A Digital System For Assembly Bolt Pattern Traceability and Poka-Yoke

Master's Thesis Defense 4.9.2021

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Thesis Committee Members

Thank You!

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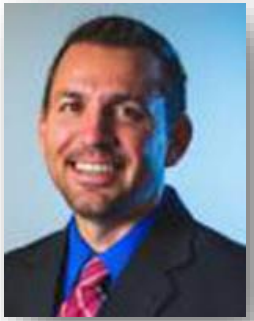

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Agenda

- **Introduction**
  - Problem Statement
  - Overview of Mechanical Fasteners
  - Assembly Processes and Risks
  - Research Questions/Hypothesis
  - Assumptions
  - Limitations/Delimitations
- **Literature Review**
  - Introduction
  - Methods of Data Recording
  - Workforce Training
  - Assembly Work Instructions and Guidance
- **Framework and Methodology**
- **Data Collection**
- **Discussion**
  - Conclusion
- **Possible Outcomes**
- **References**

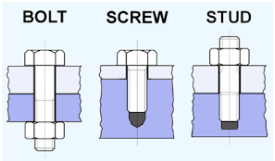
Introduction

History Mechanical Fasteners

Mechanical fasteners are present throughout all industries. From medical to construction, these fasteners play crucial roles in the success of parts, products, and structures.

- Permanent Fasteners
  - Rivets
  - Adhesives
  - Welds

- Non-Permanent Fasteners
  - Machine Screw
  - Bolts
  - Studs



Quantity of Fasteners

Boeing 777

= > 1,000,000

Through all of production over 1.5 billion fasteners used

Average Vehicle

= > 3,500

Frequently Used Tools

Manual Click Style Torque Wrench

Pneumatic Torque Tool

DC Electric Torque Tool

Digital Manual Click Style Torque Wrench

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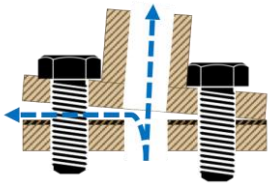
Introduction

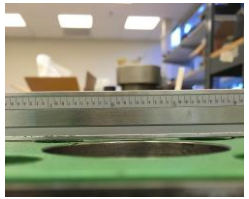
Problem Statement

Improper torqueing technique when assembling mechanically fastened products, can cause component failure or decreased product lifespan, resulting in added costs to the manufacturer.

Industry solutions for ensuring the use of proper torque technique are not effective in providing complete data traceability of as manufactured bolted joints, including torque patterns, torque values, and fasteners used.

Improper Torque Procedure Used





- When using the incorrect torque pattern, the part is at a greater risk of warping or unevenly compressing mating components potentially causing leaks

Improper Fasteners Used

Lockheed Martin Potentially Mixed Up Structural Fasteners in Most F-35s

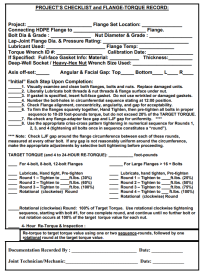
- Incorrect fasteners used during the assembly of possibly hundreds of F-35s

Improper Torque Procedure Used

NISSAN HYUNDAI INFINITI LEXUS TOYOTA

- Recent recalls for improperly torqued fasteners, or incorrect fasteners used.
- Toyota alone recalled 652,000 trucks from improperly torqued seatbelt fasteners.

Incorrectly Recorded Manufacturing Data



Torque patterns are entered manually into a computer or written on a paper data log which increases risk of operator error. (Noble, 2012)

Significance of Research

- The objective of this research is to develop and evaluate a system that will aid in monitoring the assembly process of circular bolt patterns to ensure proper assembly technique is used and all fasteners are torqued within specifications.
- With the system outlined in this study, manufactures will be able to create a digital thread of information between the as-designed torque specifications and the as-manufactured torque data.
- Evaluated the system's and the components' performance and feasibility based on standard and elevated industrial environments.

Introduction

Research Questions

This research aims to answer the following research questions:

- How can we use a vision-based system, integrated with connected tools, to enforce the proper assembly of bolted joints?

Hypothesis

My hypothesis for this study is:

- **Fastener Classification**
  - H0: The Proposed system will correctly identify fastener classification, in an industrial environment, using the shape and features of the fastener with a 90%.
  - H1: The proposed system will incorrectly identify fastener classification with a 90% confidence.
  - H2: The proposed system will correctly identify fastener classification under 90%
- **Fastener Detection**
  - H0: The proposed system will detect the presence of a fastener when a fastener is present and absence of a fastener when a fastener is missing.
  - H1: The proposed system will incorrectly detect the presence or absence of fasteners.
- **Fastener Torque Pattern**
  - H0: The proposed system will record the torque pattern correctly
  - H1: The torque pattern recorded by the system, does not reflect the torque value used to assemble the part.
- **Torque Value**
  - H0: The system records the correct torque value for the appropriate fastener
  - H1: The torque values recorded do not reflect the actual torque values used.

Introduction

Assumptions

- Because this research focuses on the evaluation of the systems technology stack, it is assumed the usability of the system is comparable to that of a standard industrial application.
- Thermal environmental conditions throughout the study are the same and have a negligible impact on torque value.
- It is assumed that the fasteners used in the study are of the same quality and pass manufacturer quality inspections.
- The torquing procedure will follow a single pass torque operation.
- The configuration of hardware is relative to the equivalency between pixels and inches.

Limitations

- Because the vision system is mounted from a top view, fastener types with distinct features on the bottom, such as countersunk screws, cannot be detected.
- The system will only work with digitally connected tools, as the system relies on torque values as triggers for recording tool position relative to the fasteners.
- The system requires the use of a GPU. The speed of the GPU will be a limitation of how fast live video can be processed and object detection can occur.
- A dataset of approximately 2000 images was used to train the object detection model with 3 classifications. A rule of thumb when training a model is to use a dataset with 1000 images per classification. Ideally, the dataset should contain 3000 images, but because of time constraints, only 2000 images were gathered.

