An Applications Approach to Digital Twins for Precision Measurement and Quality Assurance

Mid-Semester Progress Report
DSA5900 – Spring 2024
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Section 1: Motivation

If asked about an experience where I made a mistake at work, I will always talk about a “conical hole plug” that failed when under 1400 bar (20,305 psi) pressure, creating a projectile in a manufacturing environment.

The conical plug **(Figure 1 - Item 1)** was designed to fit inside of a conical hole **(Figure 1 - Item 2)** that, when compressed by a 1-1/2” – 6 Grade 8 Bolt **(Figure 1 - Item 3)**, created a seal that held elastomer being extruded into a steel tube at a maximum of 1400 bar from leaking through the hole. The pressure is depicted by red arrows in **Figure 1**. During assembly of this plug assembly, the bolt, which is reused each extrusion process, is coated with a lubricating copper coating to aid in the bolt being properly torqued while compressing the plug.

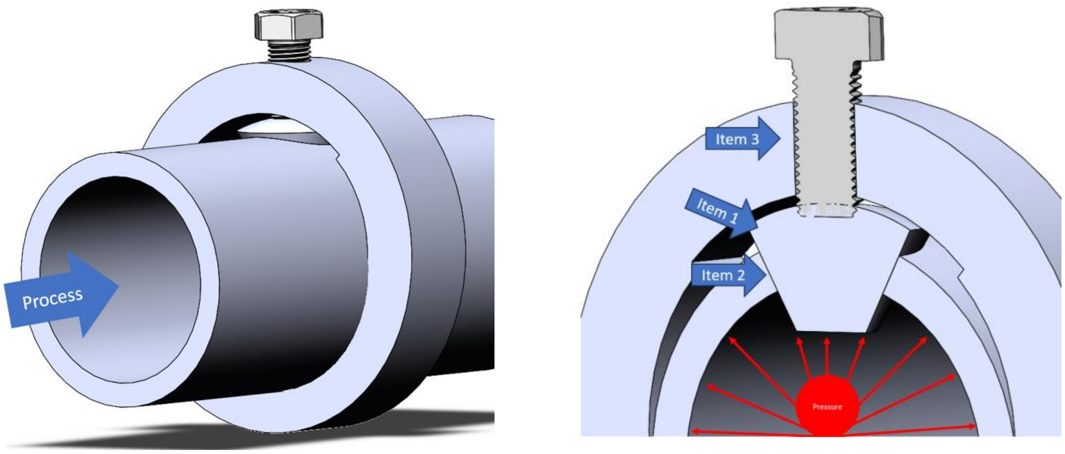

Figure 1: Conical Hole Plug Assembly

During the elastomer extrusion process, the inside of the steel tube and resultant Conical Hole Plug sees extreme outward pressure, applying an upward force onto the threads of the 1-1/2” – 6 Grade 8 Bolt. After repeated assembly, processing cycles, and disassembly, the threads of the bolt begin to fatigue and deform, like the region in red of the bolt seen in **Figure 2**. This deformation ultimately leads to thread failure, allowing pressure loss from inside of the steel tube thrusting the 1-1/2” – 6 Grade 8 Bolt uncontrollably into areas populated by manufacturing operators.

Figure 2: Deformed vs Acceptable Threads

In this scenario, a robust thread inspection process paired with continuous evaluation of extrusion process data, the Manufacturing Engineering Team could have predicted bolt failure and performed preventative maintenance prior to putting manufacturing personnel in harms way.

Section 2: Introduction

In manufacturing, it is no secret that the industry is in the middle of the Fourth Industrial Revolution. This revolution, coined "Industry 4.0", is the transformation of archaic manufacturing processes and process controls into smart, connected manufacturing systems that are developed, optimized, and controlled using digital technologies such as the Internet of Things (IoT), Big Data, Machine Learning, and other technologies that can increase product quality, product reliability, and production capacity while lowering operating costs to the production facility.

