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Real-time detection of grip length deviation for fastening operations: a Mahalanobis-Taguchi system (MTS) based approach

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REAL-TIME DETECTION OF GRIP LENGTH DEVIATION FOR FASTENING OPERATIONS: A MAHALANOBIS-TAGUCHI SYSTEM (MTS) BASED APPROACH

by

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ABSTRACT

Hand-held fastening tools are extensively used in manufacturing, especially in aerospace industry. Typically, the process is monitored by the operator and joints are visually inspected after the process is completed. When complex products, such as an aircraft, are considered, fastening process and its inspection can be very time consuming. In addition, no inspection data is typically collected during the process unless a major problem is encountered. Real-time monitoring and verification of the fastening process of joint quality are two important advancements to reduce the manufacturing lead time while ensuring safety and quality.

The first paper presents a Mahalanobis-Taguchi System (MTS) based methodology that detects grip length of bolted joints in real-time during fastening. A pneumatic, hand-held, rotary-type tool for bolted joints is integrated with sensors in order to obtain torque-angle signatures. The proposed approach reads in various characteristics from the torque-angle signature in order to infer about the quality of the bolted joint. The experimental results show that the proposed approach is successful with an accuracy of over 90% in detecting various grip lengths.

In the second paper, the same methodology is extended to a pull type pneumatic handheld tool. The tool is integrated with sensors to capture the process signature. The process signature of strain-over-displacement ratio versus displacement has shown unique features that are extracted to determine the quality of the fastening process. The experiments have shown that the proposed approach is successful, with an accuracy of over 95%, in determining the quality of fastening operations and in communicating the quality information in real-time using a wireless network to a base station.

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REAL-TIME DETECTION OF GRIP LENGTH DURING FASTENING OF BOLTED JOINTS: A MAHALANOBIS-TAGUCHI SYSTEM (MTS) BASED APPROACH

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ABSTRACT

This paper presents a Mahalanobis-Taguchi System (MTS) based methodology that detects grip length of bolted joints in real-time during fastening. Grip length is the length of the unthreaded portion of a bolt shaft. When the total thickness of joining members is greater than the grip length of the bolt, it is called under-grip, which compromises the structural integrity of a joint. In this study, a pneumatic, hand-held, rotary-type tool for bolted joints is integrated with a torque sensor and an optical encoder in order to obtain torque-angle signatures. Then, the signature is processed in real-time using the MTS-based approach in order to detect the grip-length, all of which occurs in real-time as the fastening process is completed.

The proposed approach reads in various characteristics from the torque-angle signature, including mean and standard deviation of the torque-over-angle and angle-over-torque ratios, total angle turned, and work done during the different stages of the fastening process in order to infer about the quality of the bolted joint. The experimental results show that the proposed approach is successful with an accuracy of over 90% in detecting various grip lengths.

1. INTRODUCTION

Threaded fasteners are extensively used in the manufacturing industry for connecting two or more members that can be disassembled when needed without destructive methods [1]. An acceptable threaded fastening process requires application of proper torque in order to induce a certain level of clamp force on the joint that leads to a reliable assembly. It is typical to monitor the torque level in order to ensure the desired level of clamp force. On the other hand, several problems, such as cross-threading, excessive friction, screw jamming, slippage, etc., hinder the potential success of sole torque monitoring during the fastening process and might lead to wrong conclusions about the process quality. To mitigate such consequences, torque and rotation angle are monitored. Nevertheless, when complex products, such as aircrafts, with many components to be joined are considered, inspection of such joints to ensure that the right size fasteners have been used at the right sections of the product becomes a very time-consuming and costly process. Usually, such an inspection procedure requires a sampling-based approach, as opposed to 100 % inspection.

Threaded fasteners are basically of two types, screws and bolts. Screws are used on components with tapped holes, while bolts require nuts to facilitate assembly. There are also self-tapping screws that do not require a tapped hole [2,3]. Overall, installation cost of fasteners costs four times than the procurement cost [4]. Inspection of joints is usually carried out visually and/or on a sampling basis, and requires rework. In addition, there is a large cost factor due to manual labor and more importantly a safety issue related to the actual clamp force on the joint, which determine a product's reliability. Therefore, there is a need for a robust in-process diagnostics scheme, along with the necessary hardware, equipment, and application software, to (1) capture certain process characteristics during fastening, (2) analyze the signature, and (3) determine if any abnormalities exist in real-time. With this motivation, this paper presents the design and development of a sensor-embedded fastening tool used for bolt and nut type of joints (will be referred to as “bolted joints” for the remainder of the paper) and discusses the preliminary results of the Mahalanobis-Taguchi System (MTS) scheme implemented on the tool to detect abnormalities in real-time on a torque-angle signature.

As shown in Figure 1, grip length of a bolt is the length of the unthreaded portion of the bolt shaft. Structural integrity of products is compromised when the grip length of a bolt is longer or shorter than the total thickness of the material to be fastened. If the grip length is short, the threads of the bolt will extend into the bolt hole and act as a reamer. If the grip length is too long, the nut will run out of threads before it can be tightened.

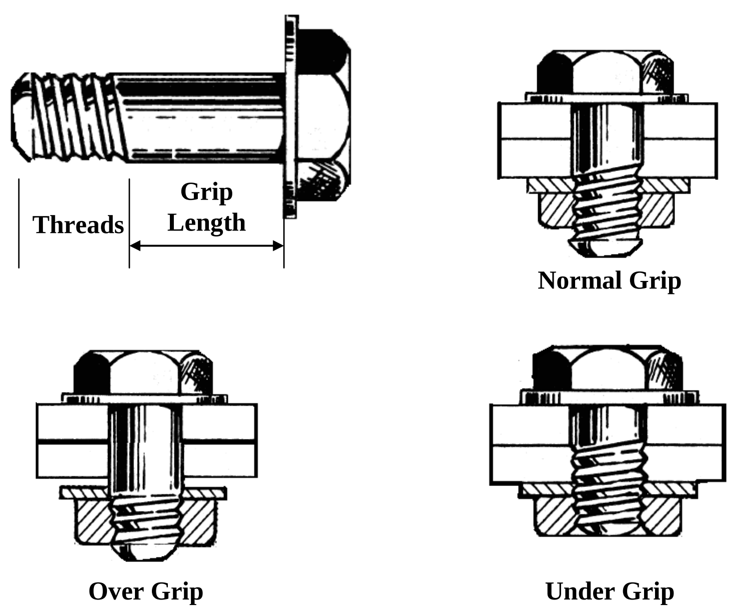


Figure 1 Grip Length

The paper is organized as follows. Section 2 presents the literature survey on the previous work done in this field. Section 3 presents an overview of the torque angle analysis. Section 4 explains the Mahalanobis Taguchi Strategy. Section 5 presents and discusses the experimentation and results and section 6 concludes the paper.

2. LITERATURE SURVEY

Screw insertions account for almost a quarter of all assembly operations employed in the manufacture of commercial products [2]. Most insertions in the manufacturing process have the purpose of affixing one component to the other. Of the two methods, which include self-taping screws and bolted joints [3], this paper is focused on bolted joints. Bolted joints are one of the most commonly employed fastening processes, where the joining members can be disassembled for repair, maintenance, or relocation [1,4].

There is relatively limited academic literature that focuses on real-time (i.e., in-process) monitoring fastening process quality and detecting possible failure modes, such as cross-threading, thread stripping, excessive friction between the nut and the bolt, etc. Torque and angle of rotation are the common characteristics that related studies in the literature are focused on to verify the quality of fastening. Methodologies include Newton Raphson method for threaded fasteners [5, 6], statistical pattern recognition [7], least square method [6,8], and neural networks [9]. Most of these studies are focused on self-tapping screws.

In spite of the scarcity of studies in the academic literature, there are many patents in this area, as shown in Table 1. The most common failure modes considered in these patents related to cross-threading or defective threads [10,14,15,17,19,21]. Other failure modes include improper final clamp force [12,15,16,20,22] and improper fastener diameter [18]. Most of the work described in the patents use torque-angle analysis as the main method [13-17, 22]. On the other hand, some patents use only torque [12, 18] whereas some others employ torque versus time signature [10]. It is also very common in most of the patents [10,13-17,19-22] to have a torque sensor integrated with a fastening tool in order to directly obtain torque readings, while some methods employ secondary means, such as monitoring the current on the motor that drives the tool [11,12,18].

Numerous methods have been proposed to best utilize the torque-angle signature in order to infer about the fastening quality. For instance, in [16], the area under the initial phases of the torque-angle signature is calculated, which is the work done, in order to find the friction-related failures, such as cross-threading, thread stripping, or similar defective threads. By comparing the amount of work done during the initial stages of fastening process with the work done under the ideal torque-angle signature, it is possible to detect friction-related failures. Another approach is to calculate the slope on a torque-angle signature and to compare it with the ideal slope [13,17,19,20].

Table 1 Overview of Patents: Fastener Inspection and Process Monitoring

Patent #	**Ref #**	**Title**	**Author(s)**	**Year**	**Scope**	**Failure mode(s) addressed**
3,962,910	10	Method and apparatus for fastener tension inspection	E. G. Spyridakis, E. E. Rice, J. Seccombe	1976	Torque-time or torque-angle relationship. Checks if a predefined torque value was attained in the specified time/angle.	Detects insufficient final torque, cross threading, defective threads or thread stripping

Table 1 Overview of Patents: Fastener Inspection and Process Monitoring (Contd.)

4,013,895	11	Clamping tool and method	T. Akiyoshi, H. Shibuya	1977	The tool is driven using an electric motor. The condition of the axial force on the members is detected by monitoring current/voltage/number of rotations/power of the motor. It claims that when the differential coefficients of the measured quantities reach 0, that corresponds to the yielding point and the operation is stopped.	Stops the operation at a desired clamp force. Detects errors that contribute towards the variations in clamp force of the joint.
4,095,325	12	Method for tightening bolts	H. Hashimoto, K. Mori	1978	The bolt is initially turned at high speed and then switched to a lower speed towards the completion of the operation. This is done in order to reduce overrun due to the inertia force when the rotation of the bolt is stopped at the tightening point.	Detects friction variations between the bolt and the member, over tightening of the bolt
4,102,182	13	Quality checking system for a threaded fastener assembly	L. R. Brown, N. L. Field	1978	Monitors the rate of increase of torque w.r.t angle within predetermined torque limits.	Detects cross threading, presence of extraneous metals and surface irregularities at the friction surface between the head and the member
4,208,775	14	Method and apparatus for making threaded joints	R. L. McCombs, J. V. Motsinger	1980	Used to tighten threaded pipe joints. The applied torque is monitored and when a reference torque is exceeded the number of turns made is counted. When either the actual torque or the actual turns are within a predefined percentage of the predefined minimum value for that parameter and the other parameter has exceeded a minimum value, the operation is stopped.	Reduces the probability of threads getting damaged while fastening and indicates the operator when to stop.
4,305,471	15	Simplified fastening technique using logarithmic rate method	S. Eshghy	1981	The fastening tool is incorporated with torque and angle sensors and is connected to an analog calculating circuit which determines while tightening below the yield point of any component of the joint being tightened, a final shutoff parameter that varies from joint to joint.	Makes a proper bolted joint by shutting off the tool as soon as it reaches the desired torque/tension

Table 1 Overview of Patents: Fastener Inspection and Process Monitoring (Contd.)

4,400,785	16	Microprocessor monitoring system for fastener tightening	W. K. Wallace, G. A. Giardino, R. Groshans	1983	A method for monitoring torque and angle developed upon a fastener during run-up and setting, which method utilizes successive area measurements under the torque-angle curve, said areas being compared at predetermined torque levels to provide an indication of whether or not the entire operation satisfies an established criteria	Detects cross threading, defective threads and misassembled (loose) fastening and overall fastening acceptability by comparing it with data from a known proper operation.
4,620,450	17	Method of evaluating tightening condition of screw	I. Yamaguchi	1986	Torque and angle are monitored. Rate of change of torque w.r.t angle is calculated and the operation is terminated when the force imparted exceeds the elastic limits and reaches a predetermined tightening point.	Detects if the torque angle signature follows a predetermined pattern by looking into the rate of change of torque w.r.t angle.
4,959,797	18	System for tightening threaded fastener assemblies	J. L. McIntosh	1990	Fastener assembly tool is affixed to a DC motor. The torque is controlled by controlling the current through the winding. An angular position encoder, attached to a microprocessor, monitors and controls the shaft motion. It divides the fastening operation into 5 phases, starting phase, run-on phase, run on end phase, tightening phase and an end phase. Monitors acceleration and velocity change to determine the changes in phase.	Detects cross threading, defective threads, improper bolt size(diameter), improper thread pitch and other abnormalities indicated by the thread frictional resistance.
5,284,217	19	Apparatus for tightening threaded fasteners based upon a predefined torque-angle specification window	S. Eshghy	1994	Tightening is controlled based on a torque-angle window defined by a low angle limit, a high angle limit, a low torque limit and a high torque limit.	Overall tightening of the fastener (failure mode is improper tension in the joint)
5,404,643	20	Method of monitoring threaded fastener tightening operations	E. E. Rice	1995	Monitors torque-angle characteristics. Checks for the presence of bearing in a fastener assembly by studying the slopes at various points in the torque angle curve.	Detects if a bearing is present, defects in the bearings or the crank shaft. Defects include, improper inserts, over and undersized bearing bores.

Table 1 Overview of Patents: Fastener Inspection and Process Monitoring (Contd.)

5,591,919	21	Method and apparatus for monitoring and controlling tightening for prevailing torque fasteners	T. J. Hathaway, F. L. Schmid, E. E. Rice	1997	Fastener tightening during the proportional zone is controlled by monitoring the prevailing torque during the non proportional zone in the torque angle curve,	Detects friction related damages like cross threading, damaged threads, improper part fit or missing parts.

