CAAP Quarterly Report

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Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Project Title: Brain-Inspired Learning Framework to Bridging Information, Uncertainty and Human-Machine Decision-Making for Decoding Variance in Pipeline Computational Models

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For quarterly period ending: *January 7th, 2021*

Business and Activity Section

(a) Generated Commitments

One manuscript is prepared and will be ready to submission: "*Convolutional Neural Network Based Damage Diagnostics for Structures with Weldment via Decoding Ultrasonic Guided Wave*". PhD student Zi Zhang who mainly takes charge of this research is the first author. Second manuscript is also nearly completed and will be for submission.

(b) Status Update of Past Quarter Activities

The research activities in the 9th quarter included: (i) Task 4: Completed all efforts, including remaining work on structural initial nonlinearity to address: (a) aging effects on with and without weldment toward data variances, and (b) aging effects on with and without protective coating are in progress and will be reported in the coming period. (iii) Task 6: survey questionnaire was developed to collect the critical information in best practices and uncertainty and will be used for calibration and verification of the concept.

(c) Cost share activity

Cost share was from the graduate students' tuition waiver

(d) Summary of detailed work for Tasks 4 and 6

Task 4: Decode Variance from Uncertainties

In this section, the aging effect of materials and the coating effect were considering in the experiment. Note that aging effects with and without protective coating associated with material degradation through both experimental and numerical investigations have prepared and are still in progress under the exposure of accelerated weathering, and will be fully summarized in the coming period.

Table 1. Remaining test matrix for decoding variance from uncertainties

Step	Sources of Variation	Task	Factors	Levels of the Factors
7	Structural initial nonlinearity	Task 4.3	Aging effect Coupled with weldment Noise interference (experimental)	Under different accelerated weathering (aging) times
8	Structural initial nonlinearity	Task 4.3	Aging effect Coupled with weldment Noise interference (numerical)	Under different accelerated weathering (aging) times

Sub-Task 4.3. Reducing variance due to structural initial nonlinearity

Oil and gas currently provide 54% of the world's primary energy need. Accordingly, the United States alone consists of over 2.6 million miles of oil/gas pipelines. However, most of the pipelines are susceptible to suffering the environment effect leading to aging and corrosion problems. Pipeline aging and corrosion problems occur because the interaction between the pipeline and the environment, resulting the deterioration and delamination of the pipeline material. The destruction of pipelines has the potential of contaminating the environment and even the risk of explosion [1]. Therefore, the detection of the corrosion in early stage is critical.

Due to the wide span of pipeline structures, it is necessary to implement the regular inspection and routine maintenance by non-destructive test (NDT) during the service life. Conventionally, the utilize of point-by-point NDT techniques, such as ultrasound thickness testing, magnetic particles, radiography, and ultrasound phased array, represent a generally time intensive and costly monitoring process [1]. Among them, the ultrasonic guided waves exhibit their merits over other techniques, due to their long distant propagating with low energy loss and sensitivity to tiny defects. Several researchers have already employed the ultrasonic guided waves to detect corrosion in structures. In 1998, Ravenscroft et al. [2] introduced a novel ultrasonic method to detect the global of pipes and vessels, where was sensitive to corrosion and cracking. In this method, ultrasound was directed into the pipe at a critical angle and two actuators was used for a transmitter and a receiver. Defects are detected by measuring the reduction in the energy of the received signal. Later, ultrasonic measurement method was used to inspect the corroded thickness of plates [3]. Huthwaite et al. [4] employed the guided wave tomography to offer a measure method which accurately predicted the wall thickness losses in plated caused by corrosion. The measurements monitored by transducer array were restricted into a map of wall thickness. The corrosion of coated plates was also detected by this method. An embedded ultrasonic sensing network was established by Ervin et al. [5] and ultrasonic guided waves were used to monitor the corrosion location of the rebar buried in mortar. Longitudinal waves at high frequency were utilized in this experiment by pulse-echo configuration due to the fastest propagating and lowest attenuation. Sun and Dai [6] proved that L (0,2) mode waves combined with wavelet transform method to detect the position of axial defects. Torsional guided waves were also used for corrosion detection, where the reflection of the waves was attenuated when the pipe was corroded. Some researchers used numerical simulation method to simulate the corrosion defect as a notch due to the corrosion can caused the thickness loss of the steel [1]. The most of research was focused on localize or detect the corrosion, however, measurement of the corrosion process is also important for engineering to estimate the situation of the pipe.

