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

Mongkorn Klingajay
Industrial Education Faculty
Rajamangala University of Technology Thunyaburi
Pathumthani, Thailand 12120
Email : mongkorn@rmutt.ac.th

Sirisorn Mitranon
Engineering Faculty
Pathumwan Institute of Technology
Bangkok, Thailand 10500
Email : mong_com@go.com

***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.

978-1-4244-1676-9/08 /$25.00 ©2008 IEEE RAM 2008

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.

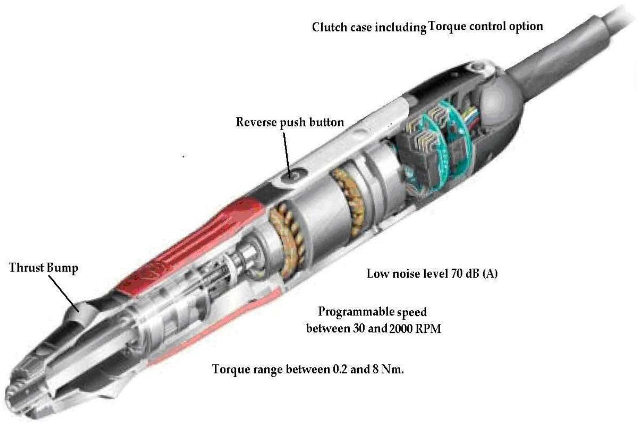


Figure 1. The illustration of screwdriver Components

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.

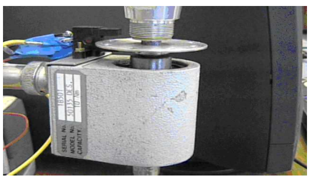


Figure 2. Torque Sensor.

Figure 3. Optical Encoder

The Torque sensor was electronically interfaced with a digital torque meter that is produced. The voltage output of torque reading from the torque meter is proportional to the measured torque during process into the hole. Each output has corresponded to the maximum capacity of torque at 10 Nm.

- Optical Encoder

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

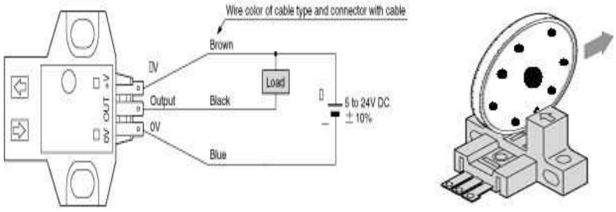


Figure 4. Wiring diagrams Optical Encoder & Dics application

The optical switch has functioned with a light sensitive device with a built-in an amplifier, the shape and wiring diagram are presented in Figures 3 and 4. Its performance is to fix-focus reflective/u-shaped type micro-photo sensors low-cost performance, it is stable detected by fixed-focus reflective. A measurement disc has attached to the Torque sensor, which fixed at the shaft of the driver bit see Figs 4 and 5. This disc is perforated every 45° allowing 8 readings per revolution. The Optical encoder has a measurement resolution of 45°, the digital signal of a pulse voltage is converted to the rotation angle during screw insertion. This applied system for reading signal on 8 holes as angle has present in Figure 5.

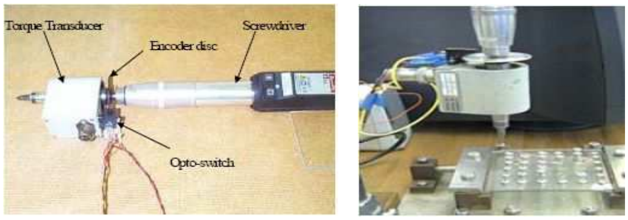


Figure 5. The applied system with Transducer &encoder

- 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.