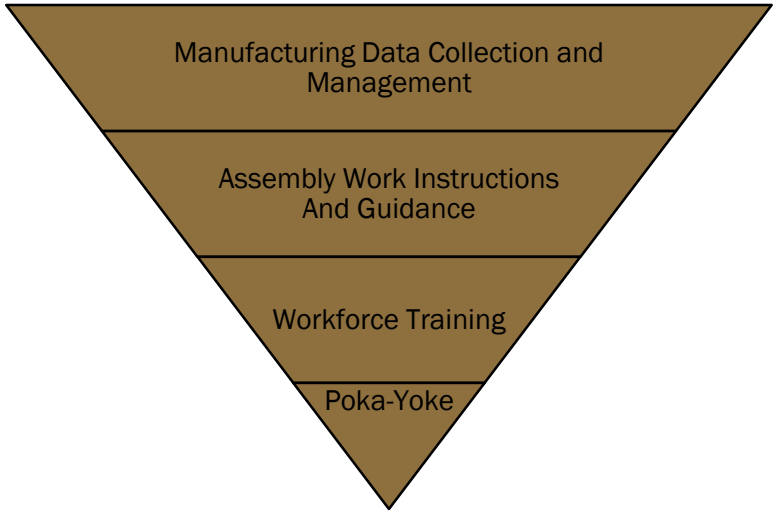
Delimitations

- Common industrial fasteners with distinct top characteristic were used.
- A digitally connected tool was used with this system that allows for live data transfer.
- A high-end NVIDIA Quadro RTX 4000 graphics card was be used to run the system. The graphics card has 8gb of memory and 416 gb/s of bandwidth.

Literature Review

Introduction

- The Industrial digital revolution has influenced many aspects of manufacturer's processes. From workforce training and assembly guidance, to error-proofing the system and collection manufacturing data.
- Even with a growth in digitizing data collection, manufactures have struggled with accurately and autonomously collecting as manufactured torque pattern and fastener data to ensure proper order of operations has been followed.



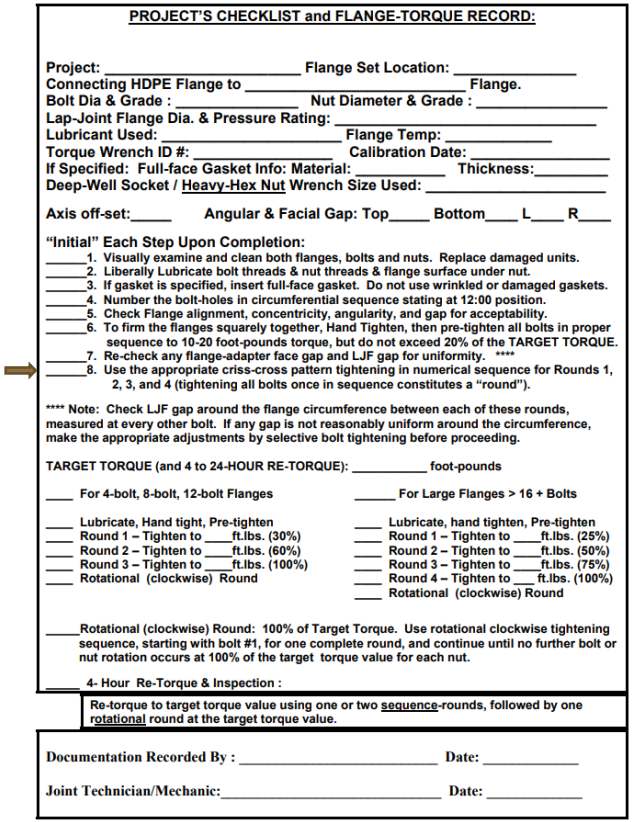
Literature Review

Methods for recording torque data

- With the use of digitally collected tools, manufactures are able to record if a product has been torqued to the appropriate torque values. The tool will often transmit live torque value data to a computer or record the torque values on the tool to be downloaded later (Tohnichi, 2019).

  What digital tools fail to take into account, is the order of operations in which the bolts were fastened.

  Companies require assemblers to manually record torque values or simply check a box signifying they followed the appropriate torque pattern.



PROJECT'S CHECKLIST and FLANGE-TORQUE RECORD:

Project: _____ Flange Set Location: _____
Connecting HDPE Flange to _____ Flange.
Bolt Dia & Grade : _____ Nut Diameter & Grade : _____
Lap-Joint Flange Dia. & Pressure Rating: _____
Lubricant Used: _____ Flange Temp: _____
Torque Wrench ID #: _____ Calibration Date: _____
If Specified: Full-face Gasket Info: Material: _____ Thickness:_____
Deep-Well Socket / Heavy-Hex Nut Wrench Size Used: _____

Axis off-set:_____ Angular & Facial Gap: Top_____ Bottom____ L____ R____

"Initial" Each Step Upon Completion:
_____1. Visually examine and clean both flanges, bolts and nuts. Replace damaged units.
_____2. Liberally Lubricate bolt threads & nut threads & flange surface under nut.
_____3. If gasket is specified, insert full-face gasket. Do not use wrinkled or damaged gaskets.
_____4. Number the bolt-holes in circumferential sequence stating at 12:00 position.
_____5. Check Flange alignment, concentricity, angularity, and gap for acceptability.
_____6. To firm the flanges squarely together, Hand Tighten, then pre-tighten all bolts in proper sequence to 10-20 foot-pounds torque, but do not exceed 20% of the TARGET TORQUE.
_____7. Re-check any flange-adapter face gap and LJF gap for uniformity. ****
_____8. Use the appropriate criss-cross pattern tightening in numerical sequence for Rounds 1, 2, 3, and 4 (tightening all bolts once in sequence constitutes a "round").

**** Note: Check LJF gap around the flange circumference between each of these rounds, measured at every other bolt. If any gap is not reasonably uniform around the circumference, make the appropriate adjustments by selective bolt tightening before proceeding.