One aspect in the manufacturing process that is often scrutinized is the quality control of products produced as, from a customer perspective, these tasks do not add any value to the overall product being produced. The constant push and pull within a manufacturing facility to confirm that product is produced to specification while limiting the amount of time machines and operators "touch" the part is a top priority for the manufacturing engineering teams.

A transformative idea to reduce inspection time while aiding in the increase in product quality and its predicted reliability is the use of a "Digital Twin" for inspection equipment such as a Coordinate Measurement Machine (CMM), Vision Inspection Systems, and other software driven equipment.

A Digital Twin is the use of a digital model which simulates a Physical Twin which represents a physical process, environment, assembly, or component. Relative to digital inspection equipment, the Digital Twin is used to generate and confirm the process the digital inspection equipment shall follow prior to implementation, eliminating the time required for a Quality Inspector to manually program these processes.

Additional to the inspection processes, a Digital Twin of a part or assembly manufactured and inspected through the entire product's lifecycle can allow Machine Learning and Predictive Models to guide engineers in making decisions on preventative maintenance while in operations prior to product failure.

To make a shift in the industrial mindset, the theoretical and academic concepts of how data, systems, and humans interact need to be applied and operationalized in an efficient manner. The Applications Approach to Digital Twins for Precision Measurement and Quality Assurance study provides a real-world overview to the implementation of this methodology in a manufacturing facility and provide a model that will allow operations and reliability engineers to make data driven decisions on how to maintain products operational in the field.

Section 3: Objectives

This project aims to explore the use and benefit of Digital Twins within manufacturing and to provide a practical implementation of a Digital Twin to represent the CyberOptics CyberGage 360 Vision Inspection System[1] (CyberGage 360) and a 1"-8 UNC Bolt (Bolt). After the Digital Twin for both items are implemented, data ingested by the Digital Twin of the 1"-8 UNC Bolt shall reflect the environment and actions performed on it and can be used to predict future performance and failures.

To accomplish the objective, the following specific objectives have been established:

1. **Implement Digital Twins to represent the CyberGage 360 and 1”-8 UNC Bolt.**

   For the first objective, a Digital Twin shall be generated using SolidWorks and Azure Digital Twins to represent the CyberGage 360 and Bolt respectively. Model Schema for each Digital Twin shall be established based on mechanical 3D models of the Equipment and Critical to Function Dimensional Measurements of the Bolt.

2. **Establish a robust workflow and data stream to utilize the Digital Twin of the CyberGage 360 to confirm the inspection process of the Bolt and to ingest fatigue testing data and dimensional inspection results of the Bolt into its Digital Twin.**

   For the second objective, the Digital Twin of the CyberGage 360 in SolidWorks will be utilized to find an efficient process to perform and confirm the inspection of Critical Dimensions for the Bolt. Additionally, data streams from the Physical Twin of the Laboratory based CyberGage 360 and Fatigue Testing Equipment shall be established to feed testing data and resultant dimensional inspection data to the Azure based Digital Twin of the Bolt.

3. **Using data ingested by the Bolt Digital Twin, implement a Lifecycle Predictive Model to predict failures of the Physical Twin to advise preventative maintenance shall be performed.**

   For the third objective, repetitive cycles of fatigue testing and dimensional inspection shall occur using the Physical Twins. The data from these cycles shall feed the established Digital Twins resulting in a database of mechanical test data and dimensional data. This data shall be used to build Linear Regression and Machine Learning Models to aid in predicting failures in the Physical Twins that the Digital Twin represents.

Section 4: Data Ingestion, Exploration, and Preparation

CyberGage 360 Digital Twin

Prior to data ingestion into the Digital Twin of the Bolt by bust data streams from Laboratory based Test & Inspection Equipment, it must first be established that the part being evaluated is capable of a full dimensional inspection using the CyberGage360. The CyberGage 360 uses image data from 6 total image sensors, two of which are, according to CyberOptics, “dual camera optical blue light scanning sensors mounted above and below the subject part sitting on an optically flat, clear glass plate calibrated for scanning. The glass plate allows simultaneous data capture from both sensors and eliminates the need to flip-over the part necessary for all other scanning and other conventional measuring systems.”[2]

