QUARTER SCALE ROBOTICS POSITOING SYSTEM

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ABSTRACT
As of 2015 nearly twenty percent of U.S. electricity production has been by nuclear means. Aging plant facilities have prompted plant managers to look for ways to extend component life. One such example is the use on non-destructive testing on the nuclear reactor and its internal components. Specifically, IHI Southwest Technologies, the sponsoring company, is interested in scanning the welds of bottom mounted instrumentation nozzles for any defects by use of ultrasonic waves. IHI has developed a robotic system which is lowered into the nuclear reactor at which point the system locks into place and begins to position an intermediate end-effector over each nozzle within the vessel. Team 4i has developed a ¼ scale model of this system. The ¼ scale model validates IHI's capability to perform the non-destructive tests to a potential customer, by mimicking all of the full-scale system's maneuvers. The ¼ scale model also displays the accuracy attainable by the systems' mutual mechanical drive systems. The ¼ scale model is accurate to with 0.250 inches over the course of a 10-loop cycle. The ¼ scale model effectively confirms the ability of the full-scale system to accurately perform necessary motions within a nuclear reactor vessel.

1. NOMENCLATURE

FS	Full Scale
QS	¼ Scale
NDT	Non-Destructive Tests/Testing
IHIswt	IHI Southwest Technologies
RSS	Rotary Scanning System
BMI	Bottom Mounted Instrumentation
UT	Ultrasonic Transducer
θ	Angular Position
r	Radial Position
h	Vertical Position

2. INTRODUCTION
The objective of this build is to mimic the physical maneuvers of full scale (FS) robotic device, with a ¼ scale (QS) replica. The full scale robotic system is used to carry out non-destructive tests (NDT) within a nuclear pressurized water reactor, specifically the scanning of the welds of the Bottom mounted instrumentation nozzle (BMI). The reactor is of a 'pill' shaped nature as seen in Figure 1.

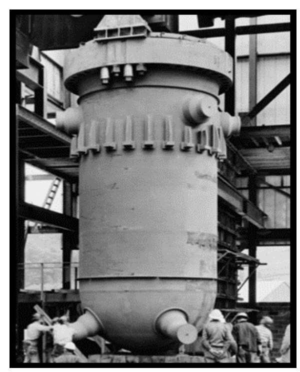

Figure 1: Pressurized Water Reactor

During in service reactor operations the BMI nozzles experience flow induced vibrations. Furthermore, throughout the life of the reactor, the BMI nozzle welds experience water stress corrosion cracking. In an effort to maximize reactor life plant managers need to perform non-destructive inspections on the nozzle welds. This involves placing and moving an ultrasonic transducer (UT) along the welds to detect any cracks or voids. Before a transducer can be placed on a weld a robotic system must be developed to accurately locate and position an intermediate end-effector directly above each BMI nozzle. This is the purpose of the full-scale prototype; to accurately locate all 50 BMI nozzles within a reactor as to enable future weld scans. The BMI nozzle are located on the lower head of nuclear reactor as shown in Figure 2.

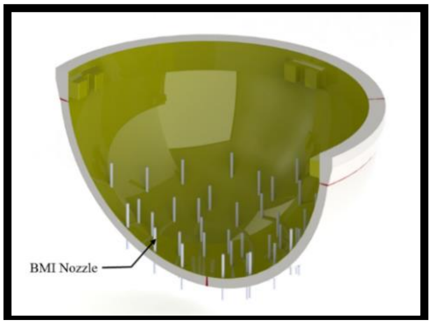

Figure 2: BMI Nozzles Protruding from Lower Head

Those maneuvers that the QS are to mimic, are a rotation motion, a linear drive motion in the x-y plane and a vertical motion in the z-axis. Figure 3 below has arrows depicting the motion.

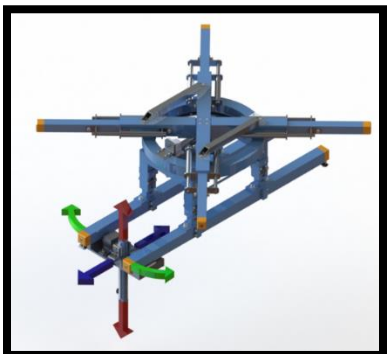

Figure 3: Angular, Radial, and Vertical Adjustments of the RSS

The ¼ scale model will be used by the sponsoring company as a mode of confirming the full-scale system's ability to perform said non-destructive test to a potential customer.