TARGET TORQUE (and 4 to 24-HOUR RE-TORQUE): _____ foot-pounds

___ For 4-bolt, 8-bolt, 12-bolt Flanges

___ Lubricate, Hand tight, Pre-tighten
___ Round 1 – Tighten to ____ft.lbs. (30%)
___ Round 2 – Tighten to ____ft.lbs. (60%)
___ Round 3 – Tighten to ____ft.lbs. (100%)
___ Rotational (clockwise) Round

_____ For Large Flanges > 16 + Bolts

___ Lubricate, hand tighten, Pre-tighten
___ Round 1 – Tighten to ____ft.lbs. (25%)
___ Round 2 – Tighten to ____ft.lbs. (50%)
___ Round 3 – Tighten to ____ft.lbs. (75%)
___ Round 4 – Tighten to ____ft.lbs. (100%)
___ Rotational (clockwise) Round

____Rotational (clockwise) Round: 100% of Target Torque. Use rotational clockwise tightening sequence, starting with bolt #1, for one complete round, and continue until no further bolt or nut rotation occurs at 100% of the target torque value for each nut.

_____ 4- Hour Re-Torque & Inspection :

Re-torque to target torque value using one or two sequence-rounds, followed by one rotational round at the target torque value.

Documentation Recorded By : _____ Date: _____

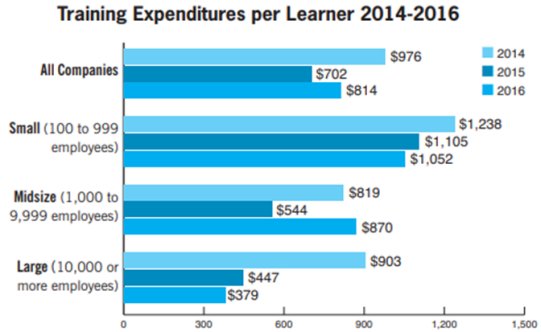
Joint Technician/Mechanic:_____ Date: _____

("Bolt Torque For Polyethylene Flanged Joints TN-38 2019," 2019)

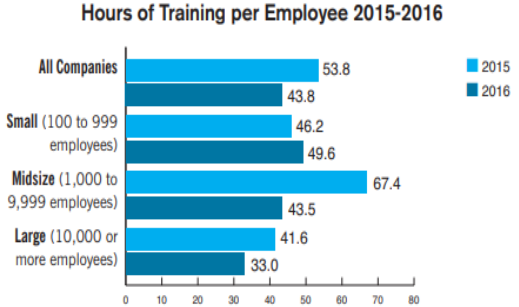
Literature Review

Workforce Training

- Industry turnover rates are increasing and with them costs to train and retrain employees. In 2018, the US voluntary turnover rate was 27%, which is a 7.6% increase from 2017. The Work Institute estimates 35% of employees will leave their job voluntarily by 2023 (Mahan et al., 2019).
- Deloitte and The Manufacturing Institute that by 2028, manufacturers are going to hire 4.6 million new employees (Deloitte, 2018).
- With an influx of new employees and the high cost of training (on average one thousand dollars in 2016), manufactures will be pinched to invest in systems that quickly train and guide users through the assembly process of products AND ensure all procedures are followed to assembly specification (Training Magazine, 2016).



Graph depicting average training cost of an employee relative to company size (Training Magazine, 2016).



Graph depicting average training time of an employee relative to company size (Training Magazine, 2016)

Literature Review

Assembly Work Instruction and Guidance

- As turnover rates increase, manufacturers are looking to decrease training time and cost by implementing more effective interactive systems that will allow the new employee to quickly understand the manufacturing process and follow along a guided interactive work instruction. Virtual tools are replacing traditional training methods and are becoming more accessible and affordable (Training Magazine, 2016).

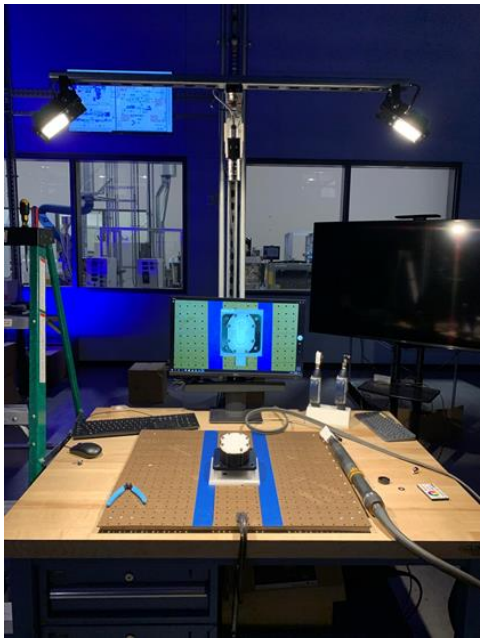
- Researchers are testing different methods of interactive work instructions that allow users to retrieve valuable assembly data quickly and effectively. Researchers Gavish et al. conducted a study comparing a guidance system using AR and comparing its usefulness to a more traditional non-immersive computer based video guidance. They found that users who used the immersive AR guidance performed better in assembly tasks, than those that just followed along using a computer (Gavish et al., 2015)

Framework and Methodology

Research Goals

- Develop system that ensures the proper assembly of bolted joints and creates a traceable record of as manufactured data. The system will identify if the correct quantity of fasteners and correct type of fasteners are used. Evaluate the effectiveness of such a system in an industrial environment.

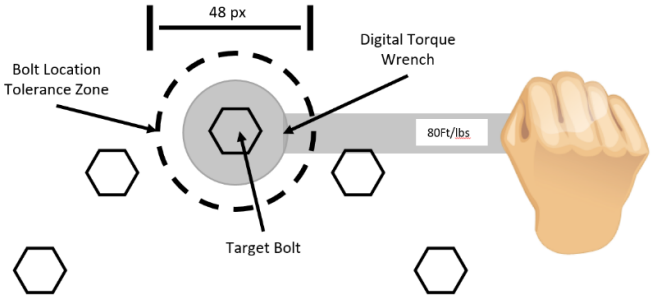
Equipment List	Equipment to be used
Torque Wrench	TOHNICHI CEM/CTB Bluetooth Model Torque Wrench
Computer	Dell Desktop with Intel XEON processor
HD Camera	Mokose HD Camera 1080p @ 60FPS
Video Capture Card	Viixem 1080P @ 60FPS HDMI Capture Card
Assembly Guidance	Computer Monitor