Given that the system uses cameras from different angles to simultaneously to scan a component that must sit at the center of the 157,909 mm^2 area rotating glass plate within a 200mm diameter x 100mm high cylinder (31,415.93 mm^2 Area), there is a ~80% chance that a portion of the component will sit outside of the inspection area when placed on the glass inspection plate**. Figure 3** provides an overview of the Digital Twin and Physical Twin of the CyberGage360 where, on the Digital Twin, the green assemblies represent the six image sensors, the blue plate represents the optically clear rotating inspection plate, and the red cylinder represents the 200mm diameter x 100mm cylindrical inspection area.

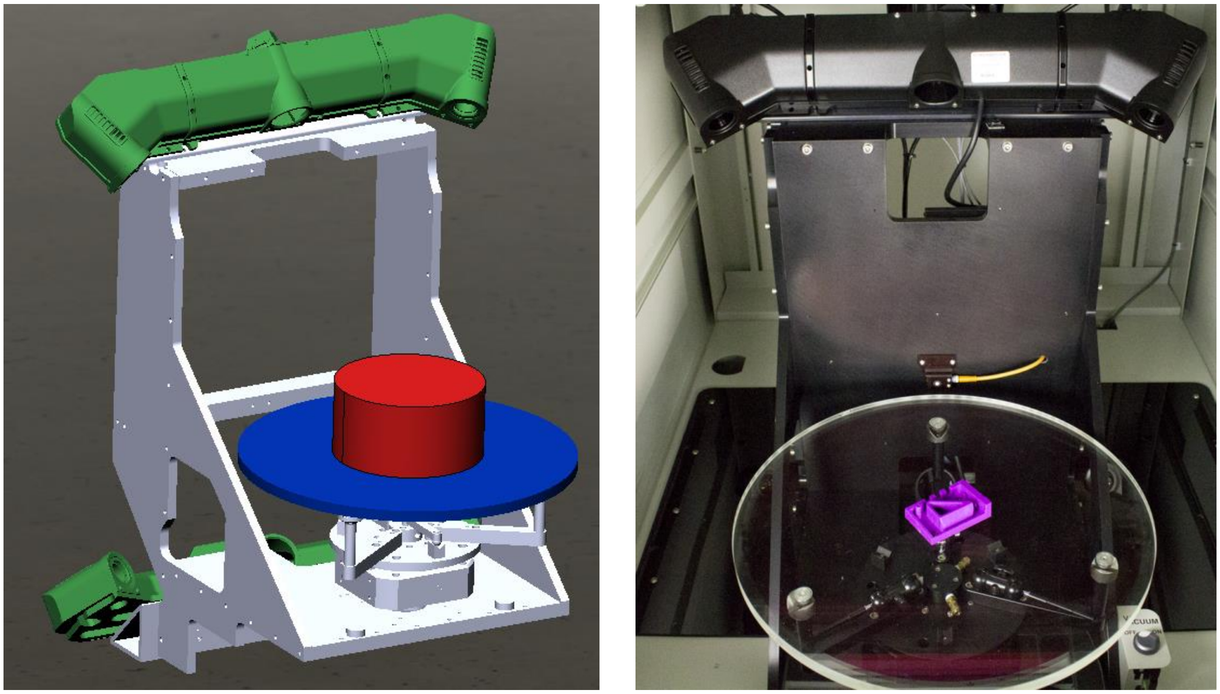

Figure 3: Left – CyberGage360 Digital Twin, Right – CyberGage360 Physical Twin[3]

Due to this potential error and to ensure an accurate inspection of all critical features of the Bolt Physical Twin, the CyberGage 360 Digital Twin allows Manufacturing and Quality Engineers to develop an inspection process that is part specific and is validated to be accurate prior to releasing to production.

