfaced with the Data Acquisition (DAQ) card. The details of these devices are following.

- Torque Transducer or Torque Sensor.

The rotary transducer in Figure 2 is used in this test, which has attached to the shaft of the screwdriver between the end of screwdriver and the nut settings. The torque sensor is in position that can reduce the effects of inactive and friction associated of the gear and the drive motor. This sensor is a measurement based on strain gauges with capable in measuring torque is in the range between 0.2 and 8 Nm.

- Optical Encoder

The optical encoder has used to measure the rotation angle of the screw. It consists of an optical switch and a measured disc.

- A Multifunction DAQ card.

The multifunction DAQ 12 Bit Analog-Digital I/O card has used in this experimental test is product of National Instrument and Sensor (NI) with model "NI PCI 6024E". The multifunction DAQ is required, which provides the full functionality of I/O 68-pin male 0.050 D-type with voltage output range of ±10 volts.
The DAQ module’s Block Diagram shown in Figure 6 to communicate between the screwdriver, the instruments, and sensors have implemented procedure and applied in Figures 9. This DAQ card shown in Figure 7 has connected with the SH68-68 cable and fixed into PCI slot on computer board. The integrated component system has applied for this test of screw fastening system, which shown in Figures 5 - 8.

- The reference label box or connector box
  This reference label box is used to select the channel, port number, and type of signal to identify during on-line process. This box has connected with the SH68-68 cable to the Multifunction DAQ card, see Figures 7 and 9.

III STRATEGY FOR ONLINE EXPERIMENTAL TEST

The experimental equipments are required to connect as the applied screw fastening software has implemented as the appropriated efficiency system with this integrated system, to get signals from the torque sensor and optical encoder during the screw insertion.

The screw insertions were performed using a screwdriver. A torque sensor mounted at the tip of the screwdriver provides torque readings, and an optical encoder provides pulses, which are related to the screw rotation angle. The stream of pulses was integrated to determine the corresponding insertion depth. Model was developed and using the curve fitting technique to filter the signal. The experimental test rig prior to presentation to the on-line screw fastening process software has shown in Figure 10 and used to manage all instruments and sensors for the input task and interfacing with the screwdriver and linking with the monitoring based-on parameters estimation.

Reading the torque from the torque transducer and the rotation angle from the optical encoder. The captured signal is applied the curve fitting and curve management techniques to identify the curve. The parameter estimation method has used to predict the unknown parameters. This technique has explained for more details in the next section. Curve management process is the straight line technique to find the slope changing for recognition of the insertion torque. These curves presented in Figure 11-12.
A. Curve fitting technique on the experiment

The smooth curve can be fitted and applied to the experimental signal. Using the interpolating polynomial of $n^{th}$ degree then we can obtain a piecewise use of polynomials, this technique is to fit the original data with the polynomial of degree through subsets of the data points. This result is quite suitable approach as a least square fit algorithm.

Curve fitting to measure the signal data is a frequently occurring problem. These signals are two vectors $x$ and $y$ of equal size. The situation is aims to fit the data because being a dependency of $y$ on $x$ in form of a polynomial. Therefore, the higher degree polynomial has represented the dependency for this fitting technique. The least square technique can be used to compute a polynomial for that best fits these data at the degree of the fitted polynomial. This technique has applied on experimentally with the relationship of two variables $x$ and $y$.

The curve fitting method has been employed using an algorithm of the polynomial technique to fit on this captured curve. Then a new smooth curve after fitting process has presented in Figure 12 and the validated curve that compared with theoretical curve are shown in Figure 13.

B. The experiment curve identification

The screw insertion process has been described on the required parameters depend on the each equation in the five different stages of insertion. Therefore, this NRM algorithm has applied with screw insertion process that required the exactly Displacement of depth, which has applied for those curves in each stage. Thus, the curve identification technique has become the important technique to employ for recognition the curves of the torque signature signal and displacement of depth of insertion.

Basically, the actual curve of the torque signature signal and rotation angle is the discontinue curve in each stage of insertions. These stages have divided the nature curves that could be generated from simulation tests or captured during experiment tests. The screw, material, and plate property in Table 1 is used to produce the simulation curve in Figure 14.