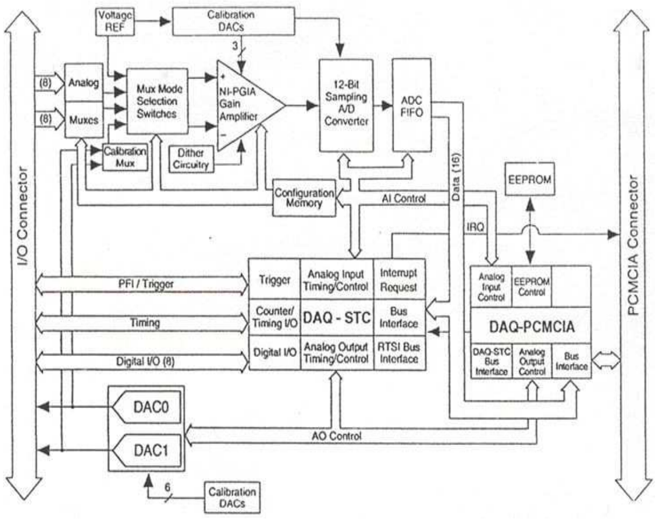
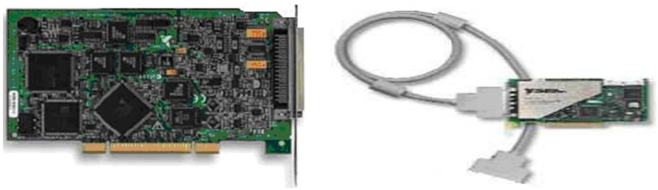


Figure 6. DAQ card-6024E Block Diagram



(a). DAQ PCI card (b). DAQ card with Cable

Figure 7. A multifunction NI DAQ PCI 6024E card.

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.

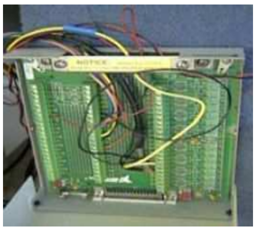


Figure 8. The wiring circuit in the Connector box.

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.

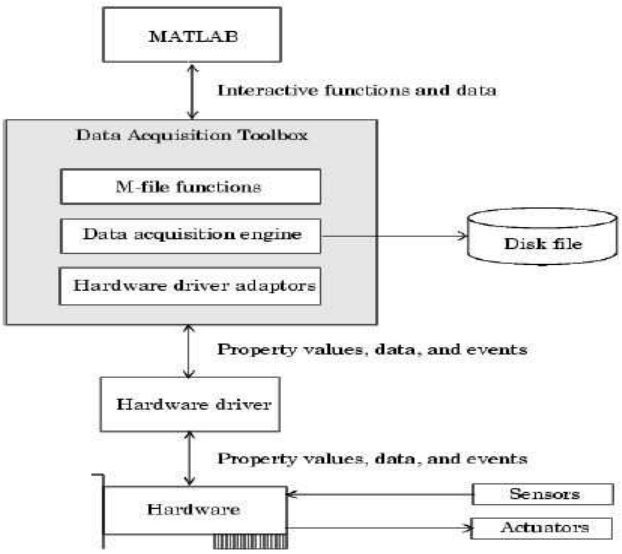


Figure 9. Flowchart of the on-line procedures

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.

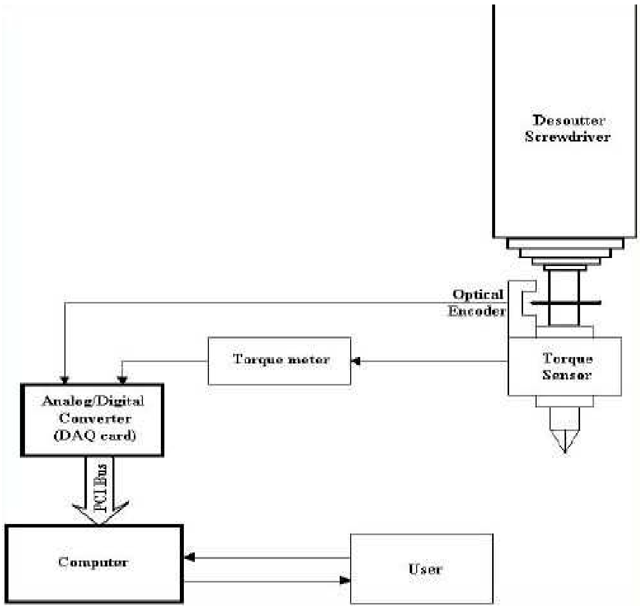


Figure 10. The overview of the experimental test rig

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 slop changing for recognition of the insertion torque. These curves presented in Figure 11-12.

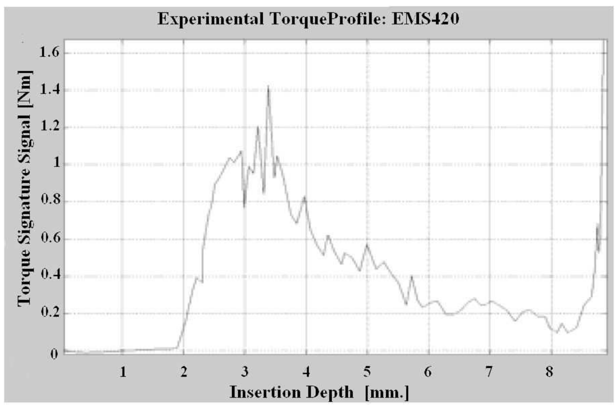


Figure 11. The result from online experimental test.