Although the approach proposed in this paper uses the typical torque-angle signature, which has been used by several researchers, it is unique due to the following reasons:

1. Grip-length has not been studied previously. Under-grip condition, which may lead to structural failure of joints, if not detected, is a very critical failure mode, especially for the aerospace industry where there are many types and lengths of fasteners that are used on an aircraft. Such a large variety of fasteners can lead to using a wrong size fastener on a joint.

2. The approach employs a Mahalanobis-Taguchi System (MTS) based scheme to detect grip length. Unlike other studies that focus on a single parameter, such as the slope or area under the torque-angle signature, the MTS-based methodology allows for using multiple characteristics in order to ensure the success rate of detecting the grip length. In addition, it uses orthogonal arrays and signal-to-noise ratio to screen important characteristics so that the complexity of the problem can be reduced without loss of performance; thus computational time is reduced making it appropriate for real-time applications.

3. The prototype fastening tool is equipped with not only process-related sensors, such as torque, optical, and pressure sensors, but also embedded hardware for making decisions in real-time and wireless communication capabilities to communicate the result of torque-angle signature analysis to the base-station. The wireless communication capabilities are required due to tool mobility.

4. Overall, this approach allows for data collection on 100% of the joints in real-time as opposed to sampling-based statistical process control methods that are applied after the fastening process as stand-alone operations, which increase the manufacturing lead time.

MTS is widely used as a pattern recognition tool for various applications that deal with data classification [23,24]. MTS is a combination of the Mahalanobis Distance (MD) and the Taguchi method. The MD method is used for constructing a measurement scale while the Taguchi method is used to optimize the system and make it robust [25]. MTS provides a measurement scale to measure the degree of abnormality on a continuous scale. Using this feature of MTS, the proposed methodology has the ability to classify different grip lengths.

MD measures distances in multidimensional spaces by taking into account the correlation among characteristics. In other words, MD is a measure of the nearness of a data-point to the mean of a group. There are other multivariate measurement techniques, such as the Euclidean distance, that give the distance to the "unknown" point from the mean point. On the other hand, the Euclidean distance does not give a statistical measurement of how well the unknown matches the reference set and it measures only a relative distance from the mean point and does not take into account the distribution of the points in a group [26].

The main reason why MD is used in this research is because of its sensitivity towards inter-variable changes in data. MD is measured in terms of standard deviations from the mean of the samples, which provides a statistical measure of how well the unknown data set matches with the ideal one. Another reason why MD is preferred over classical methods is due to its dependence on the variance and covariance of the data rather than its average, which makes the calculations robust [26].

3. TORQUE-ANGLE ANALYSIS

Torque-angle analysis provides a very practical and powerful technique for visualizing and evaluating the joint integrity for a fastening process [14-18, 22]. A typical torque-angle signature, shown in Figure 2, consists of four primary zones:

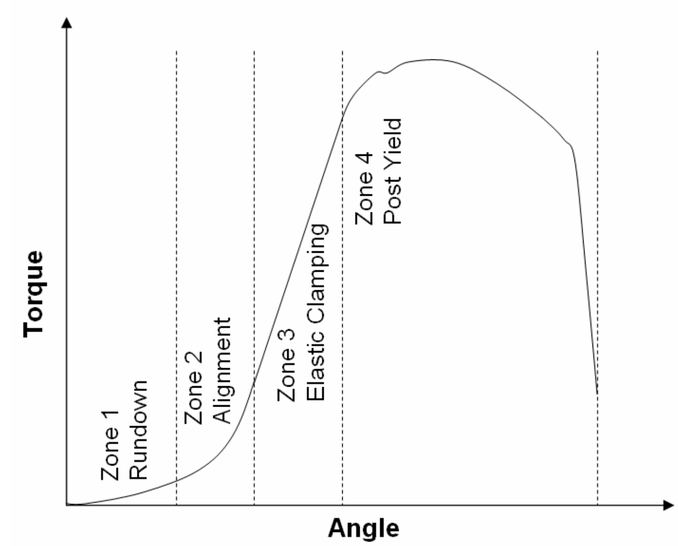


Figure 2 Torque-Angle Signature

Zone 1 Rundown: This zone consists of the prevailing torque zone where the nut is run down the length of the bolt until contact with the first joining member [27]. This zone has different curves in the literature. Some sources show a linear/flat curve [22,27]. This is intuitive because the only force that the rotary tool should have to overcome after all the threads are engaged is the frictional force of the thread mesh. This assumption does not hold if there is a self locking presence in the structure. Therefore, it is suggested that there will be a slight non linear function until all the threads have engaged the mesh [27,28]. It is possible that this curve will be near straight depending on the consistency of the thread mesh [29].

Zone 2 Alignment: In this zone, the nut comes into contact with the first joining member or washer. This zone is non-linear and is affected by multiple variables; therefore, it is by far the most complicated zone to model [27]. In this zone, as torque is applied, the nut and bolt assembly begins to draw the joining members together, therefore eliminating any gap present in the joined members. This is the time where the bolt underhead pressure begins to increase as it is mated with the joining material. Alignment and stress induced effects, which are related to deformation of plating, coatings, and threads, occur in this zone.

Zone 3 Elastic Clamping: This zone relates the mechanical energy provided by the tool directly to applying preload to the joint. This zone stays approximately at a steady slope until the applied torque takes the bolt into plastic deformation [27,30]. Most pre-calibrated tools are designed to reach their clutch point before plastic deformation occurs.

Zone 4 Post Yield: The post yield zone begins with the inflection point of the signature showing the end of elastic deformation. This zone may show critical torque values that may overstress the fastener, thus destroys the joint. It is important to note that the forth zone can be due to yielding in the joint or in a more elastic member, such as a gasket or sealant [27].

Deviation in shape and pattern in a torque-angle signature, when compared with an ideal signature, can be indicative of abnormalities, such as cross-threading, thread stripping, or under grip. For instance, an under-grip joint will reach its maximum torque in fewer rotations of the nut than a normal-grip joint. In addition, when material properties of joining members are changed, it is reflected on the signature. Therefore, detecting abnormalities on a torque-angle signature becomes a pattern recognition problem. On the other hand, visually detecting such abnormalities is not always possible, as in the case of grip length. For such cases, robust techniques, as the one proposed in this paper, are essential.

4. MAHALANOBIS-TAGUCHI SYSTEM (MTS)

The first step in MTS is to define and sample "normal" observations to construct a reference space, which is called the Mahalanobis Space (MS). MS consists of the mean vector, standard deviation vector, and correlation matrix of the normal group [26].

A pattern recognition problem starts with data collection on normal observations. Next, Mahalanobis Distance (MD) is calculated using certain characteristics to determine if MD has the ability to differentiate the normal group from an abnormal group. If MD is not capable of detecting the abnormal group using those particular characteristics, then other characteristics need to be explored. When the right number of characteristics for calculating MD are determined, then Taguchi methods are applied to evaluate the contribution of each characteristic and if possible to reduce the number of characteristics. Taguchi method uses orthogonal arrays and signal-to-noise ratios to choose such variables of importance.

MTS consists of four phases [24, 26]:

Phase 1: Construction of MS

1. Define the characteristics that determine the healthiness of a condition. In this paper, it involves identifying the characteristics from torque-angle signatures that are known to be from good fastening operations (i.e., normal behavior).
2. Calculate the mean for each characteristic in the ideal data set:

$$\overline{x_i} = \frac{\sum_{i=1}^{n} X_{ij}}{n} \tag{1}$$

3. Calculate the standard deviation for each characteristic:

$$s_i = \sqrt{\frac{\sum_{i=1}^{n} \left(X_{ij} - \overline{x_i}\right)^2}{n-1}} \tag{2}$$

4. Normalize each characteristic, form the normalized data matrix (Z_{ij}), and take its transpose ($Z^T{}_{ij}$):

$$Z_{ij} = \frac{\left(X_{ij} - \overline{x_i}\right)}{s_i} \tag{3}$$

5. Verify that the mean of the normalized data is zero:

$$\overline{z_i} = \frac{\sum_{i=1}^{n} Z_{ij}}{n} = 0 \tag{4}$$

6. Verify that the standard deviation is one:

$$s_z = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{ij} - \overline{z_i}\right)^2}{n-1}} = 1 \tag{5}$$

7. Form the correlation matrix (C) for the normalized data. The matrix elements (c_{ij}) are calculated as follows:

$$c_{ij} = \frac{\sum_{m=1}^{n}\left(Z_{im} Z_{jm}\right)}{n-1} \tag{6}$$

8. Calculate the inverse of the correlation matrix (C^{-1}).
9. Calculate MD:

$$MD_j = \frac{1}{k} Z_{ij}^{T} C^{-1} Z_{ij} \tag{7}$$

where

x_{ij} is the i^{th} characteristic of the j^{th} observation,

n is the number of observations,

s_i is the standard deviation of the i^{th} characteristic,

Z_{ij} is the normalized value of the i^{th} characteristic of the j^{th} observation,

s_z is the standard deviation of the normalized values,

C is the correlation matrix,

C^{-1} is the inverse of the correlation matrix,

MD_j is the Mahalanobis distance for the j^{th} observation, and

k is the number of characteristics.

Phase 2: Validation of MS

For validation of MS, observations outside the normal group are selected and respective MD values are calculated. The characteristics of the abnormal group are normalized using the mean and standard deviations of the corresponding characteristics in the normal group. The correlation matrix corresponding to the healthy group is used to compute the MDs of the abnormal cases. If MS is suitable for the application domain with the appropriate characteristics selected, then the MDs corresponding to the abnormal group will have higher value than that of the normal group.

Phase 3: Identification of Useful Characteristics

The right set of characteristics is determined using orthogonal arrays (OAs) and signal-to-noise ratios (S/N). The signal-to-noise ratio, obtained from the abnormal MDs, is used as the response for each combination of OA. Orthogonal Array is a table listing all the combinations of the characteristics. Level-1 in the orthogonal array column represents the presence of a characteristic and level-2 represents the absence of that characteristic. The size of the orthogonal array is depends on the number of characteristics and the levels it can take. By varying the number of characteristics used, MD values are obtained for the abnormal cases and from these MD values, the larger the better signal-to-noise ratio is obtained [23,24,26] as follows:

$$\eta_q = -10\log\left[\frac{1}{t}\sum_{j=1}^{t}\frac{1}{MD_j}\right] \quad (8)$$

Where,

η_q is the signal-to-noise ratio for the q^{th} run of the orthogonal array

t is the number of abnormalities under consideration

An average S/N ratio at level-1 and level-2 is obtained for each characteristic. Subsequently, gain in S/N ratio values for each characteristic is calculated [23,26] as follows:

$$Gain = (Avg. S / N\ Ratio)_{Level-1} - (Avg. S / N\ Ratio)_{Level-2} \quad (9)$$

Finally, the characteristics with positive gain are identified as useful in the detection of anomalies and the rest of the characteristics are discarded.

Phase 4: Decision-making

Using the MS constructed by the useful characteristics, monitor the application, collect data, calculate MD, and if MD >> 1, then the application exhibits abnormal behavior. In this case, determine under which MD range, the MD of the current application falls, and then take the respective corrective action. If MD ≤ 1, the conditions are normal.

5. PROPOSED METHODOLOGY

In this study, a pneumatic, hand-held, rotary-type tool for bolted joints is integrated with a torque sensor and an optical encoder to obtain torque-angle signatures. The tool is also equipped with wireless communication capabilities via a mote for (1) making decisions on the tool regarding the grip length; (2) communicating with a base station that displays the signature and the decision; and (3) reliable data transfer through implementation of the optimized energy-delay sub-network routing (OEDSR) protocol

[31] with multi-hop, non line-of-sight radio communications capability for obstacle-rich environments. In order to avoid possible variations in the torque-angle signature due to air pressure changes, the tool is also equipped with a pressure sensor. At low pressures, which can happen in industrial settings when there are pneumatic equipment and tools operating at the same time, the tool sends a low pressure signal to the base station without executing the proposed MTS-based approach. The tool is shown in Figure 3.

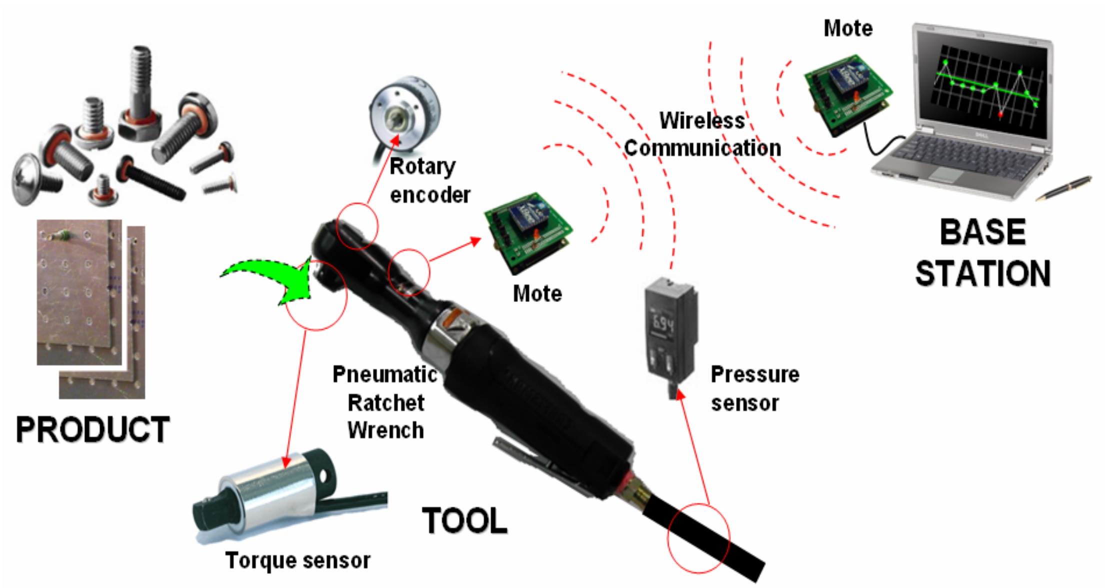


Figure 3 Sensor-Equipped Rotary Tool with Wireless Communication Capabilities

MTS can be used at two levels. At the basic level, first an ideal torque-angle signature can be obtained as a result of several replications of normal fastening operations using the right bolt, nut, and material(s). Second, since any other bolt/nut/material combination will have a different torque-angle signature, such cases, which are different than the ideal condition, will be detected by MTS as abnormal. On the other hand, the reason for abnormality cannot always be determined if no prior investigation of abnormalities and respective MD calculations have not been done.