Framework and Methodology

Variables

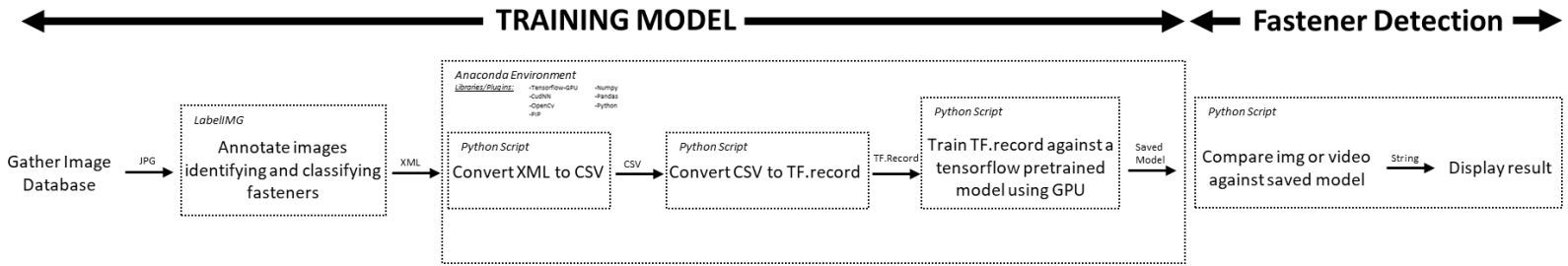
- To correctly recognize which fastener is being torqued at any moment, the system will compare a few variables:



Variable	Measurement Method
Mechanical Fastener Location and Presence	Using Python code coupled with a camera, the algorithm will be taught to recognize fasteners and record their presence or absence. Each bolt will be virtually marked with a unique ID number that will allow the system to save the torque value for each bolt using the bolts ID number.
Torque Pattern	The torque tool will have a QR code located on the head of the tool. This will allow the vision system to recognize the tool and its X and Y coordinates. Using the tool location relative to the fastener, the system will be able to identify the order in which the fasteners are torqued.
Torque Value	The torque value will be wirelessly sent from the digital torque wrench to the computer and be logged to record the 'as manufactured' torque data. Using a USB Bluetooth dongle, the torque wrench transmits a string containing the torque value, date/time, torque ID.
Fastener Type	Using Python code coupled with a camera, the algorithm will be taught to recognize fastener types. Three faster types will be used in this system: hex head, button head, and socket head.

Framework and Methodology

System Development and Fastener Detection



- System will utilize a variety of Python scripts and use Tensorflow 2 as a foundation for object detection.

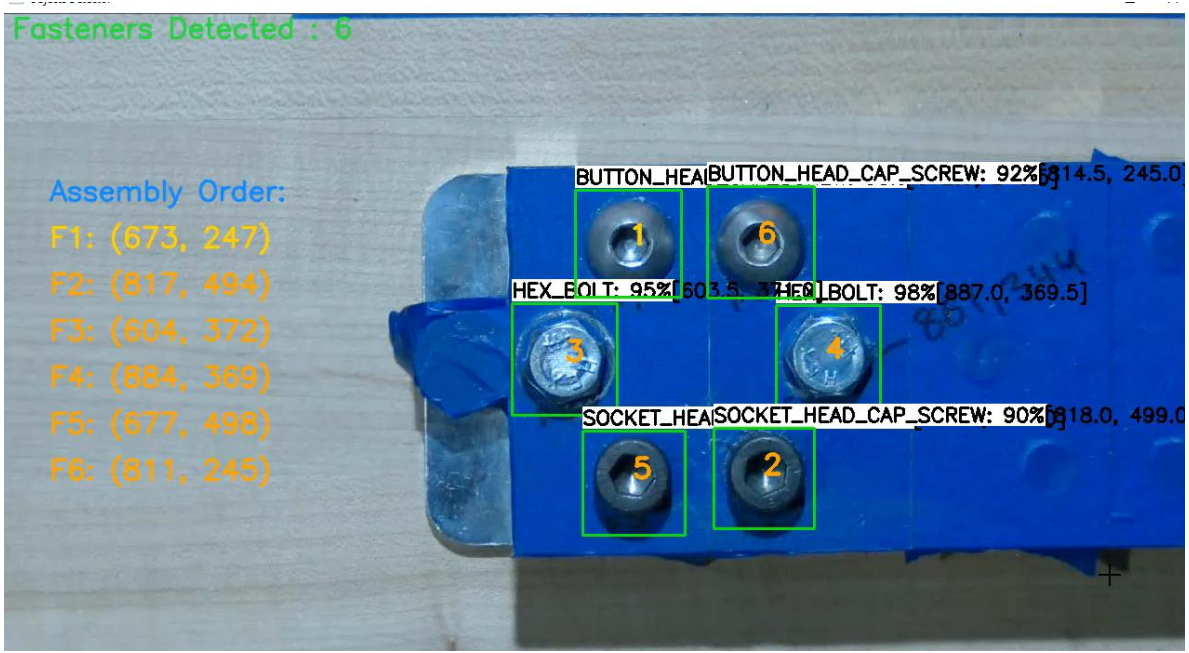
  Tensorflow 2 is a Python based machine learning API that allows the use of your computers GPU and CPU to generate object detection models and run detection algorithms

Framework and Methodology

System Operation

System's UI Displays:

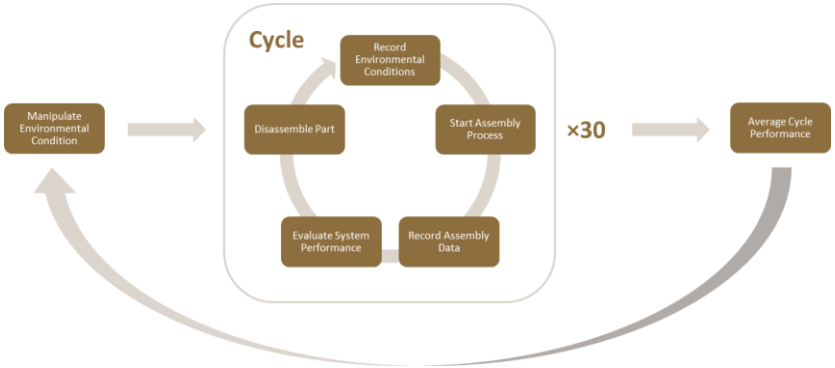
- Fastener assembly order
- Fastener IDs displayed on the fastener
- Fastener classification
- Classification Confidence
- Quantity of bolts



Framework and Methodology

Data Collection

- The systems technology stack was tested and evaluated in a manipulated industrial environment.
- A series of test cycles was conducted manipulating the environments noise conditions (Vibration and Illumination). The technology stack was tested if under standard and elevated industrial conditions, the system can effectively perform at a 90% confidence.