Therefore, as illustrated in **Fig. 1**, this study tended to inspect the aging stage of the pipelines by ultrasonic guided waves.

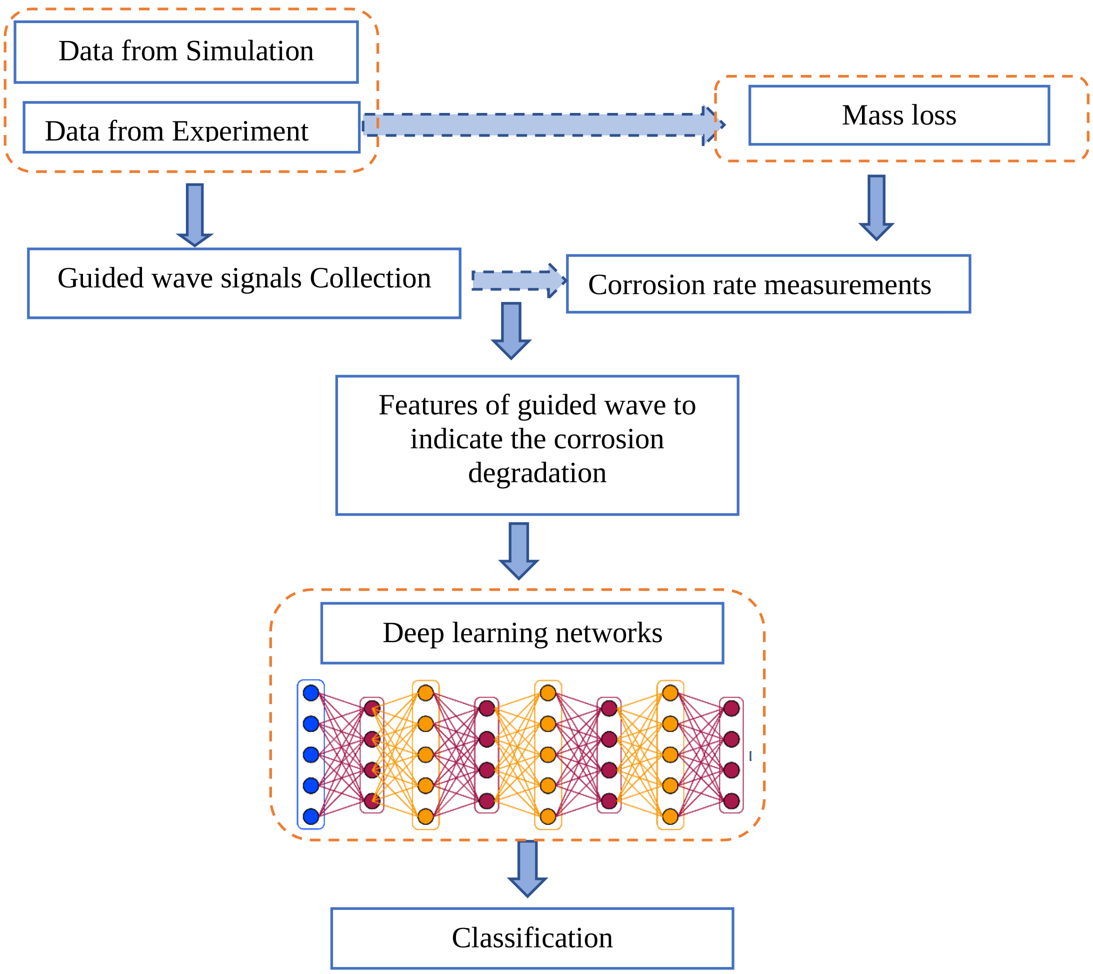


Fig. 1 Flowchart of the process

4.3.1 Step 7: Reducing variance due to aging effect

The aging problem would be occurred when corrosion damage gradually severed due to the properties of the material changed at this process. Thus, pipes with and without weldment were corroded in the salt fog chamber which accelerated the corrosion process. **Fig. 1** illustrated the whole flowchart of this study. Firstly, the data was collected from experiment and simulation. Several pipelines with different states were designed and piezoelectric transducers were glued at left side. Gathering the guided wave signals one day a time. In other hand, simulation model was set up in finite element software. Comparing the results in simulation and experiment. Next, the mass loss method was used to calculate the corrosion rate. Later, the relationship between the guided wave signals and the corrosion rate was extracted. Finally, deep learning methods, such as convolutional neural networks (CNN), was used herein to enhance information extraction and better classify structural uncertainty from data in pipeline associated with corrosion rate.