<table>
<thead>
<tr>
<th>Material and hole properties</th>
<th>Screw properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material type</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>Thickness</td>
<td>3 mm (0.003 Meters)</td>
</tr>
<tr>
<td>Yield strength</td>
<td>45Mpa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>45Mpa</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>2.35Gpa</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.19</td>
</tr>
<tr>
<td>Tap hole diameter</td>
<td>2.0 mm (0.0020 Meters)</td>
</tr>
<tr>
<td>Type</td>
<td>AB No. 6</td>
</tr>
<tr>
<td>Material</td>
<td>Zinc plated steel</td>
</tr>
<tr>
<td>Major diameter</td>
<td>3.42mm (0.00342 Meters)</td>
</tr>
<tr>
<td>Root diameter</td>
<td>2.49mm (0.00249 Meters)</td>
</tr>
<tr>
<td>Pitch</td>
<td>1.19mm (0.00119 Meters)</td>
</tr>
<tr>
<td>Length</td>
<td>9.67mm (0.00967 Meters)</td>
</tr>
<tr>
<td>Taper length</td>
<td>2.94mm (0.00294 Meters)</td>
</tr>
<tr>
<td>Head screw diameter</td>
<td>6.52mm (0.00652 Meters)</td>
</tr>
</tbody>
</table>

This insertion stage is status of the screw makes first contact with the hole wall in the tap plate. This curve has been identified the insertion stage in Figures 15 - 17. The identified insertion curve at stage 2 has been present in Figure 15.

The torque signal on this curve at stage 4 is straight line. Because this stage is status of Screw sliding. Therefore, this straight line is an identified curve at stage 4 to be present in Figure 16. In Figure 17 shows that the last stage of insertion curve is identified as the stage 5 of curve.
A self-tapping screw insertion process consists of five equations corresponding to each insertion stage [5], [10]-[12]:

\[
\begin{align*}
\tau_1 &= \frac{1}{a} R_s A_c \sigma_{UTS} \cos \theta \phi + \mu R_s K_f \sigma_f \cos \theta \phi \\
\tau_2 &= R_s A_c \sigma_{UTS} \cos \theta \phi + 2 \mu R_s K_f \sigma_f \cos \theta \phi - \alpha \\
\tau_3 &= \frac{1}{a} R_s A_c \sigma_{UTS} \cos \theta \phi + R_s K_f \sigma_f \cos \theta \phi_0 \phi \\
\tau_4 &= 2 \mu R_s K_f \sigma_f \cos \theta \phi_n \\
\tau &= \left[ \left( \frac{D_d^2 + D_h^2}{4} \right) \left( \frac{D_d + D_h}{2} \right) \right] \left[ \frac{\pi(D_d + D_h + 2\mu)}{\pi(D_d + D_h - 3\mu)} \right] K_a K_b
\end{align*}
\]

Equation (1) to (5) can be written as

\[\tau = F(X, \phi),\] (6)

Where \( \phi \) is the angular parameter, \( X \) is vector of parameters: \( X=[D_h, D_r, D_{sh}, P, L_r, L_n, T_2, E, \mu, \sigma_T, \sigma_{UTS}] \).

Where

\[
D_d \text{ and } D_r = \text{ Hole Diameter and Screw root diameter} \\
D_h \text{ and } D_{sh} = \text{ Screw major and Screw head diameter} \\
L_r \text{ and } L_n = \text{ Screw total threaded-length and taper-length} \\
T_1 \text{ and } T_2 = \text{ Tap (near) and Tap (far) plate thickness} \\
\sigma_T \text{ and } \sigma_{UTS} = \text{ Yield Strength and Tensile Strength} \\
\mu = \text{ Coefficient of Friction}, \ P = \text{ Screw thread pitch, and} \\
E = \text{ Elastic Modulus}
\]

In the equations (1) to (5), the following variables, \([\theta, \alpha, \beta, A_c, \phi_0, K_a, K_b, R_s, R_p, D_h]\) are all a function of \(X\), and are given in Appendices. Thus given the system parameter vector \((D_h, D_r, D_{sh}, P, L_r, L_n, T_2, E, \mu, \sigma_T, \sigma_{UTS})\).