At an advanced level, MTS can be used as a tool for root-cause analysis to detect the reasons for abnormality, which requires more experiments by reproducing each abnormality and calculating its MD value with respect to the ideal data. This is the approached adopted in this study. As shown in Figure 4, if there are N cases of abnormalities, then an MD range corresponding to each case is determined with respect to the ideal case.

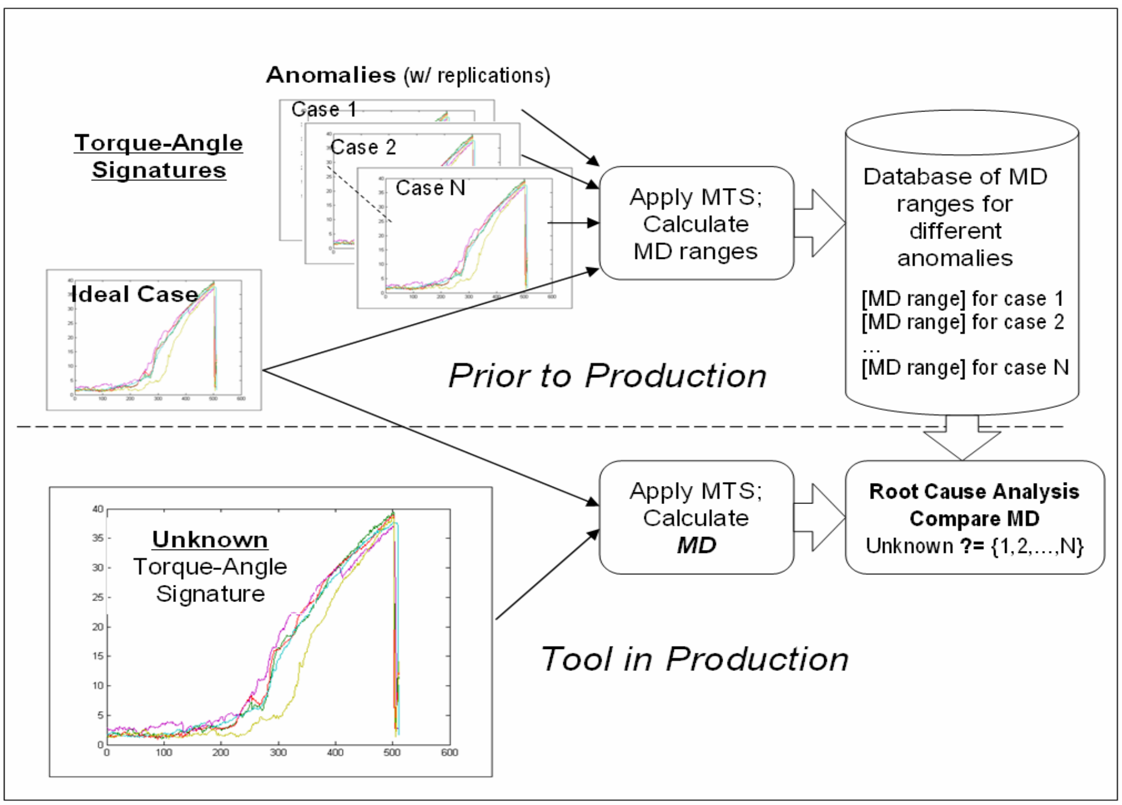


Figure 4 MTS as a Tool for Root-Cause Analysis

It is more likely to have a variation among the replications for each case, therefore instead of a single MD value, an MD range is determined for each abnormality. Then, when an unknown torque-angle signature is obtained when the tool is in production, it can be analyzed using the correlation matrix and its MD value is calculated. Then, depending on which MD range it falls under, the type of abnormality is determined.

5.1 Experimentation

In order to validate the MTS-based methodology and not to complicate data collection, the initial phase of the experimentation has been carried out with the tool connected to a laptop computer, without the wireless communication feature. The laptop computer includes a data acquisition card and runs a MATLAB® based graphical user interface. A second MATLAB® script runs the MTS methodology and makes real-time decisions. After the initial phase of the experiments, the decision-making logic has been implemented on a mote integrated with the sensors on the tool; torque-angle signatures are analyzed on the tool and final decision about the grip length is communicated to a base station.

As shown in Figure 5, a 0.25" diameter bolt and four aluminum plates with thicknesses (i.e., grip lengths) of 0.20", 0.25", 0.30", and 0.35" are used for experimentation. Of these four thicknesses, 0.20" is the normal grip case based on the type of the bolt. The other three thicknesses are the under grip cases.

In Phase 1 of MTS application, seven characteristics on the torque-angle signature, as shown in Figure 6, are identified:

1. **$(T/A)_{mean}$**: Mean of Torque/Angle ratio
2. **$(A/T)_{mean}$**: Mean of Angle/Torque ratio

3. **$(T/A)_{std}$**: Standard deviation of Torque/Angle ratio
4. **A_{total}**: Total Angle turned
5. **$T_{mean,\ Z1}$**: Area under the torque-angle signature in Zone 1 (i.e., work done) divided by the total angle turned in Zone 1.
6. **$T_{mean,\ Z2}$**: Same as in (5) – for Zone 2.
7. **$T_{mean,\ Z3}$**: Same as in (5) – for Zone 3.

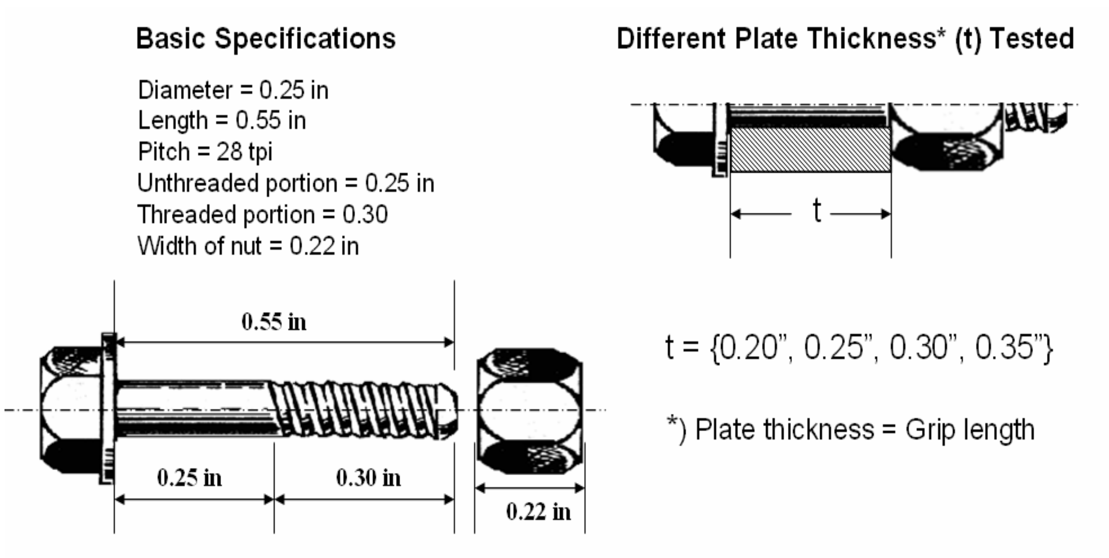


Figure 5 Bolt-Nut Dimensions and Different Grip Lengths Tested

The Mahalanobis Space (MS) is then formed using the torque-angle data collected from bolted joints on the 0.20" thick plate (normal group) using the aforementioned seven characteristics. Mean torque values for the zones (i.e., characteristics 5, 6, and 7) are determined visually on the torque-angle data obtained from the 0.20" thick plates. The same torque values are then used as a general threshold to distinguish the zones for the other plates.

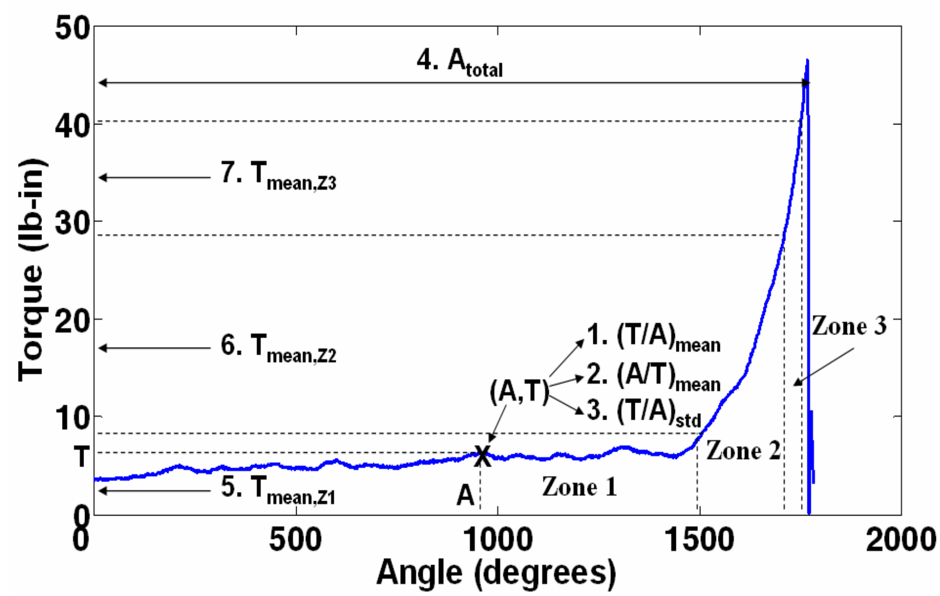


Figure 6 Initial Characteristics Identified for MTS Implementation

The MD values (Equation 7) for the normal group range from 0.1 to 1 with an average MD of 0.67. In Phase 2, the MS, as the measurement scale, is validated. The torque-angle data collected from 0.25”, 0.30”, and 0.35” thick plates (abnormal cases) using the same type of bolt and nut are processed using the same MS. Sample torque-angle signature for each grip length is shown in Figure 7. The MD ranges for 0.25”, 0.30”, and 0.35” thick plates are [8, 25], [80, 120], and [130, 170], respectively. Therefore, the MTS approach clearly distinguishes between different plate thicknesses; hence, the selected scale is validated.

In Phase 3, the impact of each characteristic identified in Phase 1 is investigated using orthogonal arrays and S/N (signal to noise) ratios (Equation 8). Then, the gain (Equation 9) is calculated for each characteristic for two of the abnormal cases, 0.25” and 0.30” thick plates. Since the initial number of characteristics is 7, a L_8 (2^7) orthogonal array is used. As shown in Table 2, $(A/T)_{mean}$ and $T_{mean,Z3}$ do not have significant impact on MD. Therefore, the number of characteristics is reduced from 7 to 5, including A_{total} with the highest impact and $(T/A)_{std}$ with the least impact.

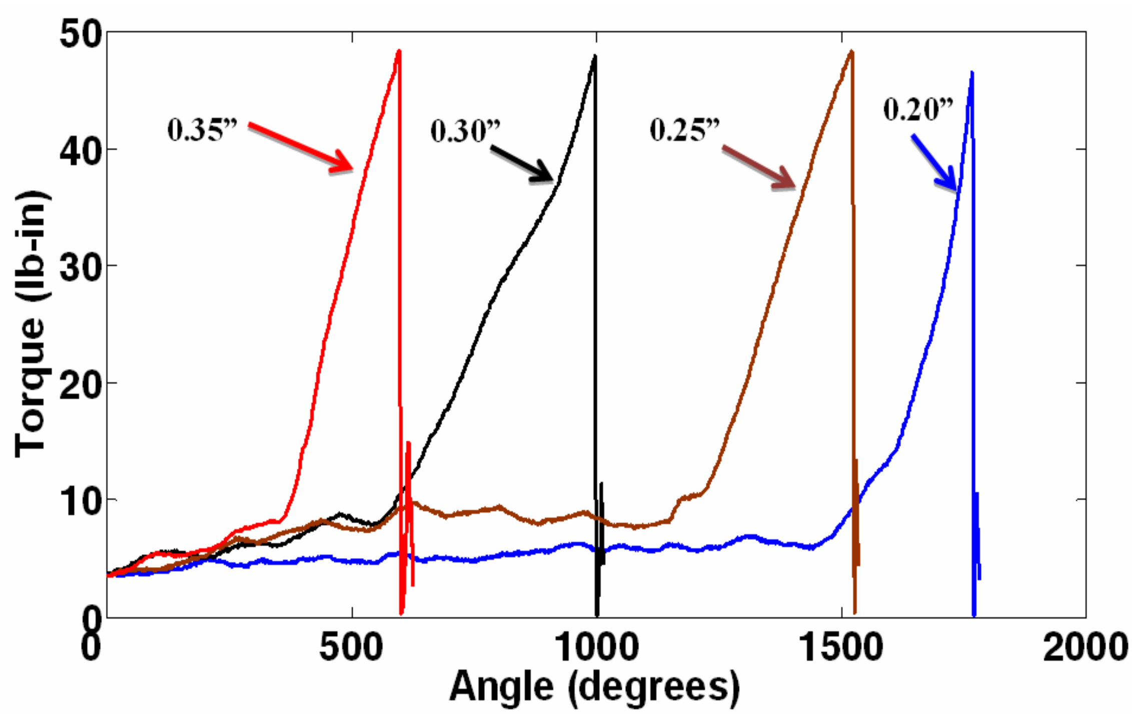


Figure 7 Typical Torque-Angle Signatures for Various Grip Lengths

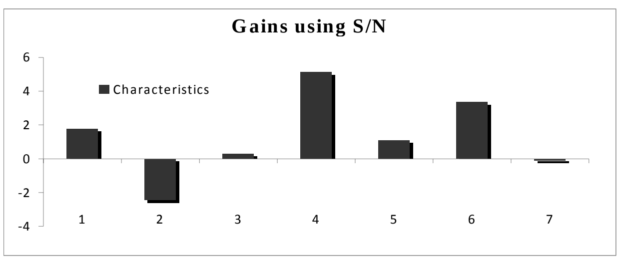
After the insignificant characteristics are screened out, the MS and MD are recalculated using the significant characteristics. As it is shown in Table 3, the MD ranges, therefore the distinction among the normal and abnormal groups, are improved. The new MD ranges for 0.25”, 0.30”, and 0.35” thick plates are [35, 65], [205, 275], and [315, 330], respectively.