Corrosion and fatigue cracks were two most important types of damage in aging structures. Studies on corrosion degradation could help engineering to have a reasonable estimation for the inspected structures. The corrosion degradation of a steel structure depends on several mechanical and electrochemical factors. Generally, the uniform corrosion or pitting corrosion are usually time-dependent parameters. Some researchers focused on quantifying the effect of corrosion by various parameters. The traditional model of corrosion rate was a linear relationship between time and the material lost [7]. Later, Guedes Soares and Garbatov [8] developed a model that describes the growth of corrosion wastage by a non-linear function of time in three phases. After that, several students made modifications based on this model. In addition, for structure with coating protection, the measurements were changed. One of the electrochemical techniques, electrochemical impedance spectroscopy (EIS), was used to measure the corrosion rate and learned the corrosion mechanisms for coating protected structures. However, the corrosion rate was varied by environment and material. In order to estimate the life cycle of the structures, the relationships between corrosion rate and inspection data should be investigated. In this research, the corrosion degradation was measured and the relationship between ultrasonic guided wave and corrosion rate were explored.

4.3.2 Common forms of pipeline corrosion

Corrosion attacks are most widespread defects occurred on pipelines. The defects can be separated into two types: one is uniform/general corrosion, the other is pitting corrosion. Uniform/general corrosion happens when the corrosion proceeds at the same rate on the surface of the steel pipe, resulting in an approximately uniform reduction in thickness. It is the most common type of corrosion which can lead to leakage or rupture of the pipelines [9-10]. To measure the corrosion rate, the depth of penetration from the surface is calculated to express in millimeters per year or miles per year. Several methods were used to prevent the corrosion, such as surface coatings. Pitting corrosion is a localized deterioration on the pipe surface leading to a pit formation. It occurred because of the material defects, mechanical damage, or chemical erosion.

4.3.3 Corrosion measurement for metallic structures

The value of corrosion rate can be calculated by mass loss measurement [11]. The coupons were taken out, cleaned and weighted. Each of the values is measured three times and take the average value. The corrosion rate is expressed as follow [12]:

$$Cr = \frac{M_1 - M_2}{S * t} \tag{1}$$

where M_1 corresponds to the initial weight of the sample, M_2 is the current weight of the sample after corrosion happened. S represents the corrosion area, and t represents the corrosion hours. When gather the weight of the sample, it should be performed under the condition with a nearly constant temperature of 25°C and low humidity [13]. The weight of the corroded sample is measured after removing the corrosion product.

4.3.4 The experiment of pipeline corrosion process

4.3.4.1 Experiment set up

Two different states of the pipe were designed, including a normal pipe without damage and a pipe with welding. The pipes were placed in a salt fog chamber to accelerate the corrosion. Due to the size of the chamber was limited, the pipe should not be too large. Thus, the diameter of the pipes was equal to 3 inches, the thickness was 0.125 inch, and the length was 34 inches. The material of the pipe was A36 steel without coating but has a film at the outside surface which is a part of the process of flattening the steel. To calculate the corrosion rate, mass loss was required for each test which means the corrosion product on the pipe surface should be removed. This process might affect the subsequence of following corrosion. Thus, several steel plates were added here to corrode together with the pipes. The value of the mass loss of steel plates were instead of the values of the corresponding pipes. **Fig. 2** showed the pipes and the steel plates. The steel pipes and the plates were put into the salt fog chamber.