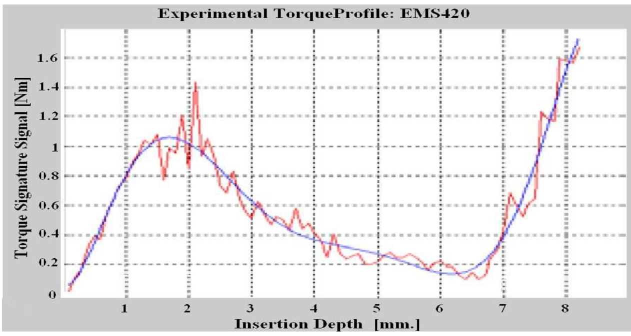


Figure 12. The signal fitted by the curve fitting technique

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 Figure13.

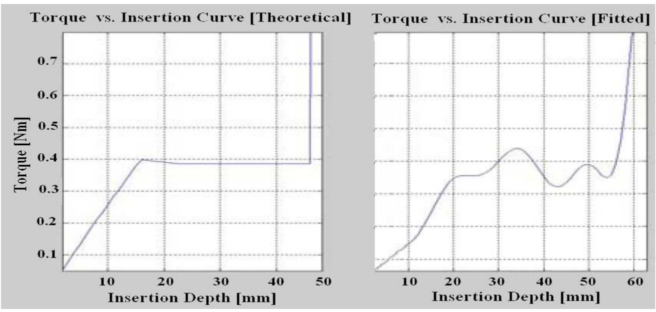


Figure 13. The theoretical and experimental curves.

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.

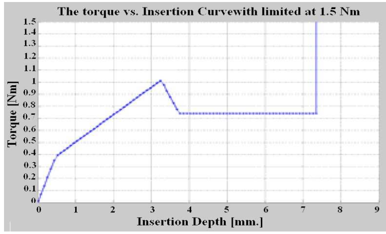


Figure 14. The curve for screw AB6 with Polycarbonate

TABLE1. PARAMETERS FOR SCREW AB6 WITH POLYCARBONATE

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

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.

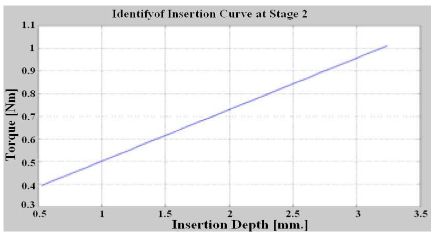


Figure 15. The identified insertion curve as stage 2

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.

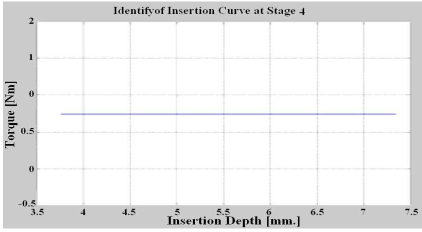


Figure16. The identified insertion curve as stage 4

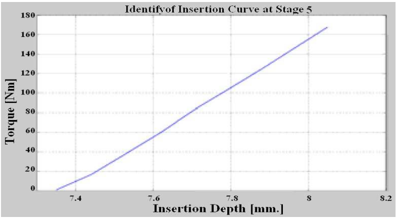


Figure 17. The identified screw insertion curve as stage 5

The estimation algorithm has applied the torque signature signal and rotation angle signal after fitting the smooth curve. This smooth curve has fitted after the experimental tests.

IV. METHODOLOGY

The appropriable techniques for the particular attention in this paper devote to discussions about the Newton Raphson Methods (NRM) is a choice of appropriate minimization criteria and the robustness of this application. The monitoring strategies have been applied the parameter estimation techniques to validate the insertion process in this test.

This paper is to apply the estimated parameter application based on NRM for threaded fastening process with testing on the torque signature vs. insertion angle. The model based monitoring has implemented with following the estimation parameters Scheme in Figure 18. The required parameters have read the input data with contain both known and unknown parameters. A V vector consists of known parameters, the rotation angle(ϕ), a torque signature signal (τ), and the unknown parameter is a vector x_n that be initialed value.