In Phase 4, plates with different thicknesses are tested using the MS and the MD ranges calculated in the previous phases. In addition to previously determined thickness of 0.25”, 0.30”, and 0.35” plates, new plate thicknesses of 0.24”, 0.27”, and 0.33” are also introduced in order to validate the strength of the proposed MTS implementation. The MD ranges for 0.24”, 0.27”, and 0.33” plates are found to be [30, 45], [45, 75], and [210, 285], respectively. The results of the final experiment are summarized in Table 4.

Table 2 Screening of Characteristics

Characteristics	1	2	3	4	5	6	7	MD Values		S/N
Run (L_8)	$(T/A)_{mean}$	$(A/T)_{mean}$	$(T/A)_{std}$	A_{total}	$T_{mean, Z1}$	$T_{mean, Z2}$	$T_{mean, Z3}$	0.25"	0.30"	(Eqn 8)
1	1	1	1	1	1	1	1	49.99	205.74	19.05
2	1	1	1	2	2	2	2	26.78	178.26	16.68
3	1	2	2	1	1	2	2	42.13	365.34	18.78
4	1	2	2	2	2	1	1	38.20	190.04	18.04
5	2	1	2	1	2	1	2	47.34	117.45	18.29
6	2	1	2	2	1	2	1	25.93	140.81	16.41
7	2	2	1	1	2	2	1	36.96	261.91	18.11
8	2	2	1	2	1	1	2	45.89	98.76	17.97

S/N when characteristic is present	72.55	70.44	71.82	74.24	72.22	73.35	71.62
S/N when characteristic is absent	70.79	72.90	71.52	69.10	71.12	69.99	71.72
Gain (Eqn 9)	1.76	**-2.46**	0.29	5.14	1.10	3.36	**-0.11**



Significant Characteristics

1	$(T/A)_{mean}$
3	$(T/A)_{std}$
4	A_{total}
5	$T_{mean, Z1}$
6	$T_{mean, Z2}$

The MTS methodology has successfully detected the grip lengths of 0.20”, 0.25”, 0.30”, and 0.35” with a detection rate of 100%, 97%, 95%, and 87%, respectively. The grip lengths of 0.24”, 0.27”, and 0.33” were unknown to the tool. Nevertheless, the methodology has either detected them as one of the known grip lengths, (i.e., 0.25”, 0.30”, or 0.35”), or categorized them in a grip length range as [0.20”, 0.25”], [0.25”, 0.30”], or [0.30”, 0.35]. In either case, the margin of error has never been more than 0.05”.

Table 3 Comparison of MD Values Before and After Screening of Characteristics

Characteristics	1	2	3	4	5	6	7	MD Values*	
Grip Length	$(T/A)_{mean}$	$(A/T)_{mean}$	$(T/A)_{std}$	A_{total}	$T_{mean, Z1}$	$T_{mean, Z2}$	$T_{mean, Z3}$	Before	After
0.20"	0.005	263	0.003	1823.5	4.1	18	38.7	0.80	0.55
	0.005	267.6	0.003	1830	3.9	18.1	38.9	0.30	0.27
	0.005	267.6	0.003	1830	3.9	18.1	38.5	0.70	0.27
	0.004	252.2	0.002	1835.5	4	18.1	38.5	0.90	1.16
	0.005	275.5	0.003	1851	3.9	18.1	38.5	0.70	0.15
	0.005	272.5	0.003	1895.5	3.9	18.1	39.8	0.70	0.12
	0.005	287.3	0.003	1901	3.9	18.1	39.3	0.50	0.14
	0.005	275.5	0.003	1903.5	3.9	18.1	39.7	0.60	0.14
	0.005	243.3	0.003	1936	4.3	18.1	39.4	0.50	0.98
	0.005	270.9	0.003	1994	3.9	18.2	39.3	1.00	1.05
							Average:	0.67	0.48
							Range:	[0.30,1.00]	[0.27,1.05]
0.25"	0.006	178.1	0.002	1522	4	19.4	40.1	18.10	36.28
	0.007	155	0.003	1683.5	5.9	18.2	38.3	11.90	36.43
	0.007	188.1	0.002	1557	5.4	18.3	38.8	8.70	38.08
	0.005	216.1	0.002	1298	3.6	19.2	39.6	15.80	43.68
	0.009	140.8	0.005	1298	4.2	18	39.8	22.90	46.03
	0.006	190	0.002	1298	3.5	18.7	40.5	16.50	46.45
	0.008	149.7	0.005	1286.5	3.8	18.1	39.9	21.50	52.32
	0.007	154.7	0.002	1522	5.6	18.1	39.3	8.60	57.17
	0.005	215.1	0.002	1388	3.3	19	39.9	13.50	61.63
							Average:	15.50	44.56
							Range:	[8.60,22.90]	[36.28,61.63]
0.30"	0.011	108.6	0.007	878.5	2.3	17.6	39.5	110.60	205.23
	0.013	106	0.008	876	2.5	18.4	40.6	96.30	211.69
	0.013	141.1	0.006	836.5	2.5	18.4	38.9	81.90	212.03
	0.013	106.2	0.007	981.5	1.9	18.2	40	96.40	220.12
	0.014	141.7	0.007	898	2.7	18.4	40.5	91.20	225.24
	0.013	108.2	0.007	875.5	2.3	18	38.1	107.40	228.42
	0.014	126.8	0.007	934.5	2.5	18.2	40.7	98.70	236.53
	0.014	152.4	0.008	805.5	2.4	19.3	41.6	89.00	247.07
	0.014	92	0.008	771	2	19.3	41.1	90.70	263.50
	0.014	156.3	0.007	717.5	2.1	19.4	39.7	84.00	264.22
	0.014	157.6	0.007	837	2.5	17.9	40.5	120.70	267.43
	0.015	137.5	0.007	787.5	2.5	19.4	40.5	82.60	272.94
							Average:	96.99	234.68
							Range:	[81.90,120.70]	[205.23,272.94]
0.35"	0.012	110.8	0.009	527.5	2.9	18.1	40.5	145.80	316.81
	0.014	94.7	0.01	563	2.7	18.3	37.9	166.40	319.87
	0.012	114.8	0.01	594	2.2	18.5	38.8	146.90	333.24
	0.012	99.6	0.01	612.5	3.3	17.8	38.6	167.10	335.19
	0.011	127	0.01	618.5	2.8	18.4	40	138.10	341.93
	0.012	104	0.01	650	2.5	18.5	39.8	135.70	349.74
							Average:	152.86	329.41
							Range:	[135.70,167.10]	[316.81,329.41]

*) *"Before" screening (all 7 characteristics), "After" screening (characteristics 1,3,4,5, and 6)*

5.2 Variability in Torque-Angle Signatures

The signatures obtained during the experimentation have exhibited a wide range of variation within the same group. It can be attributed to two main factors: Plate thickness variation and Operator variation.

Plate thickness variation is caused by the tolerance range specified by the manufacturer. When the tolerance range of each plate is considered, there is significant variation in thickness. The thickness ranges for 0.20", 0.24", 0.25", 0.27", 0.30", 0.33", and 0.35" thick plates are [0.188", 0.212"], [0.225", 0.256"], [0.238", 0.262"], [0.256", 0.284"], [0.282", 0.318"], [0.310", 0.351"], and [0.329", 0.372"], respectively. In other words, a 0.27" thick plate can have a thickness of 0.256", while a 25" thick plate can actually be 0.262" thick. Therefore, a part of the overlap between the MD ranges (Table 4) can be caused by the overlap between the thickness ranges of plates used during the experiment.

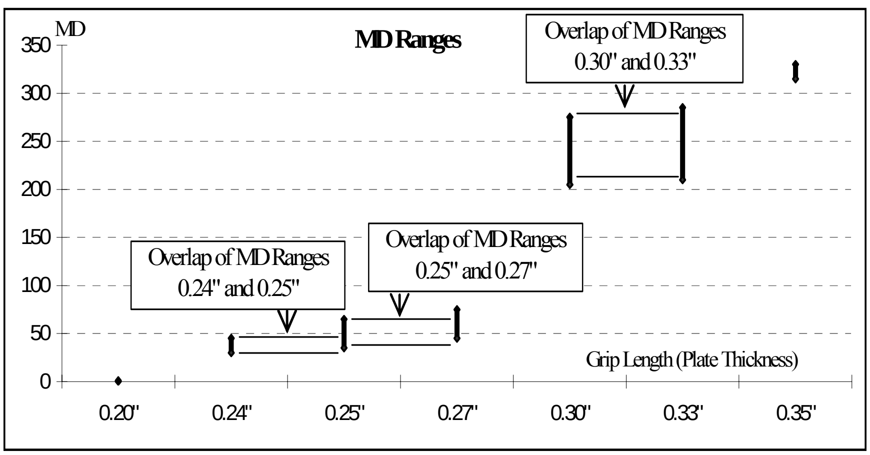
The second variability introduced is due to the manual run-down of the nut by the operator in the beginning of the operation. The operator places the nut on the bolt and turns it manually before using the tool to run it down. This initial angle is not recorded by the hand-held tool, which affects the overall angle turned used in the MTS methodology. Based on the specifications shown in Figure 5, the nut advances 0.01" for each 100^o turn. In other words, a full rotation of the nut corresponds to 0.036" of linear movement.

The experimental results show that, even for unknown thickness, the MTS methodology determines, with 100% success rate, what thickness range a plate falls under. For the particular plates selected for this study, the thickness ranges are 0.05" apart, which corresponds to 1.4 rotations of the nut. Therefore, the MTS methodology has a precision of 0.05" in determining grip lengths for the experimental conditions described in this study.

Table 4 Results of the Experiment: Detection of Grip Lengths

Grip Length*	MD Range	No of Trials	Correct Detection	False Detection	No of False Detections
0.20"	[0.27, 1.05]	30	100%	0%	0
0.24"	[30, 45]	20	70%	30%	6 of them detected as 0.25"
0.25"	[35, 65]	30	97%	3%	1 of them detected as 0.27"
0.27"	[45, 75]	25	80%	20%	5 of them detected as 0.25"
0.30"	[205, 275]	40	95%	5%	2 of them had very large MD
0.33"	210, 285]	20	20%	80%	16 of them detected as 0.30"
0.35"	[315, 330]	15	87%	13%	2 of them had very large MD

) 0.24", 0.27", and 0.33" are new plates - not tested before.



In order to improve the methodology, plates with small tolerance ranges can be used. The operator variation can be reduced by paying more attention to being consistent for each joint for manual run-down of the nuts. However, these conditions may not be justified for some production environments, where detecting under-grip conditions may not be the main concern.

6. CONCLUSIONS

It is observed that Mahalanobis distance is a reliable metric to monitor process quality and is able to classify unknown datasets that are multivariate in nature. MTS is proven to be able to distinguish between the various failure modes occurring during fastening with acceptable accuracy. There can be a scenario where two distinct data sets having the same correlation between the characteristics getting detected falsely, other than that the system is very robust and accurate.

MTS has illustrated its ability to screen out the characteristics that does not contribute towards the decision making. In the study, the 7 characteristics were reduced to 5 thereby reducing the computational complexity. This has significant impacts on operations that take into account inputs from several sensors to make decision, by reducing the number of characteristics that needs to be monitored for actual decision making. This in turn results in relatively less complexity and money savings.

Wireless implementation shows that such a methodology is practical and reliable for in-process quality control in the shop-floor environment. Such real-time quality control process reduces the amount of post-process quality control thereby saving expended capital. Similar methodologies implemented over wireless sensor networks can be very effective in other manufacturing environments as well.

In this case, practicality requires wireless communications (1) to facilitate information and data flow between tools and the base station, (2) for reliable data transfer through implementation of the optimized energy-delay sub-network routing (OEDSR) protocol [31] with multi-hop, non line-of-sight radio communications capability for obstacle-rich environments.

The proposed architecture has merits to (1) detect and report quality problems in real-time during the process , (2) reduce the number of characteristics needed for decision making, thereby reducing the complexity of the procedure, and (3) reduce post-process inspection, thereby improving quality while reducing cost and man power. In addition, the approach facilitates 100% data collection, for future analysis, on each fastener as opposed to traditional statistical process control (SPC) techniques, which rely on sampling.