3. MECHANICAL AND ELECTRICAL METHODS

The scale model is a 36-inch x 36-inch x 18-inch in dimension and has an overall weight of 35 lbs. The scale model consists of four major subsystems, these include; 1) Circular Ring with carriage system 2) Parallel Beams with carriage system for linear motion, 3) Adjustable drop structure with height adjustment, and 4) Belt and Pulley drive system. The scale model as a whole is made of 6061 Aluminum, including some 3d printed parts. Hardware used include 18-18 Stainless Steel, and the system is programmed using an Arduino Software. The figure shown below depicts the different system of the scale model (Figure 3-4)

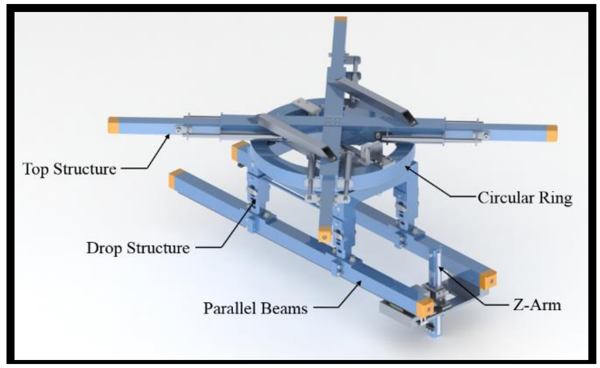

Figure 3: CAD Model Quarter Scale Robotic Testing Tool

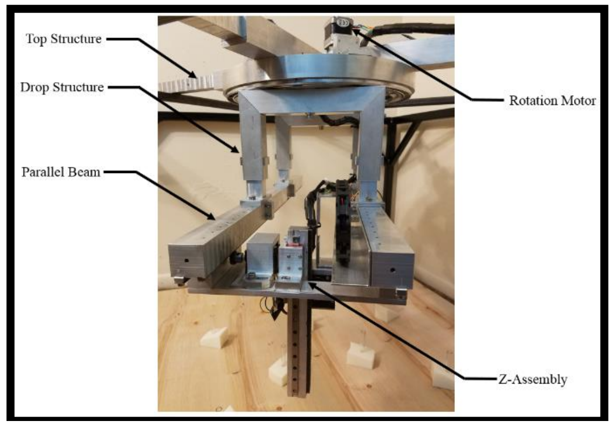

Figure 4: Quarter Scale Robotic Testing Tool

3.1.0 ANALYTICAL/EXPERIMENTAL METHODS FOR PERFROMANCE AND SIZING

Sizing of the system fell into three main categories, physical sizing of the scale model, sizing of the pulley belt system, and motor sizing. Physical sizing was done to configure the best size to replicate the full scale system and still mimics all the major functionalities that exists in the full scale system. Using solid works the full scale system was scaled down with factors of 1/4, 1/3, and ½. Based on different scaled models the quarter scale was selected with a dimension of 36-inch x 36-inch x 18-inch.

With the chosen physical size of the prototype, the next step was to select the appropriate belt and pulley system. The belt and pulley system is used to drive the rotational motion of the scale model. Sizing of the belt and pulley was determined by the minimum center distance available within the circular ring. With the quarter scale, the circular ring of the prototype was sized to be 10.75-inch inner diameter which allowed an available center distance for pulley system to be 3.75 inches. With the available center distance of 3.75 inches, an iterative process was used to select different pulley sizes using the "Belt pulley calculator" via B&B manufacturing website [1]. Based on the calculation, the driver and driven pulleys were selected to be of 17 mm and 31.30 mm outside diameter respectively which met the minimum requirement of 120° wrap angle on the driver pulley. The minimum wrap angle of 120° was required to avoid slipping of the belt and pulley during operation. Once the pulleys were selected, the belt length was calculated using the same “Belt pulley calculator” via B&B manufacturing website. Based on the diameter of the pulleys selected and minimum center distance available, the belt length was chosen to be 265 mm. The width of the belt and pulley was determined by the available vertical clearance between the drive plate and the top structure. Based on the vertical clearance between the drive plate and the top structure, the belt was selected with a width of 6mm.

After performing the physical sizing and pulley belt sizing above, a motor sizing analysis was undertaken. The factors considered in motor sizing where moments of inertia, friction, power availability, running speed, and required acceleration. The moments of inertia for the three main structural components were considered. The circular frame was treated as a ring of specified mass rotating about its imaginary center axis. The parallel beams where treated as one beam using the parallel axis theorem. And finally the z arm was treated as a point mass at its furthest position from the center axis. The drag force was also considered for these three components. The angular rotation speed is 1.5 RPM. The ramp time of the motor was set at one tenth of a second which yielded a required acceleration of 1.57 radians per second squared. The friction in the system was also considered for the required motor torque. Based on the calculation, a NEMA 14 steeper motor with a torque of 425 oz. inch was chosen for rotation. Similarly, for linear and vertical movements NEMA 11, stepper motor with a torque of 8.3 oz. inch was chosen.