For the Bolt selected, a 1" – 8 UNC Bolt that is 101mm tall, an Interference Detection process is performed between the Bolt and the cylindrical inspection area to confirm that the part fits within this envelope when sitting in the center of the rotating inspection plate, identified by the red region of the bolt in **Figure 4**. Alternatively, if the bolt was placed 225mm to the left, the Interference Detection process will show that the Bolt is not fully enveloped by the inspection area, identified by the silver portion of the bolt in **Figure 5**, and should not be placed in this region in production.

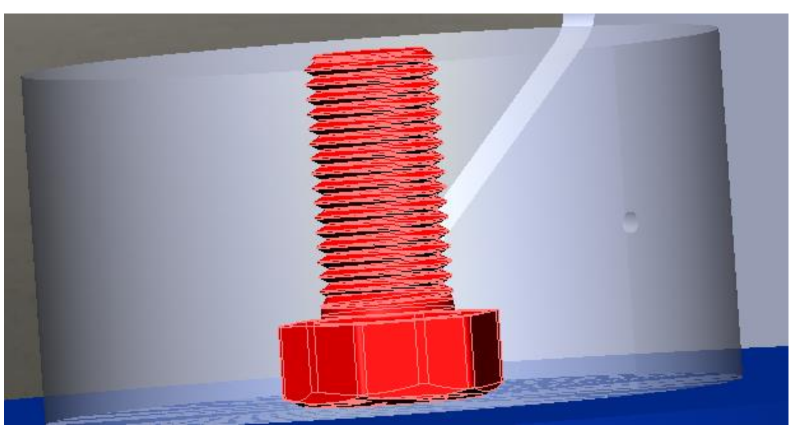

Figure 4: Bolt Inside of Inspection Region (red)

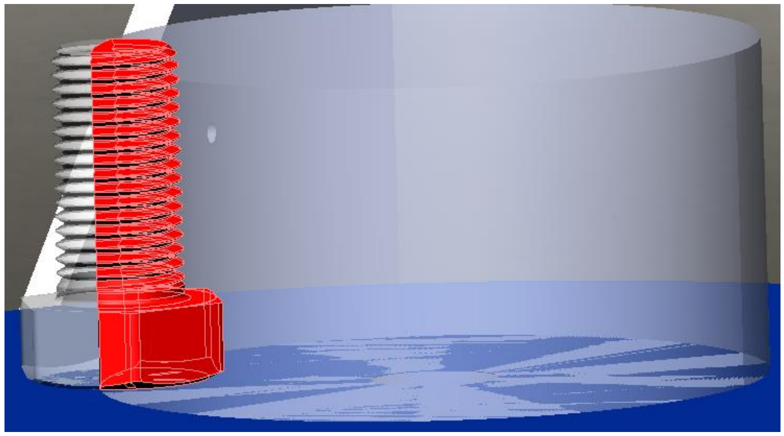

Figure 5: Bolt Outside of Inspection Region (silver portion)

Now that the CyberGage 360 Digital Twin has confirmed the Bolt will fit into the inspection region of the CyberGage360, it must be confirmed that all critical features of the Bolt can be seen by the six image sensors in the orientation confirmed the bolt will be placed into the inspection region.

NOTE: The process to confirm all critical features of the Bolt can be inspected is still working to be validated. The current method being evaluated, using a "light cone" from a single image sensor is seen in **Figure 6**, is not optimal as the light cone is depicted as a solid body and interferes completely with the Bolt sitting within the solid body.