Fig. 2 Experiment samples

4.3.4.2 Experiment results

The signals were collected from corroded pipes. Two main wave packets were clearly represented in the following figures, reporting the initial extraction and the right boundary reflection. Between two main packets, several small waves were from the reflection and scattering during the guided wave propagation. **Fig. 3(a)** demonstrated the initial state of the pipe. 4 transducers worked together to generate the activated signals. Because the signals overlapped and interfered with each other, multiple excitations were produced in the front part of the received signal. In addition, the noise from the environment, machine and sensors, the received signals were become more complicated. The result obtained from the guided wave excitation was the pipe experienced 48-hour accelerated weathering, as shown in **Fig**. **3(b).** The highest amplitude responded the middle area was increased 12% then **Fig. 3(b)**, meanwhile, the edge reflection had a 7% reduced.

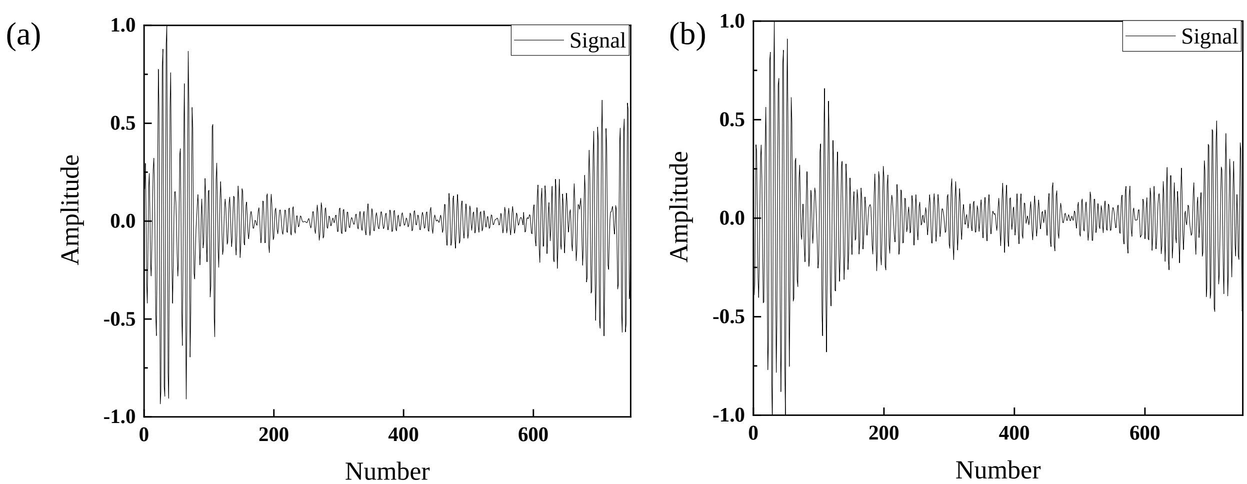


Fig. 3 Received signals from pipes: (a) onset; (b) after exposure

4.3.5 Step 8: Reducing variance due to aging effect coupled with weldment and operational noise using numerical simulation

This section attempted to calibrate the model set by finite element and indicate characteristics of guided wave propagating along a structure with corrosion defects. The prototype was a 34 inches long steel pipe. Simulating the uniform corrosion was a tough problem. Some researchers construct round-shape holes to simulate the corrosion damage. The depth of the hole represented the severity of the corrosion [14-15]. Thus, in this model, plenty of circular pits were constructed on the out surface of the pipe from 5 inches to

30 inches. Left and right ends of the pipe were sealed against corrosion, on which the sensors were mounted for ultrasonic guided waves test. Six scenarios of the pipe were listed in **Table 2**. Totally, 6 different states were discussed in this part. To ensure the calculation accuracy and computational efficiency, the meshing size of the pipe (used for simulation) ranged from 2 to 5 mm. In addition, the simulation time step is set to be 0.5 μs. The excitation was a 100 kHz 5-cycle sinusoidal signal operated by Hanning window.

Table 2 Test matrix for pipes

Case	**Label**	**Diameter**	**Weldment**	**Damage**
Reference	State #1	3 inches	\	\
	State #2	3 inches	With girth weld	\
Variance due to aging effects	State #3	3 inches	\	Uniform Corrosion (slight)
	State #4	3 inches	\	Uniform Corrosion (serous)
	State #5	3 inches	With girth weld	Uniform Corrosion (slight)
	State #6	3 inches	With girth weld	Uniform Corrosion (serous)

The simulation was calibrated, and the result was shown in **Fig. 4**. The signals from experiment and the simulation were normalized to ensure the amplitude of the data was close. The prototype was an undamaged pipeline excited by guided waves with 100 kHz. The black line was the wave collected from experiment, and the red dash line represented the simulation result. Clearly, two signals had similar excitation. Due to the experiment used several sensors worked together to excite the pipe, thus the front part overlapped by several signals.