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PAPER II

REAL-TIME DETECTION OF GRIP LENGTH DURING FASTENING USING PULL TYPE TOOLS: A MAHALANOBIS-TAGUCHI SYSTEM (MTS) BASED APPROACH

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ABSTRACT

In this paper, a diagnostics and root-cause analysis scheme for real-time monitoring of process quality of pull-type fastening operations is presented. The proposed approach encompasses (1) integrating a strain gage, an LVDT (Linear Variable Differential Transducer), a pressure sensor, and a mote on a pull-type pneumatic tool; (2) monitoring process characteristics coming from embedded sensors communicated wirelessly via the mote and generating process signatures in real-time; and (3) detecting anomalies in real-time in the process signatures for quality problems related to the fastening process. A novel diagnostic and root cause analysis scheme based on Mahalanobis-Taguchi Strategy (MTS), for monitoring the quality in real-time is introduced in this paper. The process signature of strain-over-displacement ratio versus displacement has shown unique features that are extracted to determine the quality of the fastening process. The scheme takes as input various characteristics like the peak strain, peak displacement, the depth and width of the dip present in the strain-over-displacement ratio versus displacement plot to make decisions.

The overall architecture has been implemented on a Huck45 pull-type tool, which is a hand-held pneumatic fastening tool used extensively in the aerospace industry, with lock-bolt fasteners. The prototype has been tested under a variety of experimental settings in order to verify its effectiveness and validate its performance over a wide range of different sheet metal thicknesses used for fastening. The experiments have shown that the proposed approach is successful, with an accuracy of over 90%, in determining the quality of fastening operations and in communicating the quality information in real-time using a wireless network to a base station. The most common fault scenario has been

tested: i.e., varying grip lengths (normal, over, and under-grip scenarios). Overall, the proposed architecture has merits to (1) detect quality problems in real-time during the fastening process and (2) reduce post-process inspection, thereby improving quality while reducing cost. In addition, the approach facilitates 100% data collection on each fastener as opposed to traditional statistical process control (SPC) techniques, which rely on sampling.

1. INTRODUCTION

Hand-held fastening tools are extensively used in manufacturing, especially in aerospace industry. Such tools are prone to human error; typically the process is monitored by the operator and joints are visually inspected with very limited use of gages after the process is completed. Installation of fasteners may incur up to 80% of the total fastening costs while the remaining 20% is for procurement of fasteners [1]. When complex products, such as an aircraft, are considered, fastening process and its inspection can be a very time consuming task. In addition, no inspection data is typically collected during the process unless a major problem is encountered. Real-time monitoring of the fastening process and verification of joint quality are two important factors to reduce the manufacturing lead time while ensuring safety and quality.

In this study, a pull-type fastening tool has been, (1) integrated with sensors and (2) equipped with a mote for on-the-tool, real-time decision-making and wireless communication. The tool is capable of monitoring pull-type fastening processes and determining the grip length deviation for joints as normal grip, under grip, or over grip employing the decision-making methodology that resides on the mote.

As shown in Figure 1, a typical pull-type (i.e., tension) tool operates as follows:

1. Fastener is inserted into the hole and the collar is placed over the fastener pintail.
2. The tool nosepiece is placed on the shank of the fastener. When the tool is actuated, the pintail is pulled against the push on the collar. As a result, the head of the fastener is seated into the hole and the tool starts swaging the collar.
3. Continued swaging of the collar forces the collar material into the pin locking grooves creating an extrusion action that stretches the collar, which results in a corresponding stretch of the pintail.
4. When collar is completely swaged (i.e., collar is resting against the plate), the tool continues pulling the pintail until it breaks at the break neck groove. The nosepiece is then removed away form the joint and the pintail is discharged.

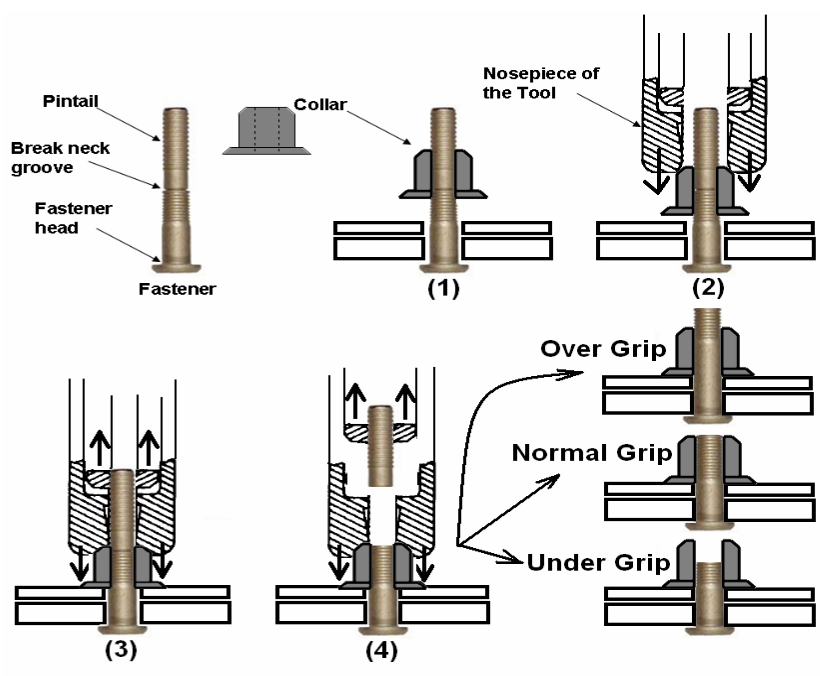


Figure 1 Operation of the Fastening Tool and Types of Grip Length Deviations

One of the quality issues for this operation is caused by a mismatch between the fastener/collar length and the plate thickness. If the plates are thicker or equivalently the fastener is shorter, then the break neck grove stays inside the collar, which is the under-grip condition. If the plates are thinner or equivalently the fastener is longer, then the break neck grove sticks out of the collar, which is the over-grip condition. In both cases, the strength of the joint is compromised. As shown in Figure 1, for normal grip condition, the sizes of the plates and the fasteners match so that the break neck groove breaks almost flush with the top of the collar.

The focus of this study is to automatically determine the grip length deviation as normal grip, under grip, or over grip in real-time during the operation of a sensor-integrated tool and to communicate this information to a centralized database server via wireless networking.

2. LITERATURE SURVEY

The most common approach to ensure that fasteners of correct grip length are being used in a fastening operation is to use gages and probes after the operation is completed. Such post-process inspection techniques increase the overall manufacturing lead time since they are conducted as a stand-alone process using a different tool than the fastening tool. Due to this fact, joints are usually inspected on a sampling basis, as opposed 100% inspection. Therefore, not only the manufacturing lead time is increased but also some defective joints can pass through unnoticed.

A survey of patents in this area is summarized in Table 1. The techniques are either pre-process or in-process monitoring. In pre-process monitoring the fastener grip length to be used are detected using measuring probes [2, 3], image processing systems

[4] or measuring gages [5, 6]. In-process monitoring address detection methodologies for quality issues and failure modes such as proper orientation of fasteners [7], improper fastener head heights [8], improper rivet lengths [9], improper fastening joints due to insufficient force deformation [10] and improper plate thickness [11, 12]. In [11], the authors propose a methodology for detecting under grip and over grip cases and improper material usage using a clamping analysis, which is based on pressure (of hydraulic fluid acting on the rivet mandrel) and displacement (of the air piston) signatures. Since such fastening tools are very compact in design, it is very difficult to retrofit them with sensors installed inside the tool. In addition, the proposed methodology for under grip and over grip detection is purely based on displacement signature and hence, may be unreliable.

Table 1 Summary of Patent Survey

Ref #	Patent Number	Title	Author(s)	Year	Scope	Quality Problems
2	4,649,753	Verification probe	D. Goodsmith	1987	Pre-process verification probe for selecting the proper grip length for fastener installation	Improper fastener length
3	4,876,800	Portable grip length indicator	G. Pekar J. Mason M. Blane	1989	Pre-process fastener grip length measuring technique using a portable probe for selecting the proper grip length for fastener installation	Improper fastener length
4	5,727,300	Fastener verification system	M. Ekdahi J. Hanks B. Hiller J. LaChapelle K. Thomas M. Turley	1998	Automatic fastener selection prior to installation: Image based - determines the fastener size to be installed and then has an automation to get the right fastener to be installed	Selection of right fastener prior to installation
5	7,065,897	Fastener Grip Length Selector	J. Luner L. Hoeckelman	2006	A measuring gage to determine the grip length of fastener required	Pre-process detection for selecting the right length fastener

Table 1 Summary of Patent Survey (Contd.)

6	7,070,375	Fastener Grip Length Indicator	L. Hoeckelman	2006	Grip length determination technique using a mechanical measuring gage	Pre-process detection for selecting the right length fastener
7	4,237,612	Fastener grip length measuring system	E. Christian R. Blunck	1980	In-process fastener grip length measuring technique based on a hand held measuring device utilizing an insertable sliding probe	Improper material or structural part thickness
8	5,673,839	Real-time fastener measurement system	B. Howard J. Avery	1997	Measurement of fastener head heights in real-time using 3 embedded proximity sensors – for flush head fastener types	Improper fastener head heights
9	6,276,050	Riveting system and process for forming a riveted joint	D. Mauer H. Roeser R. Opper A. Wojcik C. Schoenig	2001	Sensors and an electronic control unit to determine the riveting/actuator characteristics using force vs. distance signatures	Incorrect rivet length and actuator power output
10	6,851,167	Method for installing blind fasteners	G. Harlow R. Dise	2005	Real time control of fastening operations for blind fasteners: Uses force-deformation curve to generate a stop signal to control the fastening operation	Improper fastening joints due to insufficient force deformation
11	5,661,887	Blind rivet set verification system and method	D. Byrne E. Chitty	1997	Monitoring the fastening operation based on displacement vs. pressure signatures	Under grip and over grip analysis – using the displacement data of the air piston
12	7,024,746	Method and apparatus for monitoring blind fastener setting	G. Weeks D. Hull S. Godwin G. Jackson	2006	Monitoring the setting operation of blind fasteners: Time based analysis to determine whether the set fastener complies with the predetermined setting procedures using load vs time signatures	Improper fastener setting (incorrect rivet size)
13	5898379	Wireless cycle monitoring system for power tools	E. Vanbergeijk	1999	Wireless monitoring: Monitoring the operation of a pneumatic tool using pressure sensor and transmitting it wirelessly to a receiver	Improper air pressure during operation of pneumatic tools

Several other studies are available in the literature for in-process monitoring and detection of failures in fastening operations, such as the Newton-Raphson Method for threaded fasteners to detect improper fastener alignment [14,15], statistical pattern recognition in thermal system protection panels to monitor the structural health of fasteners being installed [16], least square method based on Torque versus Insertion Depth curves for screw insertions [15, 17] to detect improper fastener alignment, and the weightless neural network based monitoring of screw fastenings in automated assembly to detect improper fastening operations due to screw jamming, screw wedging, thread stripping or cross threading [18].

Although the problem being addressed in this has been studied several researchers, it is unique due to the following reasons:

1. It employs strain/displacement vs. displacement characteristic which has never been used before (Table1)

2. The approach employs a Mahalanobis-Taguchi System (MTS) based scheme to detect the different grip conditions. The MTS-based scheme allows for using multiple characteristics in order to ensure the success rate of detecting the multiple grip length conditions. It also uses orthogonal arrays and signal-to-noise ratio to screen important characteristics so that the complexity of the problem can be reduced without loss of performance; thus computational time is reduced that make it appropriate for real-time applications.

3. In addition, MTS is used to classify different grip lengths and material thicknesses based on MD values, instead of its typical use where the result is simply described as normal or abnormal.

4. The prototype fastening tool is equipped with not only process-related sensors, such as strain, displacement, and pressure sensors, but also wireless communication capabilities to communicate the result of the signature analysis in real-time with the operator, as well as a base-station. This approach allows for 100% data collection on the fastened joints as opposed to sampling-based statistical process control methods.

MTS is widely used as a pattern recognition tool for various applications that deal with data classification [19,20]. MTS is a combination of the Mahalanobis Distance (MD) and the Taguchi method. MD method is used for constructing a measurement scale while the Taguchi method is used to optimize the system and make it robust [21]. Most applications based on MTS normally differentiate the normal group from the abnormal group, for example, healthy people from unhealthy ones. The proposed methodology has the ability to classify different grip lengths within the abnormal group. This is extremely useful where there are multiple failure modes to be detected.

MD measures distances in multidimensional spaces by taking into account the correlation among variables. In other words, MD is a measure of the nearness of a data-point to the mean of a group. There are other multivariate measurement techniques, such as the Euclidean distance, that give the distance to the “unknown” point from the mean point. On the other hand, the Euclidean distance does not give a statistical measurement of how well the unknown matches the reference set and it measures only a relative distance from the mean point and does not take into account the distribution of the points in a group [22].

The main reason why Mahalanobis distance is used in this research is because of its sensitivity towards inter-variable changes in data. Mahalanobis distance is measured in terms of standard deviations from the mean of the samples which provides a statistical measure of how well the unknown data set matches with the ideal one. Another reason why Mahalanobis distance is preferred over classical methods is due to its dependence on the variance and covariance of the data rather than its average, which makes the calculations robust.

3. MAHALANOBIS-TAGUCHI SYSTEM

The first step in MTS is to define and sample "normal" observations to construct a reference space, which is called the Mahalanobis Space (MS). MS consists of the mean vector, standard deviation vector, and correlation matrix of the normal group [22].

A pattern recognition problem starts with data collection on normal observations. Next, Mahalanobis Distance (MD) is calculated using certain characteristics to determine if MD has the ability to differentiate the normal group from an abnormal group. If MD is not capable of detecting the abnormal group using those particular characteristics, then other characteristics need to be explored. Once the right characteristics for calculating MD are determined, Taguchi methods are applied to evaluate the contribution of each characteristic and if possible to reduce the number of characteristics. Taguchi method uses orthogonal arrays and signal-to-noise ratios to choose such variables of importance.