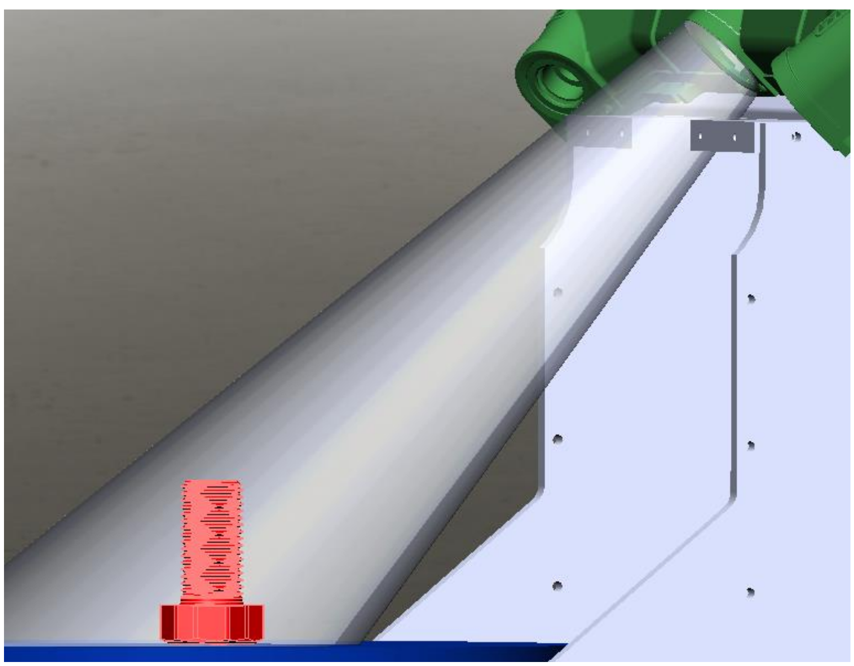

Figure 6: Interference Detection between Bolt and Image Sensor

Bolt Digital Twin

As observed in the previous section, a 3D Model representing the 1"-8 UNC Bolt is used to confirm all inspection processes within the CyberGage 360 Digital Twin. As future predictive models in this project will use data representing fatigue testing performed on the Bolt and dimensional data output from the Physical Twin of the CyberGage 360, a Digital Twin model shall be developed using the Digital Twin environment in Azure.

Within Azure, a Digital Twin model can be input by generating a JSON file containing the Digital Twin Definition Language (DTDL)[4]. For each Digital Twin representing a Physical Twin, a model shall be input into Azure with the schema defined below in **Table 1**.

name	@type	schema
Overall_Length	Property	Double
Average_Major_Diameter	Property	Double
Minimum_Major_Diameter	Property	Double
Average_Tensile_Load	Property	Double
Temperature	Property	Double
Fracture	Property	Boolean

Table 1: Bolt Digital Twin Schema

A portion of the Azure representation can be seen below in **Image 7**.

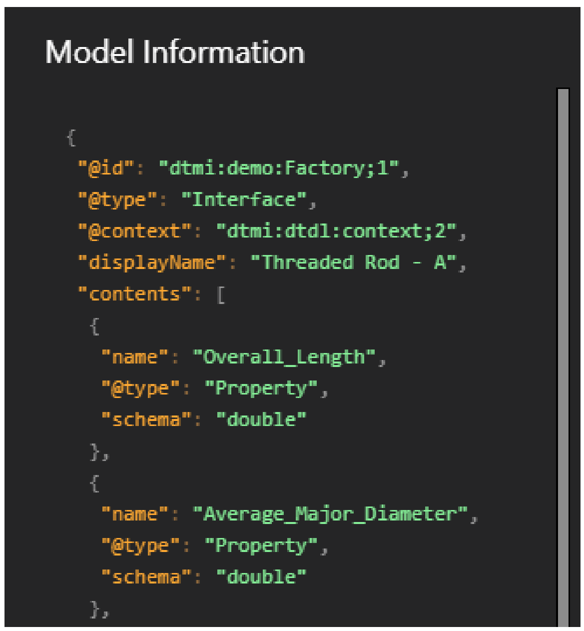

Figure 7: Digital Twin Schema in Azure

For this project, 10 Bolt Digital Twins representing 10 Bolt Physical Twins are generated using the schema provided above and initialized with preliminary inspection data from the Physical Twin CyberGage 360. An example of the loaded properties of Bolt #1 are below in **Figure 8.**