The entire procedure of the guided waves propagation in the pipeline was clearly shown in **Fig. 5**. Without damage, the waves had less reflection. The energy of the excitation had less attenuated during propagating. The waves spent about 4E-4 s to be received by the sensors.

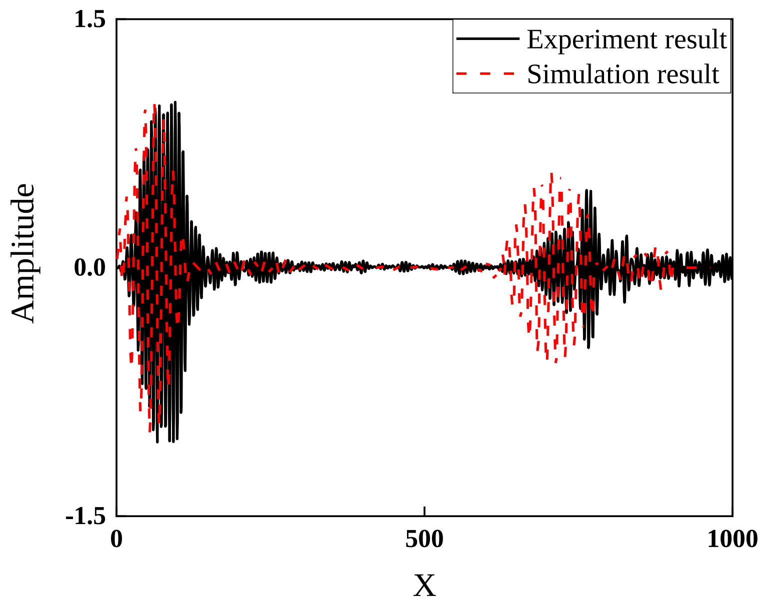


Fig. 4 Calibration of numerical simulation

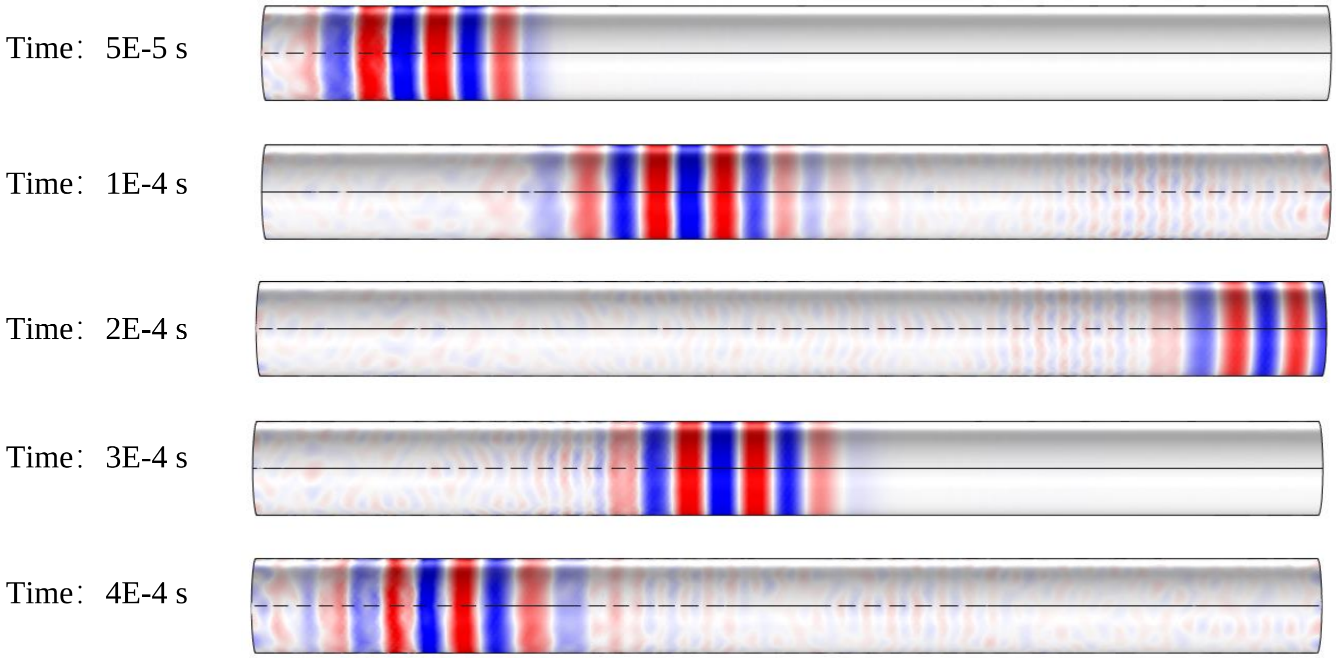
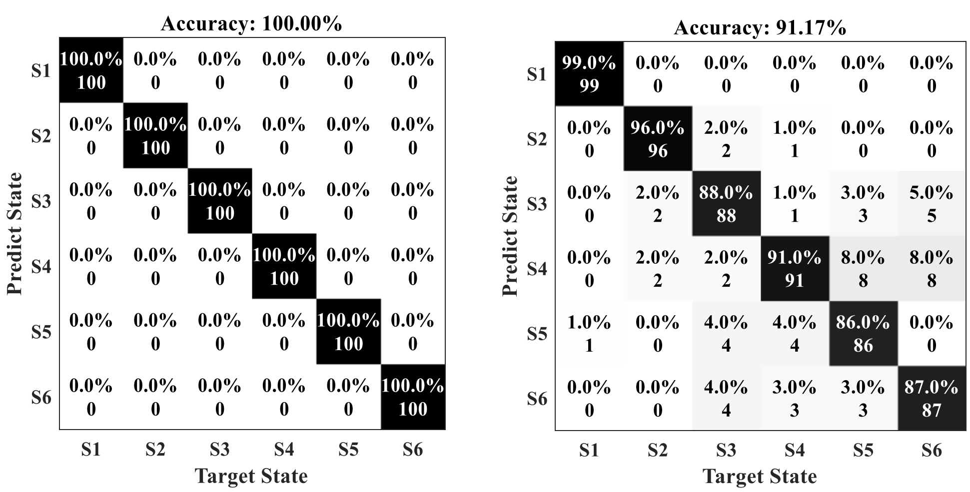


Fig. 5 Guided waves propagated through the pipe.

The test results were shown in **Fig. 6**. A total number of 600 signals were input into the pretrained CNN model, and the prediction of each data was obtained. In most case, the CNN model could accurately predict the result. Specifically, the accuracies were equal to 100% when noise levels were from 100 dB and 70 dB as shown in **Fig 6(a).** When noise level increased to 60 dB, the total accuracy was 91.17%, which means 53 data points were misled into wrong categories. The confusion matrix in **Fig. 6(b)** illustrated the specific results, where the categories S1 to S2 represented the signals in State #1 to #6. Obviously, 99% of the data in State #1 was predict correctly, and only 1.0% of data was misclassified into State #5. 4 data in State #2 were failed identification, with 2 points misclassified into State #3 and State #4 respectively.



(a)SNR=100 dB (b) SNR=70 dB

Fig. 6 Test results

Task 6: Explore Variance from Human-Machine Interfaces

In this section, we developed survey questionnaire to gain a deep understanding of human-machine interaction. In addition, the decision tree for the human-machine was developed, in order to calibrate and verify the concept.

Sub-Task 6.1. Survey design

Totally 12 questions below were developed for coming survey questionnaire. These raised questions aim to understand different perspectives of different fields associated with health monitoring of pipelines and expectations. Thus, the first question is for the status of audience.

1. What pipeline-related industry are you working in

☐ Pipeline Regulator ☐ Pipeline Owner ☐ Pipeline Consultant ☐ Pipeline Manufacturers ☐ Pipeline Constructor ☐ Pipeline Designers ☐ Pipeline Inspector ☐ Academic ☐ Specify Others_____________

The second question is to understand the lifetime of the normal pipeline. This data may vary according to the geographic location and the different uses, and different transport materials. We just need to get a general value to estimate the pipeline. The third question is to study the inspection period of pipelines. The choices are from 1 year to 5 years.