MTS consists of four phases [20,22]:

Phase 1: Construction of MS

1. Define the characteristics that determine the healthiness of a condition. In this paper, it involves identifying the characteristics from the signatures that are known to be from good fastening operations (i.e., normal behavior).
2. Calculate the mean for each characteristic in the ideal data set:

$$\overline{x_i} = \frac{\sum_{i=1}^{n} X_{ij}}{n} \tag{1}$$

3. Calculate the standard deviation for each characteristic:

$$s_i = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{ij} - \overline{x}_i\right)^2}{n-1}} \tag{2}$$

4. Normalize each characteristic, form the normalized data matrix (Z_{ij}), and take its transpose ($Z^T{}_{ij}$):

$$Z_{ij} = \frac{\left(X_{ij} - \overline{x_i}\right)}{s_i} \tag{3}$$

5. Verify that the mean of the normalized data is zero:

$$\overline{z}_i = \frac{\sum_{i=1}^{n} Z_{ij}}{n} = 0 \tag{4}$$

6. Verify that the standard deviation is one:

$$s_z = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{ij} - \overline{z_i}\right)^2}{n-1}} = 1 \tag{5}$$

7. Form the correlation matrix (C) for the normalized data. The matrix elements (c_{ij}) are calculated as follows:

$$c_{ij} = \frac{\sum_{m=1}^{n} \left(Z_{im} Z_{jm} \right)}{n-1} \tag{6}$$

8. Calculate the inverse of the correlation matrix (C^{-1}).
9. Calculate MD:

$$MD_j = \frac{1}{k} Z_{ij}^T C^{-1} Z_{ij} \tag{7}$$

Where

x_{ij} is the i^{th} characteristic of the j^{th} observation,

n is the number of observations,

s_i is the standard deviation of the i^{th} characteristic,

Z_{ij} is the normalized value of the i^{th} characteristic of the j^{th} observation,

s_z is the standard deviation of the normalized values,

C is the correlation matrix,

C^{-1} is the inverse of the correlation matrix,

MD_j is the Mahalanobis distance for the j^{th} observation, and

k is the number of characteristics.

Phase 2: Validation of MS

For validation of MS, observations outside the normal group are selected and respective MD values are calculated. The characteristics of the abnormal group are normalized using the mean and standard deviations of the corresponding characteristics in the normal group. The correlation matrix corresponding to the healthy group is used to compute the MDs of the abnormal cases. If MS is suitable for the application domain with the appropriate characteristics selected, then the MDs corresponding to the abnormal group will have higher value than that of the normal group.

Phase 3: Identification of Useful Characteristics

The right set of characteristics is determined using orthogonal arrays (OAs) and signal-to-noise ratios (S/N). The signal-to-noise ratio, obtained from the abnormal MDs, is used as the response for each combination of OA. Orthogonal Array is a table listing all the combinations of the characteristics. Level-1 in the orthogonal array column represents the presence of a characteristic and level-2 represents the absence of that characteristic. The size of the orthogonal array is depends on the number of characteristics and the levels it can take. By varying the number of characteristics used, MD values are obtained for the abnormal cases and from these MD values, the larger the better signal-to-noise ratio is obtained [19,20,22] as follows:

$$\eta_q = -10 \log \left[\frac{1}{t} \sum_{j=1}^{t} \frac{1}{MD_j} \right] \tag{8}$$

Where,

η_q is the signal-to-noise ratio for the q^{th} run of the orthogonal array

t is the number of abnormalities under consideration

An average S/N ratio at level-1 and level-2 is obtained for each characteristic. Subsequently, gain in S/N ratio values for each characteristic is calculated [19,22] as follows:

$$Gain = \left(Avg.S / N\ Ratio\right)_{Level-1} - \left(Avg.S / N\ Ratio\right)_{Level-2} \qquad (9)$$

Finally, the characteristics with positive gain are identified as useful in the detection of anomalies and the rest of the characteristics are discarded.

Phase 4: Decision-making

Using the MS constructed by the useful characteristics, monitor the application, collect data, calculate MD, and if MD >> 1, then the application exhibits abnormal behavior. In this case, determine under which MD range, the MD of the current application falls, and then take the respective corrective action. If MD ≤ 1, the conditions are normal.

4. PULL-TYPE FASTENERS AND TOOLS: THE UNDERLYING CONCEPT

As shown in Figure 1, the pintail breaks off at the end of the process and the remaining portion of the fastener with the collar form a permanent joint. The underlying concept is very similar to a tensile test in terms of stress-strain relationship. During the fastening process, the outer sleeve of the nosepiece rests against the collar causing it to swage, while the inside jaws pull the pintail. The pintail goes through its yield point, passes from the elastic range to the plastic range, then reaches its ultimate tensile strength, and finally at its fracture point it breaks and the process is completed. While the pintail of the fastener is going through this sequence, the outer sleeve of the nosepiece stays under compression pushing the collar against the plates. Due to superior material properties of the nosepiece compared with the materials properties of the fastener, the outer sleeve of the nosepiece goes through a slight elastic deformation (i.e., no plastic deformation occurs on the nosepiece) during the process and when the process is completed, it recovers back to its original state.

The preliminary studies that led to the approach proposed in this study have shown that there is a relationship between the elastic deformation occurring on the nosepiece and the elastic-plastic deformation on the fastener. In order to use this relationship, the nosepiece of the tool has been integrated with a strain gage that shows the elastic deformation, in the form of compression, of the nosepiece. This behavior has been plotted as Strain versus Time to generate a process signature. In order to investigate the impact of grip length on the strain-time process signature, different combinations of plates have been tested. In addition, plates with rubber washers in between have also been tested to investigate the impact of material properties on the process signature.

As shown in Figure 2, the test results have shown visible differences among process signatures. Therefore, for a given combination of plates and fasteners, there is a unique process signature. Any deviation from this unique signature is a sign of an abnormality, which could be a quality problem. The reliability of this approach depends on how much variability in the process signature can be attributed to noise, such as the way the operator holds the tool, and how much variability is caused by the mismatch between the plate thickness and the fastener length.

Fastening processes are required to yield a certain amount of clamping force, which is the force acting on the joined members after the operation is completed [1]. Swaging of the collar onto a certain number of grooves on the fastener's shank ensures a certain level of clamping force. If the collar is not in contact with the right number of grooves, then the fastening operation will not yield the desired level of clamping force. The total thickness of the joined members with respect to the length of the fastener affects the number of grooves to come in contact with the collar. For both over grip and under grip cases, there are fewer grooves in contact with the collar; thus clamping force on the joint is less than the design requirement.

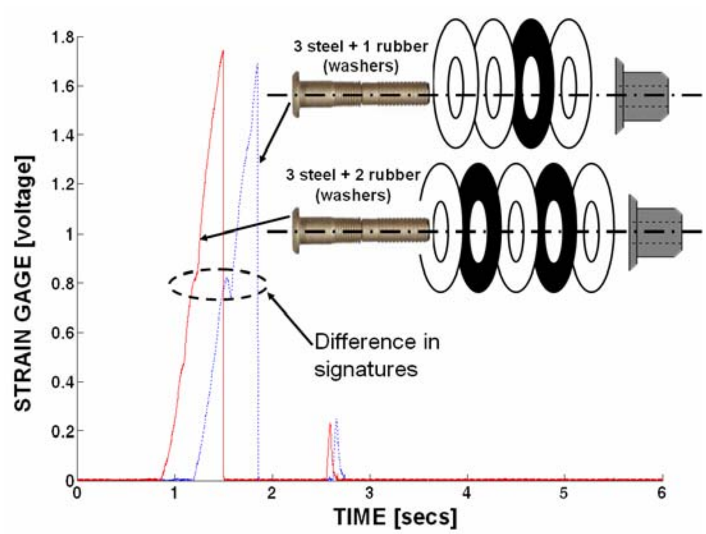


Figure 2 Process Signatures

Ensuring right grip length is extremely costly for manufacturing environments where a particular product is made up of different thicknesses of materials and requires many different types and sizes of fasteners. Aerospace industry is a good example that falls under this category. In such aerospace assembly plants, fasteners of different grip lengths may be chosen using different techniques, such as a fastener grip length selector/gage [2-6]. Nevertheless, such selections made prior to production do not guarantee that there will not be a mismatch between the plates and the fasteners. The proposed approach provides a solution to detect such a mismatch at the point of use.

5. REAL-TIME DETECTION OF GRIP LENGTH DEVIATION: THE PROPOSED APPROACH

As shown in Figure 3, three sensors have been integrated with a pull-type fastening tool in order to implement the proposed data collection scheme. A resistive-type strain gage is placed on the nosepiece of the tool and used in a quarter bridge configuration with a nominal resistance of 120 Ω. During fastening operation, the strain gage measures the strain on the nosepiece by developing a differential voltage output due to change in resistance.

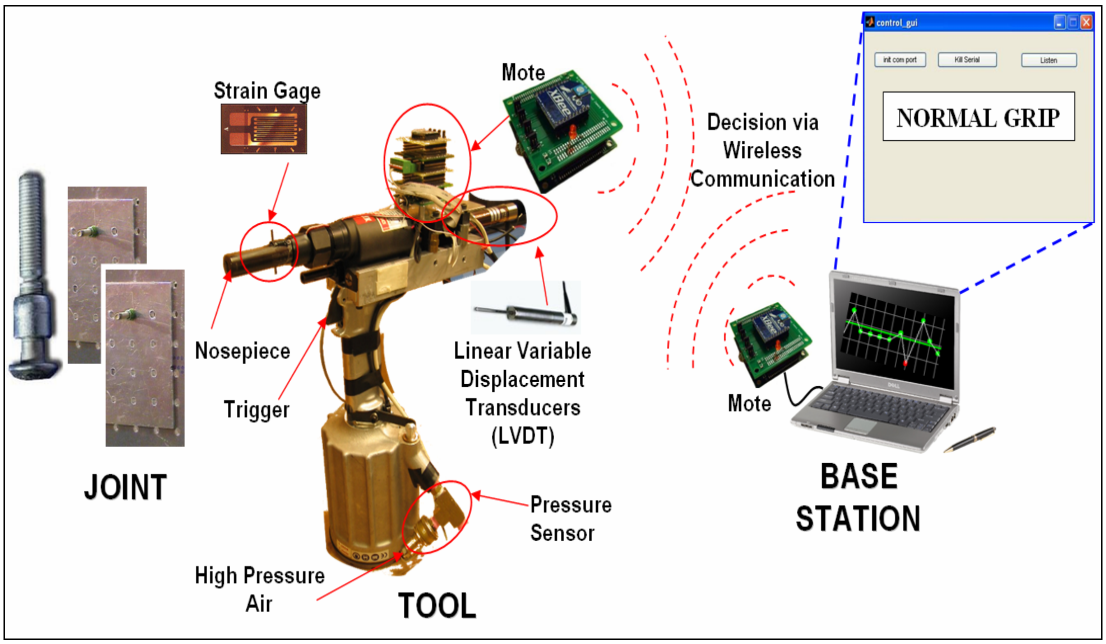


Figure 3 Sensor-Integrated Pull-Type Tool with Wireless Communication Capabilities

A linear variable differential transducer (LVDT) with a sensitivity of 181.4 milli volts/mm is integrated in order to measure the displacement of the inner jaws in the nosepiece during the fastening operation. Finally, a pressure sensor with a sensitivity of 29.5 milli volts/psi is attached at the air inlet port of the tool in order to measure pressure variations in process. At low pressures, which can happen in industrial settings when there are several pneumatic equipments and tools operating at the same time, the tool sends a low pressure signal to the base station without executing the proposed grip length detection methodology.

The nosepiece strain data from the strain gage conditioning layer are calibrated through simulation of known strain values by connecting the respective values of calibration resistors R_{cal} as calculated by the equations below:

$$\Delta R = \varepsilon_{sim} \cdot GF \cdot R_g \tag{10}$$

$$\Delta R = R_g - \frac{R_g \cdot R_{cal}}{R_g + R_{cal}} \tag{11}$$

$$R_{cal} = \frac{\Delta R \cdot R_g}{R_g - \Delta R} \tag{12}$$

Where

ε_{sim} : Simulated strain,

GF : Gage factor set to 2.07,

R_g : Nominal resistance of strain gage (120Ω)

Thus, resistors of 36kΩ, 100kΩ, and 240kΩ corresponding to strain values of 1,604 microstrain, 580 microstrain, and 240 microstrain, respectively, are connected in parallel to the R_g. The corresponding differential voltages are then measured and plotted as strain versus output voltage to obtain a slope S. The strain is then calibrated from the output voltage as follows:

$$\varepsilon = Vo \times S \tag{13}$$

Where

Vo : Output voltage

S : Slope on strain versus voltage plot

ε : Strain developed

The sensor data are processed on the mote and the decision (i.e, normal grip, under grip, or over grip) is communicated to the base station over a wireless sensors network using the Optimized Energy-Delay Sub-network Routing OEDSR protocol [23].

The 5-layer stack mote includes the following layers:

1. Power layer: This layer supplies regulated power supply of ±5V to the sensors and 3.3V to the processing layer and the communication layer. The power layer accepts a bipolar input in the range ±7.2V to ±10V.
2. Sensor input layer: Output voltages from the sensors are fed to the processing layer through this layer.
3. Strain gage conditioning layer: Strain gage conditioning is done on this board. The strain gage placed on the nosepiece is operated in a quarter bridge configuration. Two potentiometers on this board allow setting the offset and the gain of the out voltage.
4. Processing layer: This layer is built based on a Silabs® C8051F120 processor for processing the data and provide the decision to the communication layer.
5. Communication layer: This layer is built based on a MaxStream® XBee, and sends the decision received from the processing layer to the base station.

5.1 Process Signature Analysis: Initial Testing

Initial experiments have shown that there are unique features in Strain-Time and Displacement-Time signatures that can be used to differentiate grip lengths, as shown in Figure 4. On the other hand, due to variations within each grip length category, these signatures alone are not robust enough to detect normal, over, and under grip conditions with high confidence.