Number of Combinations	27
Number of Cycles per Combination	30
Total Number of Cycles	810

LIST
IL: 300 / VWB: 0.005 / VC: 0.005
IL: 300 / VWB: 0.005 / VC: 2.5
IL: 300 / VWB: 0.005 / VC: 5
IL: 300 / VBW: 2.5 / VC: 0.005
IL: 300 / VBW: 2.5 / VC: 2.5
IL: 300 / VBW: 2.5 / VC: 5
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IL :700 / VBW: 2.5 / VC: 5
IL :700 / VBW: 5 / VC: 0.005
IL :700 / VBW: 5 / VC: 2.5
IL :700 / VBW: 5 / VC: 5

Severity Level	Illumination (LUX)	Workbench Vibration (mm/s^2)	Camera Vibration (mm/s^2)
Baseline	700	0.005	0.005
Moderate	500	2.5	2.5
Elevated	300	5	5

Environmental Variable Combinations

Framework and Methodology

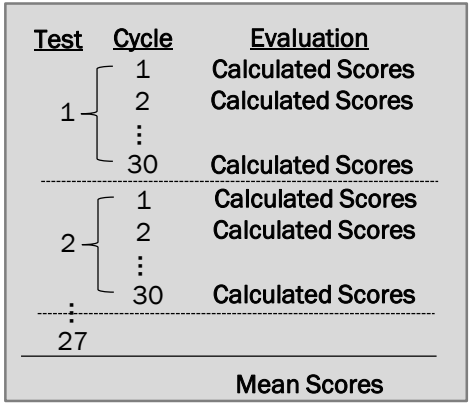
Data Analysis STEP

- Using the Standardized Technology Evaluation Process (STEP), the system was evaluated on a scale of 0-1. Each of the system factors were weighted and a total score calculated.
- An ideal total score of 1 indicates all system factors met evaluation criteria and a score below one indicates the system did not successfully meet evaluation criteria.

Weighted Factors	How to Test	Weight	Proposed System Score	Comments
Fastener Presence Tracked	System will display a bounding block around the fastener, acknowledging it as detected	.1		
Fastener Torque Order Recorded	During and at the end of the assembly, the software will report the torque pattern followed.	.5		
Correct Fastener Types Detected	System will display what fasteners are detected. At least 95% Confidence is required.	.3		
Torque Value Recorded	System will record the torque value for each fastener and the value is within ±3nm	.1		
Total Score		1	0	

Standardized Technology Evaluation Process (STEP) method for technology evaluation

Score	Description
0	Factor Does NOT Meet Evaluation Criteria
0.5	Factor Partially Meets Evaluation Criteria
1	Factor DOES Meet ALL Evaluation Criteria



Framework and Methodology

Environmental Conditions

Data collection took place in the Intelligent Manufacturing Testbed located at the Indiana Manufacturing Institute. Testing took place at night to allow for full control of environmental variables.

- Illumination

  The minimum standard lighting conditions in a workplace should be 300 LUX (OSHA, 2010) and the typical factory/workshop is 700-750 (Avetta, 2020). Conditions were manipulated using dimmable LED work lights.

- Workstation and Camera Vibration

  Medical experts and researchers in the US accept a daily limit of vibration of 5mm/s² for an employee. The testbed in which testing was held, had a baseline vibration of 0.005 mm/s². Conditions were manipulated using a variable speed rotating motors with offset cams.

Severity Level	Illumination (LUX)	Workbench Vibration (mm/s²)	Camera Vibration (mm/s²)
Baseline	700	0.005	0.005
Moderate	500	2.5	2.5
Elevated	300	5	5

- Calibration

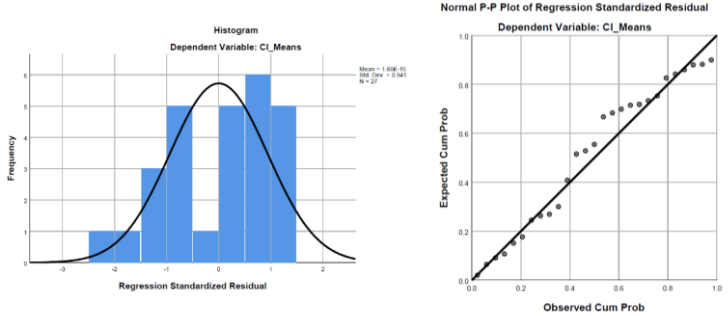
  To ensure the system was performing within the outlined tolerance, every permutation the fastener's detected locations were compared against the nominal values.

  The workbench was also fastener to the ground to reduce the need of recalibration during data collection.

Results

Data Analysis

- Workbench Vibration Coefficient: -1.901
  Significance < 0.05
- Camera Vibration Coefficient: -5.463
  Significance < 0.05
- Illumination Coefficient: .004
  Significance > 0.05



SPSS Regression Output Showing Data Normally Distributed

Regression

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Vibration_CAM, Vibration_WB, LUX[b]	.	Enter

a. Dependent Variable: CI_Means

b. All requested variables entered.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.860[a]	.740	.706	7.595479415

a. Predictors: (Constant), Vibration_CAM, Vibration_WB, LUX

b. Dependent Variable: CI_Means

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3769.193	3	1256.398	21.778	.000[b]
	Residual	1326.900	23	57.691		
	Total	5096.093	26			

a. Dependent Variable: CI_Means

b. Predictors: (Constant), Vibration_CAM, Vibration_WB, LUX

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	91.685	5.348		17.144	.000
	LUX	.004	.009	.050	.472	.642
	Vibration_WB	-1.901	.717	-.282	-2.652	.014
	Vibration_CAM	-5.463	.717	-.811	-7.621	.000

Coefficients[a]