2. What is the probability of a service life of pipeline you are expected to be?

20 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
30 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
50 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
70 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
70 years+: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
(scale 1: unlikely; scale 5: most likely)

3. How often should the pipeline be inspected? (select the probability of following years)

1 year: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
2 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
3 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
4 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
5 years: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
5 years+: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
(scale 1: unlikely; scale 5: most likely)

4. What types of defects/damages you think are important to collect from pipeline inspection for quantification of pipeline damage probability?

Cracks: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Corrosion: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Welding defects/damage: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Aging degradation: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Pipe leaking: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
External damage: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Internal damage: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
(scale 1: unlikely; scale 5: most likely)

5. What types of defects/damages you think are important to collect from pipeline inspection for quantification of pipeline damage probability?

6. **What type of mechanical damage are most difficult to quantify?**
Cracks: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Corrosion: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Welding defects/damage: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Aging degradation: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Pipe leaking: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
(scale 1: unlikely; scale 5: most likely)

7. **What three types of sensors or systems have you used or is planning to use for cracking detection:**
☐ In-line inspection using smart pigs or other robotics ☐ guided wave inspection ☐ Ultrasound thickness testing ☐ Radiography ☐ Magnetic particles ☐ Liquid penetrant ☐ Acoustic emission ☐ Ground probing radar and other locating device
☐ Mini-camera ☐ Specify Others______________

8. **What three types of sensors or systems have you used or is planning to use for corrosion detection:**
☐ In-line inspection using smart pigs or other robotics ☐ guided wave inspection ☐ Ultrasound thickness testing ☐ Radiography ☐ Magnetic particles ☐ Liquid penetrant ☐ Acoustic emission ☐ Ground probing radar and other locating device
☐ Mini-camera ☐ Specify Others______________

9. **What three types of sensors or systems have you used or is planning to use for weld defect/damage detection:**
☐ In-line inspection using smart pigs or other robotics ☐ guided wave inspection ☐ Ultrasound thickness testing ☐ Radiography ☐ Magnetic particles ☐ Liquid penetrant ☐ Acoustic emission ☐ Ground probing radar and other locating device
☐ Mini-camera ☐ Specify Others______________

10. **What three types of sensors or systems have you used or is planning to use for aging degradation:**
☐ In-line inspection using smart pigs or other robotics ☐ guided wave inspection ☐ Ultrasound thickness testing ☐ Radiography ☐ Magnetic particles ☐ Liquid penetrant ☐ Acoustic emission ☐ Ground probing radar and other locating device
☐ Mini-camera ☐ Specify Others______________

11. **What three types of sensors or systems have you used or is planning to use for pipe leaking:**
☐ In-line inspection using smart pigs or other robotics ☐ guided wave inspection ☐ Ultrasound thickness testing ☐ Radiography ☐ Magnetic particles ☐ Liquid penetrant ☐ Acoustic emission ☐ Ground probing radar and other locating device
☐ Mini-camera ☐ Specify Others______________

12. **What is the probability of following uncertainty experienced in pipeline?**
Uncertainty from data collection: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Uncertainty from inspector qualification: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Uncertainty from data analysis: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Uncertainty from data reporting: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Uncertainty from operation conditions Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
Uncertainty from environmental conditions: Unlikely ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Most likely
(scale 1: unlikely; scale 5: most likely)

13. **What are the variances on measuring the above defects/damages with the currently used inspection methods, and what are the critical factors that affect the accuracy of the measurements?**

14. **Are there available pipeline inspection data that can be shared to validate the machine learning model and methodology developed in this project?**

6.2. Summary of the research activities in the 9th report

The major research activities are: (i) Task 4: Continue the remaining work on structural initial nonlinearity to address: (a) aging effects on with and without weldment toward data variances; and (b) aging effects on with and without protective coating toward data variances are in progress and will be reported in the coming period. (iii) Task 6: survey questionnaire was developed to collect the critical information in best practices and uncertainty.

(e) Description of any Problems/Challenges

No problems are experienced during this report period

(f) Planned Activities for the Next Quarter

The planned activities for the next quarter are listed below:

- We will document and report the complete remaining part to variances due to pipe with and without coating in Task 4 in both numerical and experimental investigations.
- The survey questionnaire will be conducted, and the collected information will be used for our model calibration in Task 6.

Reference

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