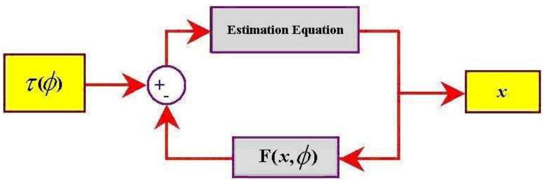


Figure 18. Estimation Parameters Scheme

V. ANALYTICAL MODEL

The focus on the experimental test parameter estimation based on NRM, which is the non-linear estimation parameter techniques that can solve problem over threaded fastening for screw insertion process. With parameters on the screw properties, plate properties, and material properties including friction, these techniques have been applied to predict two unknown parameters in this paper. These two unknown parameters are required by the mathematical model can be estimated reliably on-line experimental results without noise is presented to validate the estimation procedure in this paper.

A self-tapping screw insertion process consists of five equations corresponding to each insertion stage [5], [10]-[12]:

$$\tau_1 = \frac{1}{\alpha} R_s A_c \sigma_{UTS} \cos\theta . \phi + \mu R_f K_f \sigma_f \cos\theta(\phi) \quad (1)$$

$$\tau_2 = R_s A_c \sigma_{UTS} \cos\theta + 2\mu R_f K_f \sigma_f \cos\theta(\phi - \alpha) \quad (2)$$

$$\tau_3 = \frac{1}{\alpha} R_s A_c \sigma_{UTS} \cos\theta + \mu R_f K_f \sigma_f \cos\theta(\phi_b + \phi) \quad (3)$$

$$\tau_4 = 2\mu R_f K_f \sigma_f \cos\theta(\phi_b) \quad (4)$$

$$\tau_5 = \left[\left(\frac{\mu(D_{sh}^3 + D_s^3)}{3(D_{sh}^2 - D_s^2)}\right) + \left(\frac{D_s + D_h}{4}\right)\left(\frac{\pi\mu(D_s + D_h) + 2P}{\pi(D_s + D_h) - 2\mu P}\right)\right]\left[\frac{K_{th} K_{tb}}{K_{th} + K_{tb}}\right] \quad (5)$$

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

$$\tau = F(X, \phi), \quad (6)$$

Where ϕ is the angular rotation, X is vector of parameters: $X=[D_h, D_r, D_s, D_{sh}, P, L_s, L_t, T_1, T_2, E, \mu, \sigma_Y, \sigma_{UTS}]$.

Where

D_h and D_r = Tap Hole Diameter and Screw root diameter
D_s and D_{sh} = Screw major and Screw head diameter
L_s and L_t = Screw total threaded-length and taper-length
T_1 and T_2 =Tap (near) and Tap (far) plate thickness
σ_Y and σ_{UTS} = Yield Strength and Tensile Strength
μ = Coefficient of Friction, P = Screw thread pitch, and
E = Elastic Modulus

In the equations (1) to (5), the following variables, [θ, α, β, A_c, ϕ_b, K_{th}, K_{tb}, R_s, R_f, K_f] are all a function of X, and are given in Appendixes. Thus given the system parameter vector (D_h, D_r, D_s, D_{sh}, P, L_s, L_t, T_1, T_2, E, μ, σ_Y, σ_{UTS}).

These parameters are important parameter 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:

$$\tau_2 = f(\mu, \theta, \sigma_{UTS}, \beta, \phi, D_s, D_h, L_t, P) \quad (7)$$

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^{th} 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 generalitazion 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 ϕ is the screw rotation angle, and x is the vector of two unknown parameters (μ and Ds) that can be followed[10]:

$$x = \begin{pmatrix} \mu \\ D_s \end{pmatrix}, \; f(x, \phi) = \tau_2(\phi) - F(V,x,\phi). \qquad (8)$$

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

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

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

$$\bar{x}(k+1) = \bar{x}(k) - J^{-1} \begin{pmatrix} f_1(x, \phi_1) \\ f_2(x, \phi_2) \end{pmatrix} \qquad (9)$$

Where,

$$J = \begin{bmatrix} \dfrac{\partial f_1}{\partial x_1} & \dfrac{\partial f_1}{\partial x_2} \\ \dfrac{\partial f_2}{\partial x_1} & \dfrac{\partial f_2}{\partial x_2} \end{bmatrix} \qquad (10)$$

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"curves are signal from the on-line experiment that is fitted with the curve fitting technique. The Ds and μ are assumed unknown and need to find out.