Model		95.0% Confidence Interval for B Lower Bound	95.0% Confidence Interval for B Upper Bound
1	(Constant)	80.622	102.748
	LUX	-.014	.023
	Vibration_WB	-3.384	-.418
	Vibration_CAM	-6.946	-3.980

a. Dependent Variable: CI_Means

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	56.13280869	94.60302734	75.37405338	12.04030553	27
Residual	-15.5510025	9.713118553	.0000000000	7.143851777	27
Std. Predicted Value	-1.598	1.597	.000	1.000	27
Std. Residual	-2.047	1.279	.000	.941	27

a. Dependent Variable: CI_Means

SPSS Output For Multiple Linear Regression

$$-1.901(Vibration_{WB}) - 5.463(Vibration_{CAM}) + 91.685 = System\ Confidence$$

Linear regression formula from coefficient output from SPSS

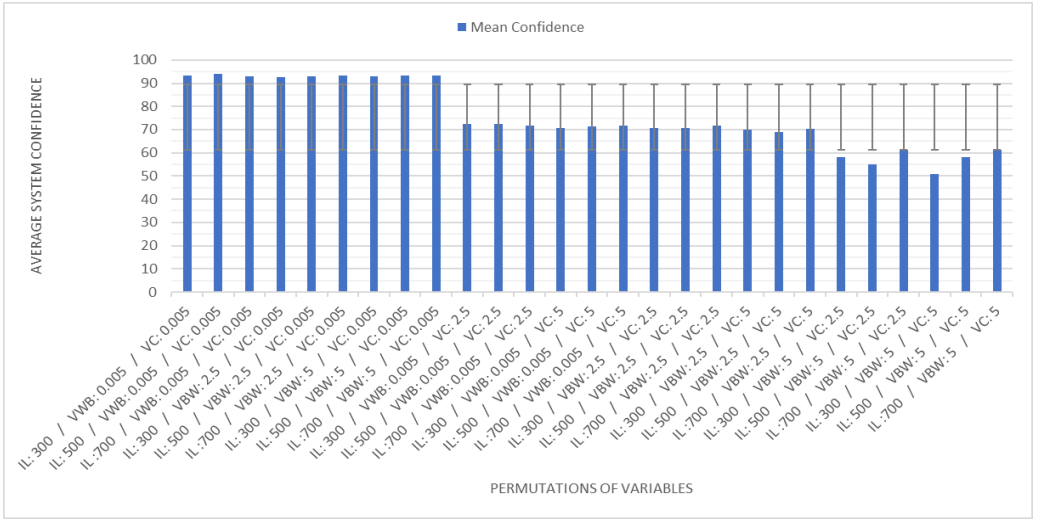
- Residuals normally distributed and have a r^2 of .740
  Strong relationship between the variables
- Regression equation explains most of the variation of the system confidence variable

Results

Overall System Confidence

- The average system confidence for all permutations was 75.37%
- The standard deviation for all permutations was 18.932

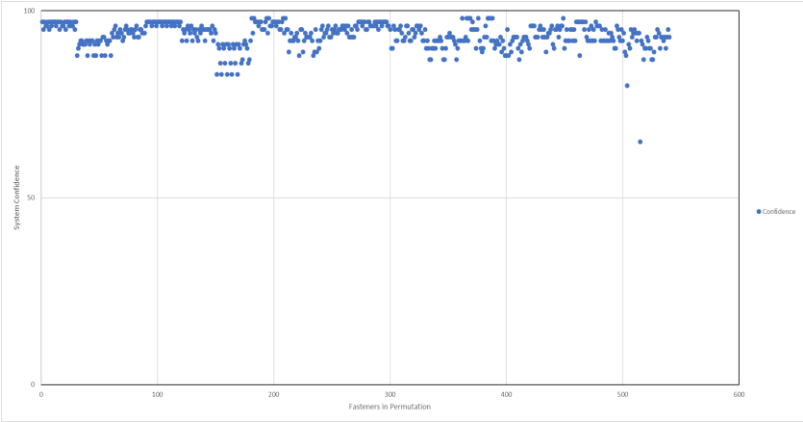
- When comparing all permutations, the high standard deviation indicated widespread system confidence
- An average confidence score of 75.37% is less than the 90%



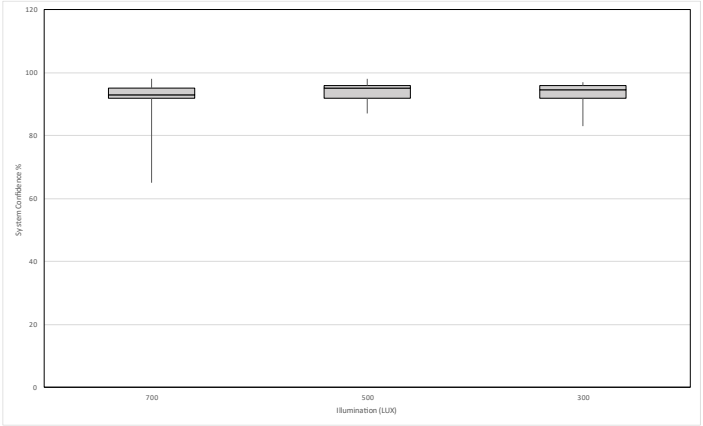
System Confidence per Variable Permutation

Results

System Confidence With Manipulated Lighting and Baseline Vibrations



System Confidence for Fasteners During Permutations With Manipulated Lighting Conditions And Baseline Vibration Conditions



Box Plot Showing System Confidence for Illumination With Workbench Vibration and Camera Vibration at Baseline Severity.