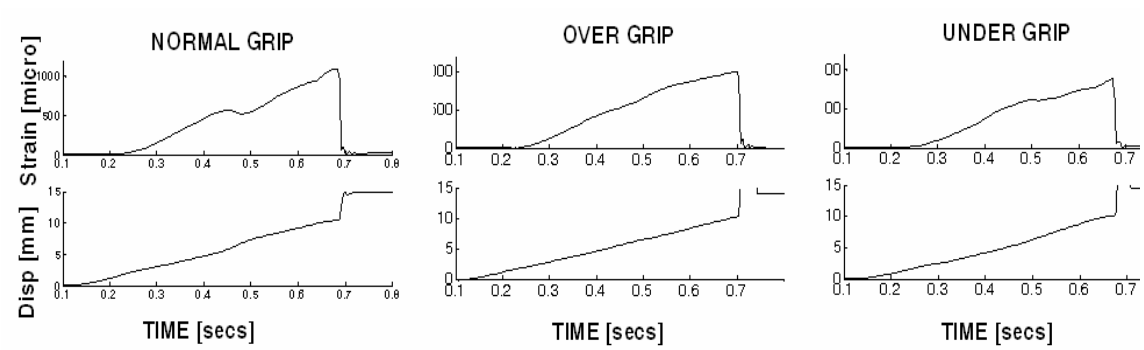


Figure 4 Process Signatures for Different Grip Length Deviations

In order to amplify the effect of grip length deviations on process signatures, a new parameter, namely Strain/Displacement ratio (S/D), has been introduced. By using the primary sensor data (i.e., nosepiece strain and displacement), a compound process signature Strain/Displacement versus Displacement has been developed. As shown in Figure 5, normal grip data exhibits a unique bowl-shaped dip. In addition, over grip and under grip data are also unique. Therefore, presence of a bowl-shaped dip shows that it is a normal grip case.

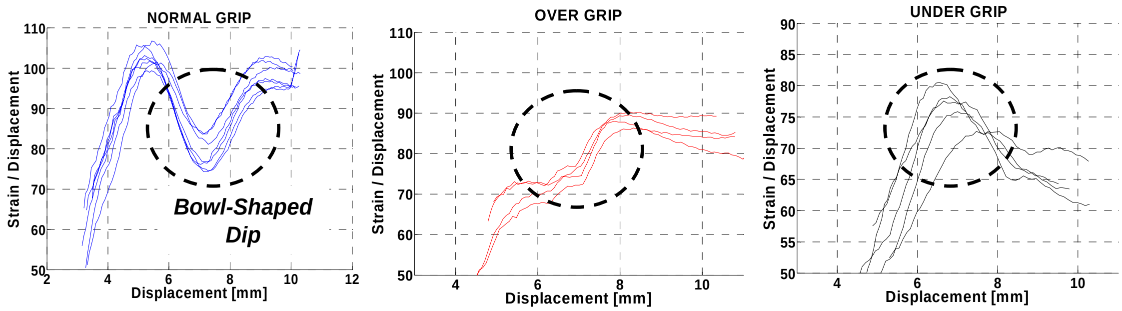


Figure 5 Strain/Displacement versus Displacement Signatures: Visible Differences

5.2 Real-Time Feature Extraction

In real-time, the strain and displacement data are continuously monitored in time. The data are collected at 5,000 samples per second and smoothened by averaging every 20 samples. Each smoothened strain and displacement data are calibrated and S/D is calculated.

There are four unique features that are used to detect grip length variations. First one is the peak strain on the strain-time signature, which occurs right before the tool completes the fastening operation. The other three features are on the strain/displacement-displacement signature; peak displacement, depth and half-width (will be referred to as width for the rest of the paper) of the bowl measured.

As shown in Figure 6, the fastening operation starts at t_{start}, which is the time at which the strain value exceeds 80 microstrains. Based on the observations during the initial experimentation, the fastening operation is considered complete when the strain value drops by at least 100 microstrains than its previous value, which is shown as t_{end}. The peak strain (ε_p) is extracted as the strain value at time t_{end}. As sensor data are received, S/D is calculated in real-time period from t_{start} to t_{end}. It has been observed that the first max (f_1) is detected when at least 4 recent, consecutive S/D values are lower than the previous 4 S/D values samples at time t_0. The first min (f_2) is detected as the minimum value S/D between t_0 and t_{end} , which is shown at time t_1. Therefore, width is calculated as $W = d_1 - d_2$, and depth is calculated as $D = f_1 - f_2$.

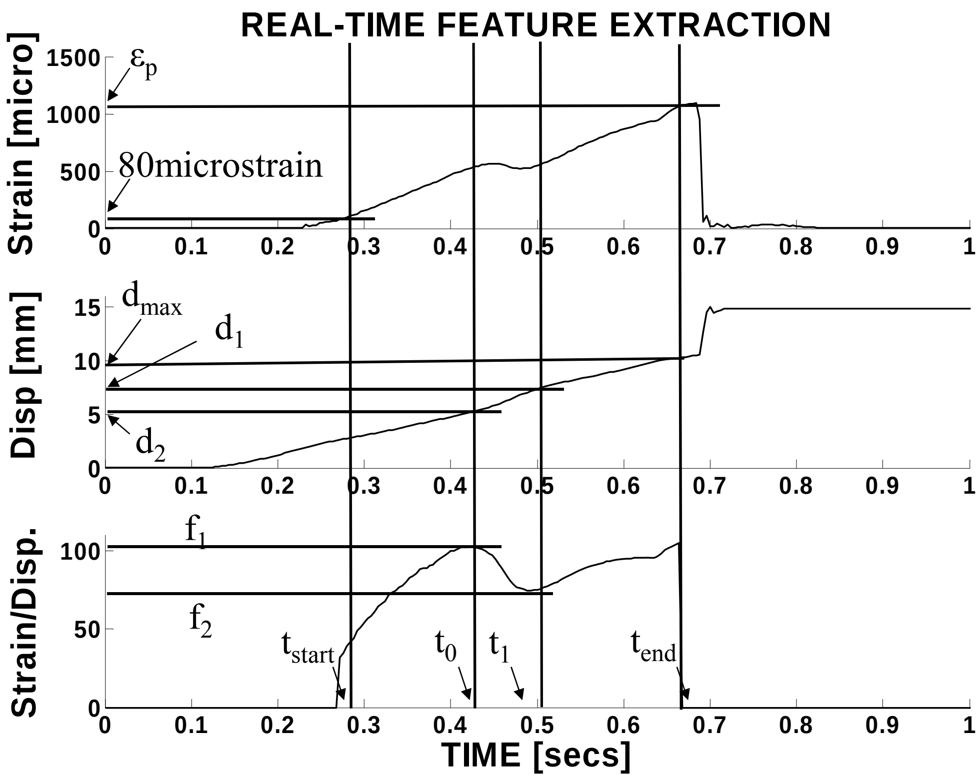


Figure 6 Features for Grip Length Detection

5.3 MTS Based Decision Making

MTS can be used at two levels. At the basic level, first an ideal process signature can be obtained as a result of several replications of normal fastening operations using the right fastener and material(s). Second, since any other fastener/material combination will have a different signature, such cases, which are different than the ideal condition, will be detected by MTS as abnormal. On the other hand, the reason for abnormality cannot be stated.

At an advanced level, MTS can be used as a tool for root-cause analysis to detect the reasons for abnormality, which requires more experiments by reproducing each abnormality and calculating its MD value with respect to the ideal data. This is the approached developed in this study. As shown in Figure 7, if there are N cases of abnormalities, then an MD range corresponding to each case is determined with respect to the ideal case. It is more likely to have a variation among the replications for each case, therefore instead of a single MD value, an MD range can be determined for each abnormality. Then, an unknown signature can be analyzed using the correlation matrix and its MD value is calculated. Then, depending on which MD range it falls under, the type of abnormality is determined.

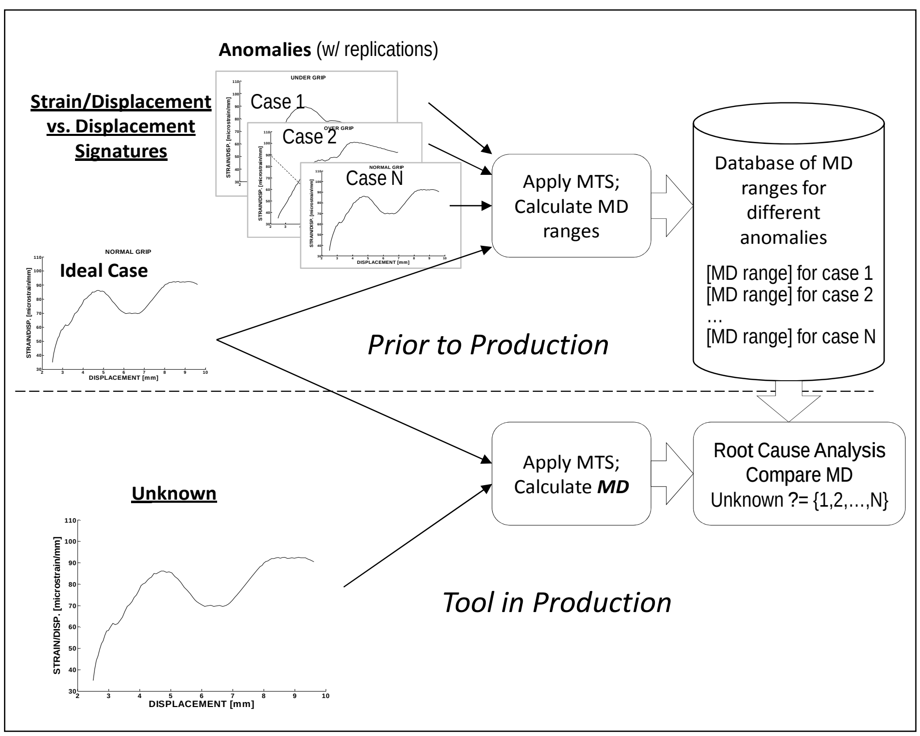


Figure 7 MTS as a Tool for Root-Cause Analysis

6. EXPERIMENTATION

Three thicknesses have been tested: 0.20”, 0.29”, and 0.144” to represent normal grip, under grip, and over grip cases, respectively. The sensor data are acquired using a Universal Serial Bus based Data Acquisition Card with 8 analog input channels. The data have been sampled and stored at 5,000 samples per second for each sensor data. The proposed methodology has been implemented on a 5-layer stack mote.

In Phase 1 of MTS application, four characteristics on the signature, as shown in Figure 6, are identified:

1. Depth of the dip (D)
2. Width of the dip (W)
3. Peak displacement (d_{msx})
4. Peak Strain(ε_p)

The Mahalanobis Space (MS) is then formed using data collected from the 0.20” thick plate (normal group) using the aforementioned four characteristics. The MD values (Equation 7) for the normal group range from 0.1 to 3.0 with an average MD of 1.2. In Phase 2, the MS, as the measurement scale, is validated. The data collected from 0.144” and 0.29” thick plates (abnormal cases) using the same type of fastener are processed using the same MS. Sample process signature for each grip length is shown in Figure 8. The MD ranges for 0.144”, and 0.29” thick plates are [5, 15] and [20 and above] respectively. Therefore, the MTS approach clearly distinguishes between different plate thicknesses; hence the selected scale is validated.

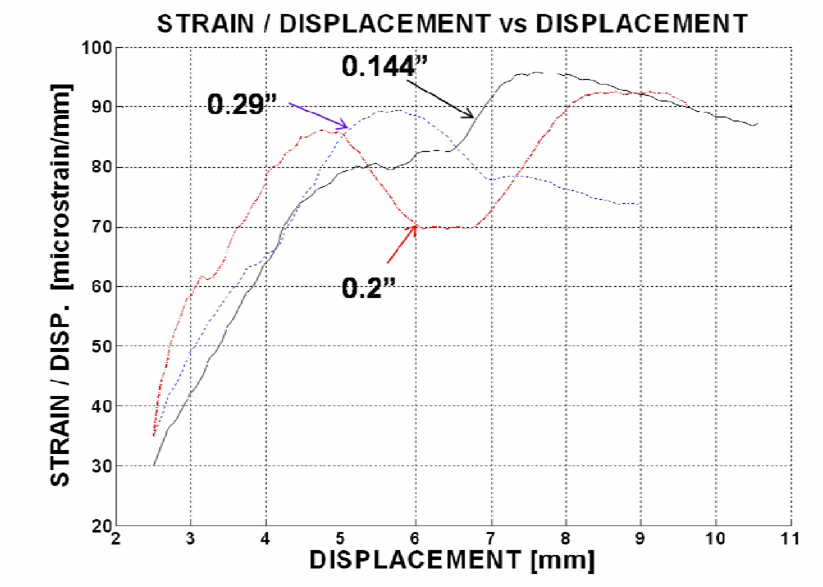


Figure 8 Typical Strain/Displacement over Displacement Plots for Various Grip Lengths

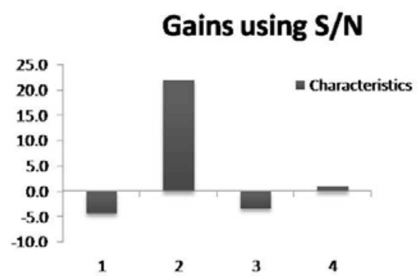
In Phase 3, the impact of each characteristic identified in Phase 1 is investigated using orthogonal arrays and S/N (signal to noise) ratios (Equation 8). Then, the gain (Equation 9) is calculated for each characteristic for two of the abnormal cases, 0.144" and 0.29" thick plates. Since the initial number of characteristics is 4, a L_8 (2^7) orthogonal array is used. As shown in Table 2, peak displacement and depth of the dip does not have significant impact on MD. Therefore, the number of characteristics is reduced from 4 to 2.

After the insignificant characteristics are screened out, the MS and MD are recalculated using the significant characteristics. The MD ranges, therefore the distinction among the normal and abnormal groups, are improved. The new MD ranges for 0.144" and 0.29" thick plates are [5.3, 21.9] and [22.7, 82.7], respectively. Some typical characteristics and their MD values for each of the different grip length scenarios are listed in table 3.