VII. TEST RESULTS

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

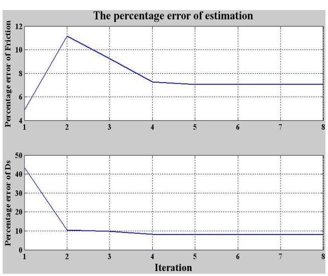


Figure 19. Percentage error.

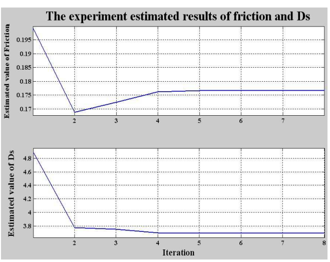


Figure 20. Estimated parameters.

Figure 19 shown the estimated μ and Ds for the case without noise with values of 0.18 and 3.69 mm. However, these actual values are 0.19and 3.42. The percentage error of μ and Ds shown in Figure 20. It is noted that the friction value and Ds 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.

ACKNOWLEDGMENT

Dr. Mongkorn Klingajay is lecturer at Rajamangala University of Technology Thunyabury, Thailand, he graduated Ph.D in Robotics Engineering from King's College London. And Mr. Sirisorn Mitranon is lecturer at Pathumwan Institute of Technology, Thailand, he hold a Master degree in Electrical engineering from King's Mongkut Ladkabang, Thailand. Both worked together in area of electronic and control engineering.

REFERENCES

[1] L.D. Seneviratne, F.A. Ngemoh and S.W.E. Earles. "Theoretical Modeling of Screw Tightening Operations," proceedings ASME European Joint Conference on Systems, Design and Analysis, 1992, vol. 1, pp.189-195.

[2] F.A.Ngemoh,"Modelling the Automated Screw Insertion Process",Ph.D.Thesis, University of London. 1997.

[3] P.Visuwan, "Monitoring Strategies for Self-Tapping Screw Insertion Systems",Ph.D.Thesis,University of London, 1999.

[4] B.L.Guzman, "Intelligent Monitoring of Screw Insertions", Ph.D.Thesis, University of London, 2000.

[5] L.D. Seneviratne, F.A. Ngemoh, S.W.E. Earles and K. Althoefer, "Theoretical modelling of the self-tapping screw fastening process", PartC, Journal of Mechanical Engineering Science (IMechE), 215:135-154, 2001.

[6] M.Klingajay, L.D.Seneviratne, "Friction Estimation in Automated Screw Insertions", proc. of Inter. Symposium on Robotics & Automation (ISRA02), Vol.1,pp.682-688.

[7]M.Klingajay, L.D.Seneviratne, K. Althoefer,"Parameter estimation during automated screw insertions", proc. of IEEE International Conference on Industrial Technology (ICIT02),Vol.II, pp.1019-1024.

[8]M.Klingajay,L.D.Seneviratne,K.Althoefe,"Identification of threaded fastening parameters using the Newton Raphson Method", proc. of RSJ International Conference on Intelligent Robots and Systems(IROS2003), Vol.1, pp.5055-2060.

[9] M. Klingajay, L. D. Seneviratne, N.I. Giannoccaro, "Optimization of four estimated parameters for autonomous threaded fastenings", proceedings of 12th International Workshop on Robotics in Alpe-Adria-Danube Region, RAAD2003, 2003, Italy.

[10] M. Klingajay, L. D. Seneviratne, Kaspar Althoefer, "Model Based Automation Strategies for Threaded Assembly Systems", proc. of International Federation of Automatic Control (IFAC), Problems in Manufacturing (INCOM2004), Brazil.

[11] M. Klingajay, N. I. Giannoccaro, "Parametric Estimation of Autonomous Threaded Fastenings Operation based on Non-linear Least Square Method", proc. of the ISCA 16th International Conference: Computer Application in Industry and Engineering (CAINE03),Vol.1,pp.211-215.

[12] M. Klingajay, N. I. Giannoccaro, "Comparison between Least Square & Newton Raphson for Estimation Parameters of an Autonomous Threaded Fastenings", proc. of 2003 IEEE International Conference on Industrial Technology (ICIT'03), Vol. 1, pp.163-168.

[13] Fisher, R. A., "Statistical Methods and Scientific Inference", Oliver & Boyd, Hafner Publishing Co., New York, 1959.