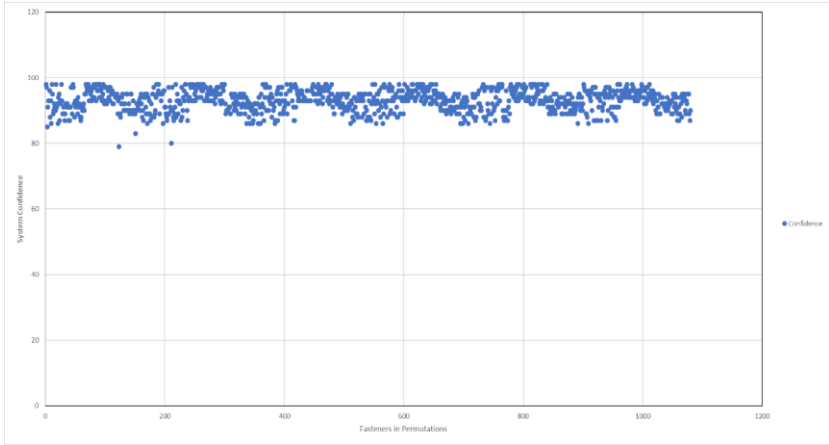
LUX 700	
Min	65
1st Q	91.75
Median	93
3rd Q	95
Max	98

LUX 500	
Min	87
1st Q	92
Median	95
3rd Q	96
Max	98

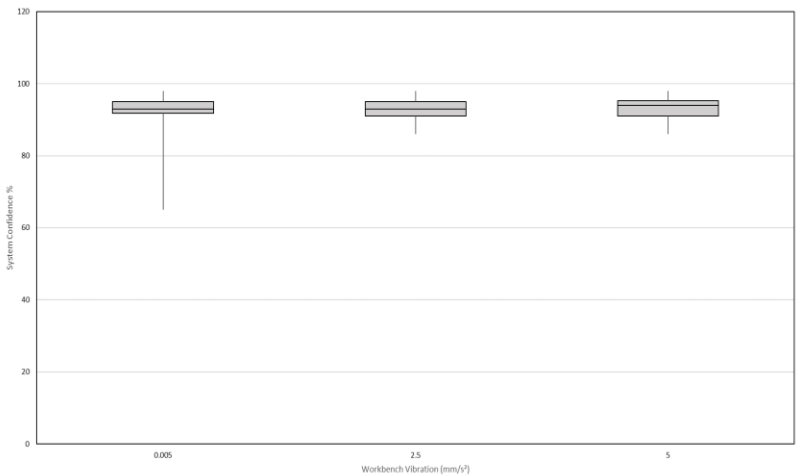
LUX 300	
Min	83
1st Q	92
Median	94.5
3rd Q	96
Max	97

Results

System Confidence With Manipulated Illumination and Workstation Vibration with Baseline Severity Camera Vibration



System Confidence For Fasteners During Permutations With Manipulated Lighting and Workbench Vibration Conditions And Baseline Camera Vibration Conditions



Box Plot Showing System Confidence for Workbench Vibration With Illumination and Camera Vibration at Baseline Severity.

0.005 mm/s²	
Min	65
1st Q	91.75
Median	93
3rd Q	95
Max	98

3.5 mm/s²	
Min	86
1st Q	91
Median	93
3rd Q	95
Max	98

5 mm/s²	
Min	86
1st Q	91
Median	94
3rd Q	95.25
Max	98

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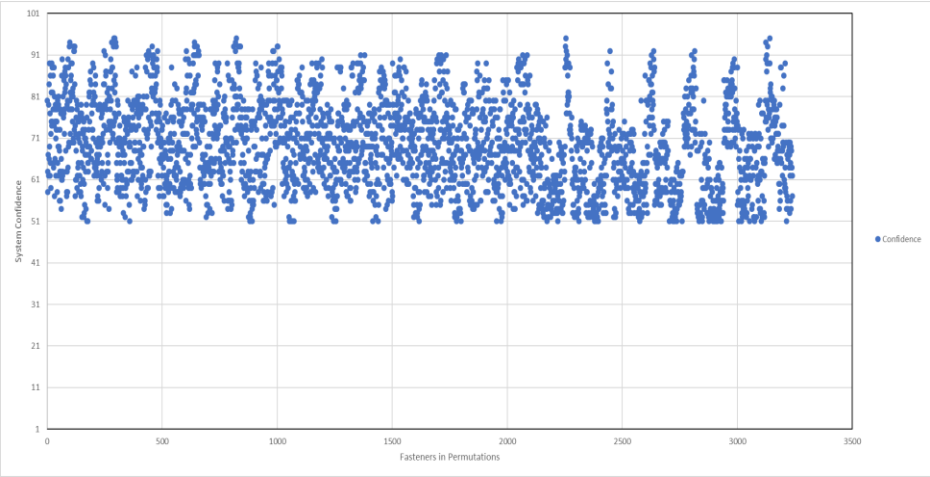
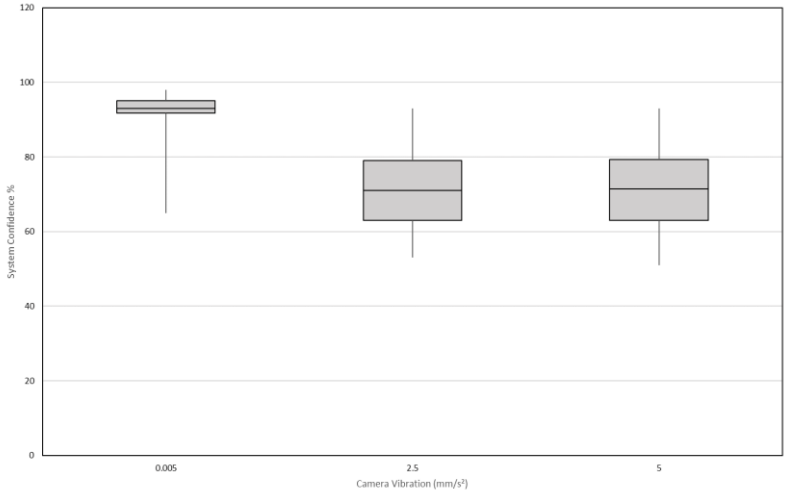
Results



System Confidence for Fasteners During Permutations With Moderate and Elevated Camera Vibration



Box Plot Showing System Confidence for Camera Vibration With Illumination and Workbench Vibration at Baseline Severity.

0.005 mm/s²	
Min	65
1st Q	91.75
Median	93
3rd Q	95
Max	98

2.5 mm/s²	
Min	53
1st Q	63
Median	71
3rd Q	79
Max	93

5 mm/s²	
Min	51
1st Q	63
Median	71.5
3rd Q	79.25
Max	93

Results

Torque Pattern Tracking

- The system's ability to correctly track the torque pattern was recorded. (A)
- Out of the 810 assemblies, 50 were randomly selected to be incorrectly assembled to test if the system will recognize the incorrect assembly attempt. (B)

Fastener Presence and Absence

- In total, 4860 fasteners were assembled during data collection with 97% of the fasteners presence correctly detected. (C)

  103 were randomly covered to test the systems ability to recognize the absence of fasteners. Out of 103 fasteners, the system correctly detected the fasteners missing.