These parameters are important parameters that to be both variable and fixed parameters and the set of equations (1) - (5) required these parameters and can be used to predict the torque signature signals. These values could be solved by parameter estimation techniques. As the torque signature signal at stages 1 and stage 3 is very small value.

Initially, the stage 2 equations, that is the torque required to drive the screw from screw engagement till initial breakthrough, is used for parameter estimation in equation (2) and can be written as:

\[\tau_2 = f(\mu, \theta, \sigma_{UTS}, \beta, \phi, D_h, D_{sh}, L_r, P) \quad (7)\]

In conventional estimation theory, these parameters of screw insertion are generally determined using the technique of numerical method with the initial value and number of independent samples. An algorithm of NRM has developed and used for inversion purposes is presented. It achieves convergence in about \(n^m\) iterations and produces exact values of the parameters depends on the number of unknown parameter that is going to apply. The curves of torque signature and insertion angle signal are simulated using the successful data from Ngemoh to validate in different screw, material, and plate properties. The NRM technique is fed with torque-insertion depth signature signals, which is based on the generalization for single parameter.
As considering for the $j^{th}$ function $f_j$ of $n$ functions that define our system. This is to calculate the total derivative as sum of partial derivatives respect to the $n$ variables $\{x_1, x_2, \ldots, x_n\}$ of the functions. However, this model requires various parameters used to automate the operation. The NRM works by modifying the unknown parameters in order to force an error function to approach zero. Both equations (2) and (7) can be revised for the two unknown parameters as: $\tau_2 = F(V,x,\phi)$. Where $V$ is the vector of known parameters $\phi$ is the screw rotation angle, and $x$ is the vector of two unknown parameters ($\mu$ and $D_s$ ) that can be followed:

$$x = \left[ \begin{array}{c} \mu \\ D_s \end{array} \right], \quad f(x, \phi) = \tau_2(\phi) - F(V,x,\phi). \quad (8)$$

Rotation angle $\phi$ is chosen as the independent variable, and the remaining parameters are investigated as a function of $\phi$. The error function $f(x, \phi)$ is sampled at two distinct instances of $\phi$, providing two independent equations, which can be solved in an iterative manner to find the two unknown parameters by generate at two angle locations:

$$f_1(x_1, \phi_1) = 0 \quad \text{at} \quad \phi_1 \quad \text{and} \quad f_2(x_2, \phi_2) = 0 \quad \text{at} \quad \phi_2$$

Let $\bar{X}(k)$ be the $k^{th}$ estimate of the unknown parameters. Applying NRM, $x$ can be calculated iteratively:

$$\bar{X}(k+1) = \bar{X}(k) - J^{-1}(f(x, \phi)) \quad (9)$$

Where,

$$J = \left[ \begin{array}{ccc} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{array} \right] \quad (10)$$

Applying Equation (9) iteratively until the error given in Equation (10) is reduced to a value close to zero will provide an estimate of the unknown parameters.

VI. IDENTIFICATION OF EXPERIMENTAL TEST

The optimization test is tested at stage 2 of screw insertion with properties in Table 1. However, the “torque signature” and “insertion depth” are signals from an online experiment that is fitted with the curve fitting technique. The $D_s$ and $\mu$ are assumed unknown and need to find out.

VII. TEST RESULTS

The estimation algorithm is implemented and tested with and without noise.

Figure 19 shown the estimated $\mu$ and $D_s$ for the case without noise with values of 0.18 and 3.69 mm. However, these actual values are 0.19 and 3.42. The percentage error of $\mu$ and $D_s$ shown in Figure 20. It is noted that the friction value and $D_s$ are estimated as 0.18, and 3.7 m, with an estimation error of 5.26% and 8.18% respectively.

VIII. CONCLUSION

The experimental tests have presented the validation of estimated parameters with the experiment data to validate. The test results can be identified up-to two parameters in this test.

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