Table 2 Screening of Characteristics

	1	2	3	4	5	6	7	MD Values			
Run	**Depth**	**Width**	**Displacement**	**Peak Strain**	**X**	**X**	**X**	**Over grip**	**Under Grip**	**1/sum**	**S/N (Eq 8)**
1	1	1	1	1	1	1	1	8.8	29.0	0.1	11.3
2	1	1	1	2	2	2	2	10.8	35.9	0.1	12.2
3	1	2	2	1	1	2	2	6.7	8.3	0.3	8.7
4	1	2	2	2	2	1	1	7.0	2.4	0.6	5.5
5	2	1	2	1	2	1	2	11.4	44.6	0.1	12.6
6	2	1	2	2	1	2	1	19.6	66.2	0.1	14.8
7	2	2	1	1	2	2	1	6.7	5.5	0.3	7.8
8	2	2	1	2	1	1	2	13.1	3.0	0.4	6.9

S/N when present	37.7	50.9	38.2	40.4
S/N when absent	42.1	29.0	41.6	39.5
Gain (Eq 9)	-4.4	21.9	-3.4	0.9



Significant Characteristics

2. Width of the Dip
4. Peak Strain

Table 3 Comparison of MD Values Before and After Screening of Characteristics

Normal Grip(0.20")	Depth	Width	Displacement	Peak Strain	MD before screening	MD after screening
1	15.86	1.44	10.2	929	0.1	0.2
2	26.1	1.73	10.2	1001	0.4	0.3
3	19.83	1.93	10.2	934	0.4	0.8
4	12.23	1.66	10.3	908	0.6	0.5
5	6.21	0.76	10.3	842	2.3	4.3
6	24.08	1.69	10.3	1066	1.0	1.8
7	22.93	1.54	10.3	967	0.4	0.0
8	27.74	1.79	10.3	1083	1.3	2.4
9	25.03	1.87	10.3	941	0.7	0.5
10	10.73	1.49	10.4	916	0.5	0.3
11	6.94	1	10.4	934	1.1	1.8
12	14.38	1.41	10.4	981	0.4	0.4
13	23.89	1.744	10.4	995	0.3	0.2
14	11.01	1.642	10.4	947	0.9	0.0
15	11.59	1.4	10.5	941	0.4	0.2
16	15.73	1.77	10.5	920	0.5	0.5
17	17.91	1.3	10.5	949	0.6	0.4

Table 3 Comparison of MD Values Before and After Screening of Characteristics (Contd.)

18	30.58	1.96	10.5	1071	1.5	2.1
19	11.9	1.48	10.5	894	0.5	0.6
20	20.4	1.82	10.6	928	0.8	0.5
21	29.79	1.92	9.5	927	1.8	0.9
22	22.96	1.85	9.5	890	1.4	1.4
23	17.62	1.48	9.5	1008	1.7	0.6
24	19.04	1.31	9.5	1001	1.5	1.0
25	24.36	1.35	9.5	977	1.5	0.5
26	22.12	2.29	9.5	956	2.5	2.6
27	12.64	0.99	10.8	963	1.6	2.1
28	17.19	1.47	10.8	1016	1.0	0.8
29	7.45	1.13	9.1	913	4.1	1.2
30	20.01	1.50	9.1	1022	3.0	0.9
31	22.33	1.36	9.1	1010	2.7	1.0
32	28.2	1.9	9.1	998	2.0	0.5
				Mean MD	1.2	1.0
Under Grip(0.29")	**Depth**	**Width**	**Displacement**	**Peak Strain**	**MD before screening**	**MD after screening**
1	19.95	3.64	10.4	772	19.7	34.7
2	4.11	0.27	10.7	582	20.9	24.4
3	34.69	4.36	10.3	891	24.7	44.6
4	6.96	3.48	10.4	810	23.6	27.5
5	29.2	4.25	10.3	850	25.4	44.5
6	30.2	4.31	10.5	912	25.5	41.7
7	30.18	4.27	9.5	950	25.8	38.4
8	31.27	4.36	10.4	954	25.9	40.8
9	19.84	3.98	12	816	30.6	39.6
10	15.92	3.89	9.5	891	27.9	31.4
11	18.36	4.07	11.1	886	28.3	36.5
12	26.62	4.38	10.5	898	29.0	44.8
13	39.5	4.73	9.5	910	30.5	55.3
14	25.04	4.4	10.8	836	31.4	50.4
15	34.27	4.66	9.1	926	33.1	51.8
16	29.12	4.83	10.2	875	38.3	61.5
17	13.91	4.29	9.5	787	38.5	51.7
18	21.7	4.2	10.4	551	42.5	82.7
				Mean MD	29.0	44.6

Table 3 Comparison of MD Values Before and After Screening of Characteristics (Contd.)

Over Grip (0.144")	Depth	Width	Displacement	Peak Strain	MD before screening	MD after screening
`1	1.04	0.27	10.5	1008	6.0	11.1
2	1.32	0.1	10.2	956	6.2	12.0
3	1.28	0.177	9.5	964	7.6	11.0
4	0.4179	0.1	10.5	974	6.3	12.5
5	0.78	0.09	10.4	981	6.6	12.9
6	0.18	0.1	10.2	984	6.8	12.8
7	0.83	0.198	10.1	1013	7.1	12.4
8	1.03	0.08	10.4	995	6.9	13.6
9	2.39	1.81	10.9	962	5.6	0.2
10	0.89	0.1	11.1	993	7.2	13.2
11	0.06	0.09	11.2	983	7.3	13.0
12	0.3	0.09	11.5	952	7.9	12.0
13	0.252	0.099	11.5	984	8.2	12.8
14	0.99	0.29	12.3	971	10.8	9.5
15	3.07	0.386	12.4	983	11.2	8.5
16	0.02	0.188	12.1	985	10.3	11.5
17	0.18	0.092	12	987	10.6	13.1
18	0.12	0.09	12.5	966	13.8	12.4
19	0.53	0.11	13.2	958	20.1	11.9
				Mean MD	8.8	11.4

In Phase 4, plates with different thicknesses are tested using the MS and the MD ranges calculated in previous phases. The results of the final experiment are summarized in Table 4. The MTS methodology has successfully detected the grip lengths of 0.144”, 0.20” and 0.29with a detection rate of 87.5%, 100%, and 96.8%, respectively.

Table 4 Results of The Experiment: Detection of Grip Lengths

Grip Length	MD range	No of Trails	Correct Detection	False Detection	No of false detection
0.144"	[5.3, 21.9]	32	87.5%	12.5%	4 detected as 0.2"
0.2"	[0.1, 4.3]	32	100%	0%	0
0.29"	[22.7, 82.7]	32	96.8%	3.2%	1 was detected as 0.144"

6.1 Variability In The Process Signatures

This section presents the analysis of variability in the sensor data collected and variability of the characteristics in the signatures used for determining the quality of the fastening process. The analyses are based on the characteristics used for detecting the "bowl-shaped" dip as shown in Figure 5. The variability in the depth, width and peak strain for different grip length signatures collected across 15 trails are shown in Figure 9.

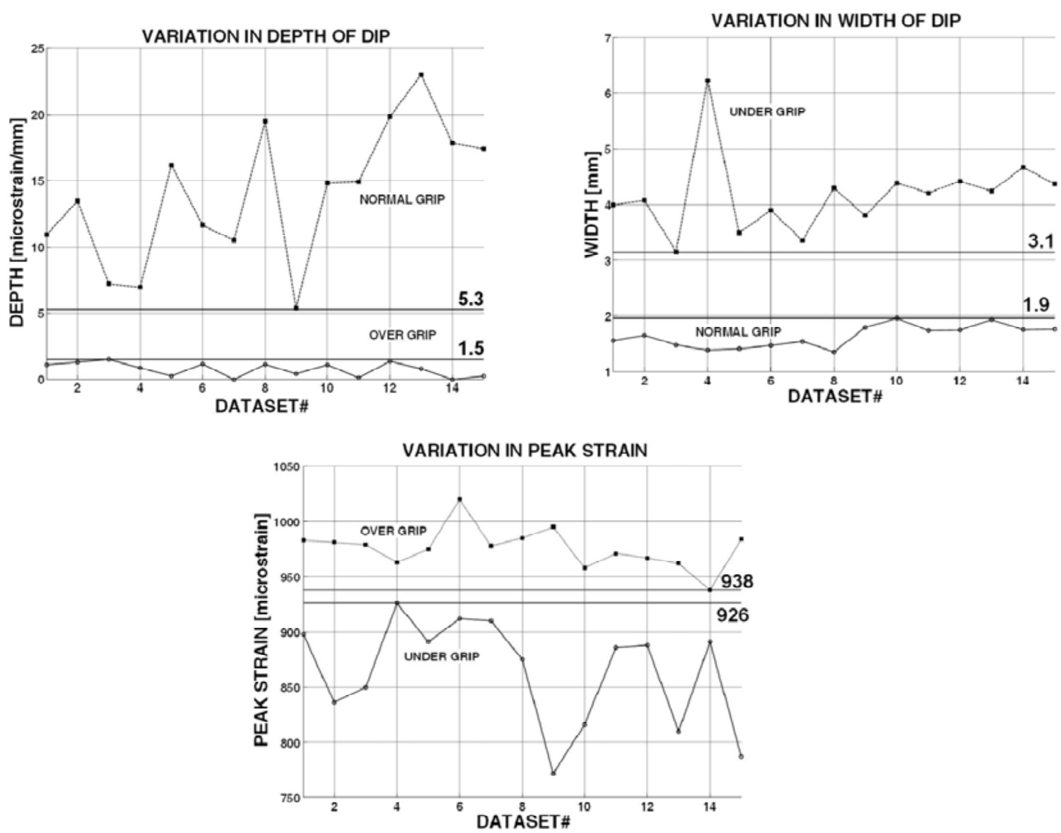


Figure 9 Variability for Characteristics

In general, several factors can contribute to variability in data: tolerance on plate thickness, sensitivity of sensors on the tool, and operator. The manufacturers specify a tolerance range for plates. For instance, a plate of a nominal thickness of 0.29" has been used during experimentation for under grip cases. According to the specifications sheet, the tolerance on the plate is ± 0.016”. Hence, the variability in plate thickness could vary from 0.306” to 0.274”. Since this paper present a prototype tool, rather than a production-ready tool, no measurements were made on plate thickness at the joints during validation of the proposed proof-of-concept model. Therefore, tolerance on plates is introduced here as a factor that can cause potential variation in data in actual production environments, not necessarily as a factor that has caused variations in the experiments presented in this study.

Another factor is the sensitivity of the sensors integrated with the tool. For instance, the strain gage used on the nosepiece has a 120 ohm configuration with ± 0.0015 % variability in resistance. It yields a variability of ± 7.24 microstrain. Similarly, the displacement data are acquired via an LVDT, which has a sensitivity of ± 6.2 nanometer per mm. Consider the following example. For 500 microstrain and 5 mm displacement, the nominal value for S/D is 100 microstrain/mm. When the variation is considered, it is possible that this value could range from 98.56 to 101.44.

Operator variability can also play a major role in variation in an actual production environment. During the development phase of this study, several trips were made to industry to observe how the tool is actually being used. It was observed that, for instance, some operators would operate the tool by holding it at a different angle than the other operators. Similarly, using both hands or pressing harder on the nosepiece by using the body weight is a common practice. In order to avoid the potential effect of operator variability, only one person has collected data during the experimentation for this study.

Another factor that has been considered in this study is material properties. In order to investigate the impact of material properties, aluminum (Modulus of Elasticity, E

= 74 GPa) and copper (Modulus of Elasticity, E = 130 GPa) plates of same thickness have been tested. In terms of depth, width, and peak strain, the analysis of the data obtained form both plates has shown no statistical significant difference between the two plates. Therefore, the proposed methodology is insensitive to changes in material properties, specifically for the modulus of elasticity in the range of 70-130 GPa. However, when a 4-mm thick rubber washer is placed between two plates with a total thickness that falls in the normal grip range, the process signatures are extremely different than what has been observed without the rubber washer.

7. CONCLUSIONS

It is observed that Mahalanobis distance is a reliable metric to monitor process quality is able to classify unknown datasets that are multivariate in nature. MTS is proven to be able to distinguish between the various failure modes occurring during pull type fastening with acceptable accuracy. There can be a scenario where two distinct data sets having the same correlation between the characteristics getting detected falsely, other than that the system is very robust and accurate.

MTS has illustrated its ability to screen out the characteristics that does not contribute towards the decision making. In this case, displacement was found to have had no impact on the decision making, thereby reducing the complexity. This has significant impacts on operations that take into account inputs from several sensors to make decision, by reducing the number of characteristics that needs to be monitored for actual decision making. This in turn results in relatively less complexity and money savings.

Wireless implementation shows that such a methodology is practical and reliable for in-process quality control in the shop-floor environment. Such real-time quality control process reduces the amount of post-process quality control thereby saving expended capital. Similar methodologies implemented over wireless sensor networks can be very effective in other manufacturing environments as well.

The proposed architecture has merits to (1) detect and report quality problems in real-time during the process, (2) reduce the number of characteristics needed for decision making, thereby reducing the complexity of the procedure, and (3) reduce post-process inspection, thereby improving quality while reducing cost and man power. In addition, the approach facilitates 100% data collection, for future analysis, on each fastener as opposed to traditional statistical process control (SPC) techniques, which rely on sampling.

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FUTURE WORK

The methodology can be further extended to detect various other anomalies that might occur during the fastening operation, like a different type of fastener being used, or any other defect that might affect the process signature. This methodology is can be used to determine the tool health along with the process health and can be ported to other tools or systems that has multiple sensors or process parameters**.**

VITA

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