A

All Permutations	
Total Amount of Assemblies	810
Amount of Assemblies Pattern Correctly Recorded	270
Amount of Assemblies Pattern Incorrectly Recorded	540
Success Rate	33%

A

Permutations Excluding Camera Vibration	
Total Amount of Assemblies	270
Amount of Assemblies Pattern Correctly Recorded	270
Amount of Assemblies Pattern Incorrectly Recorded	0
Success Rate	100%

B

All Permutations	
Total Amount of Assemblies	810
Number of Incorrect Assembly Attempts	50
Number of Correctly Detected Inorrect Assembly Attempts	29
Success Rate	58%

B

Permutations Excluding Camera Vibration	
Number of Incorrect Assembly Attempts	21
Number of Correctly Detected Inorrect Assembly Attempts	21
Success Rate	100%

C

Total Amount of Fasteners Assembled	4860
Total Amount of Fasteners Un-Recognized/Missed	135
Percentage Accuratly Detected and Recognized	97%

Results

STEP Results

- If all fasteners were detected/classified the result was a score of 1, if any of the fasteners were not detected, that cycles score was 0.5. If non of the fasteners were detected for that cycle, the cycle's score was 0.

- **STEP Scores Excluding Camera Vibration**

  Fastener Presence Tracked: .996

  Fastener Pattern Recorded: 1

  Corrected Faster Classification: .996

  Tool Presence Tracked: 1

Weighted Factors	How to Test	Weight	System Score Average	Comments
Fastener Presence Tracked	System will display a bounding block around the fastener, acknowledging it as detected	.1	.6247	When camera vibration introduced, some fasteners could not be detected
Fastener Order Pattern Recorded	During and at the end of the assembly, the software will report the torque pattern followed.	.5	.333	When camera vibration introduced, system could not track tool and could not record location
Correct Fastener Types Detected	System will display what fasteners are detected. At least 90% Confidence is required.	.3	.332	When camera vibration introduced, faster detection became unreliable
Tool Presence Tracked	System will display a bounding block around the tools QR coding	.1	.333	When camera vibration introduced, system could not track tool
Total Score		1	.3621	

Standardized Technology Evaluation Process (STEP) method for technology evaluation

Score	Description
0	Factor Does NOT Meet Evaluation Criteria
0.5	Factor Partially Meets Evaluation Criteria
1	Factor DOES Meet ALL Evaluation Criteria

Discussion

Environmental Effects on System Performance

- The relationships between the environmental conditions and system performance are important to understanding the systems feasibility in an industrial environment.

  Illumination

  - Illumination did not prove to have a significant effect on the system's performance. This means the systems performance was good and consistent across all severity levels.

  Vibration

  - Vibration proved to have a significant effect on the system's performance. Vibration experienced by the workbench and camera resulted in negative relationship with a coefficient of -1.901 and -5.463 respectively.

- The system performed at an average of 93.4% confidence with no vibration and an average of 93.04% with only workbench vibration. With camera vibration the average dropped down to 69.37%.

- System has the potential to operate at over 90% confidence in an industrial environment if the camera was isolated from environmental vibration.

Discussion

Fastener Detection

- System was able to detected to correct number of fasteners 97%.
- The 3% of fasteners missed, were due to camera vibration. With no camera vibration, fasteners were correctly detected 100% of the time.
- 103 fasteners were randomly covered to evaluate the systems ability to recognize missing fasteners, the system successfully detected 103 of those fasteners.

Torque Pattern

- Out of 810 cycles, the torque pattern for 270 was correctly recorded.
  - This was due to the systems inability to recognize the tools QR code.
  - When a torque value was received, it was recorded, but no tool location was saved
  - In cycles without camera vibration, the torque pattern was recorded correctly every time.

Torque Value

- Out of the 4860 fasteners that were torqued during testing, all the torque values received and decoded by the system matched the as manufactured torque value.

Discussion

STEP Analysis

- The method outlines a 0-1 score that weighs the system's key factors.
- After every cycle, the STEP criteria was applied to a formula and the cycle was rated based on it’s performance and an average for all the criteria was recorded.
- The STEP method regards a score of 1 as the highest, meaning the system performed as expected.

  Anything below a 0.5 score is regarded as low in performance and not meeting most of the evaluation criteria

  The average weighted score during data collection was .3621, which indicated poor system performance. This was due to the inability to track torque patterns when camera vibration was introduced.

  When camera vibration was isolated, the system performed at an average of .9985, indicating good system performance and meeting all evaluation criteria.

Discussion

Conclusion

- The system outlined in this study was designed to aid manufactures in completing a digital record of as manufactured data ensuring the assembly is correctly torqued.
- 810 cycles were tested under various industrial environmental conditions resulting in data 4860 fasteners worth of data.
- When determining the systems feasibility in an industrial environment, the systems ability to track torque patterns, record torque values, recognize the appropriate fasteners and fastener count were evaluated.

- After analyzing data, it can be concluded that, the system is a feasible solution for industrial applications, with the exception that the vision camera is isolated from vibration.

Possible Outcomes

Potential Use Cases For the System

- Poka-Yoke Vision System

  This proposed system can be used as a supplement to current physical Poka-Yoke methods. System can be used to locate tools within the workstation and prevent incorrect tools from used or prevent the tool from becoming a foreign object.

- Process Traceability

  The system has the potential to reduce the amount of risk associated with operator inputted data and increase torque sequence data accuracy and reliability.

- Operator Training and Guidance

  If the system results are significant and the system proves to be more accurate at recording as manufactured data and ensuring operators follow proper torque sequences, the system can be used to reduce operator training time and allow users to simply follow the guided system in properly torqueing an assembly.

- Lean 5S (Sort, Set, Shine, Standardize, and Sustain)

  Lean 5S principles focus on workstation organization and safety. With an organized and sorted workstation, it is believed to increase employee performance and safety (Filip & Marascu-Klein, 2015). This system can be used to detect bolts that are not part of the current assembly, and can potentially used or become debris within the part.

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Thank You, Questions?

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