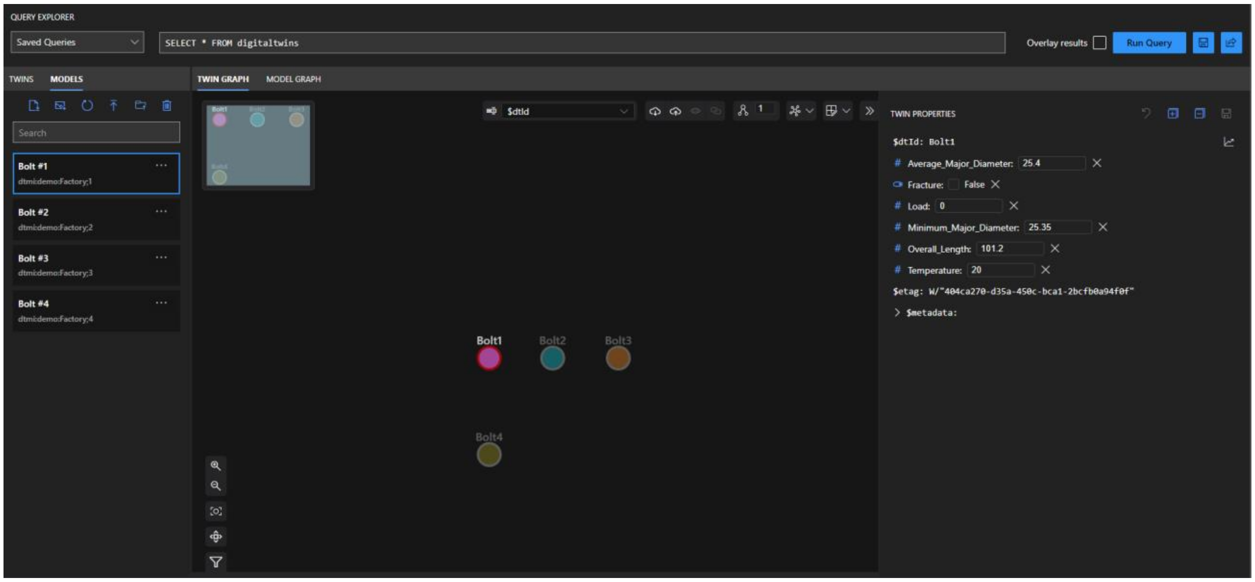

Figure 8: Initialized Digital Twins of Bolt, with Bolt #1 Data Visualized

Data Stream

With the Digital Twin of the Bolt generated, fatigue testing of the 10 Bolt Physical Twins shall be performed using the test plan defined in **Table 2**. For each Bolt and each step of the plan, real-time logging of data shall occur and ingested by the relevant Digital Twin in Azure.

Test	Duration	Variable
Temperature Cycling	12 Hours, 1 Hour / Variable	-20C – +100C
Tensile Load	5 Cycles / Variable	500 – 2500 lbs
Dimensional Inspection using CyberGage 360		
Temperature Cycling	12 Hours, 1 Hour / Variable	-20C – +100C
Tensile Load	5 Cycles / Variable	500 – 2500 lbs
Dimensional Inspection using CyberGage 360		
Temperature Cycling	12 Hours, 1 Hour / Variable	-20C – +100C
Tensile Load	5 Cycles / Variable	1500 – 4000 lbs
Dimensional Inspection using CyberGage 360		
Temperature Cycling	12 Hours, 1 Hour / Variable	-20C – +100C
Tensile Load	1 Cycle	Load To Failure

After testing, the database of Bolt Digital Twins will consist of fatigue test data and dimensional data after each cycle of testing. Each Bolt Physical Twin will have been tested to Failure as to ensure an accurate information is fed into the Linear Regression Model with loads experienced during testing and the resultant dimensional data after the testing occurred.

Section 5: Methodology

Section 6: Results and Analysis

Section 7: Deliverables

Section 8: References

1. https://www.cyberoptics.com/products/cybergage360/

2. https://www.cyberoptics.com/download/industrial-metrology/powered-by-mrs/CYBERGAGE360-8024761-REV_E.pdf

3. https://www.laserdesign.com/products/CyberGage360/

4. https://github.com/Azure/opendigitaltwins-dtdl/blob/master/DTDL/v3/DTDL.v3.md