3.1.1 ELECTRICAL AND PROGRAMING

The electrical components used for the system consisted of, stepper motors, motor drivers (Easy Drivers), limit switches, and an Arduino Uno (Micro-controller). Figure 5 below shows the layout of the electrical enclosure.

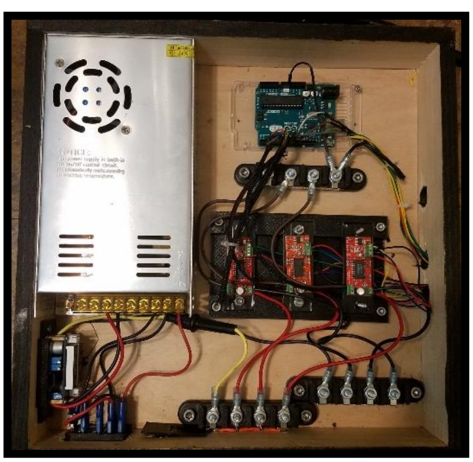

Figure 5: Electrical Enclosure

In order to operate the system, the Arduino Uno was flashed using and open source software called Grbl. This software is a high performance g-code-parser and CNC milling controller written in optimized C that has the ability to run straight into the Arduino [2]. With the arduino flashed, this allowed for a g-code software . Software, Universal G-code Sender was used for this operation. Figure 6 shows the window screen of the software.

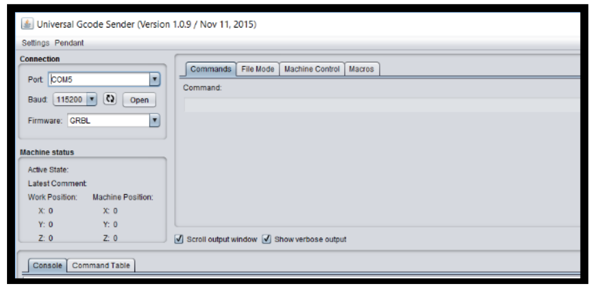

Figure 7: Universal G-code Sender

Knowning the location of the BMI nozzle, a coordinate system was developed to postion the system a top of the nozzle using g-code. Figure 8 shows the location of 10 nozzles that were used.

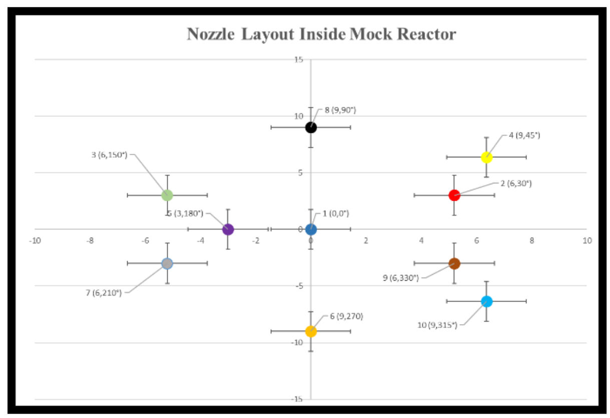

Figure 8: Nozzle Layout

Having the ability to correlate the number a steps the motor needed to move made the process easier. Using experimental data, it was determined that for the linear movement in the x-y plane each step accounted for .275 of and inch. Each step in the ratational motion provided 1.6 degrees of movement. In order for the system to be able to postioning accuratly, a homing sequence was used to generate a home postion (0,0,0). Limit switches were used for the homing sequence by placing them in three locations of motion. Figure 9 shows part of the g-code that was generated.

```
$H
G4 P1
G91 G0 Y-44.09
G91 G0 Z-7
G4 P1
G91 G0 Z7
G91 G0 X27
G91 G0 Y33.73
G91 G0 Z-3
G4 P2
G91 G0 Z3
G4 P2
G91 G0 Y-65.46
G91 G0 Z-3
G4 P3
G91 G0 Z3
G4 P3
G91 G0 Y21
G91 G0 Z-7
G4 P3
G91 G0 Z7
G4 P3
```

Figure 9: G-code

4. RESULTS

Testing of the system was done using 10 nozzle locations inside a mock reactor on a 6 loop cycle. This meant that system position over 10 nozzles, returned to home position and located the same nozzle again. Figure 10 below shows the z-arm positioning over a BMI nozzle.

Figure 10: Nozzle Positioning

The robot was proven a success on both quantitative and qualitative levels. Quantitatively the robot is accurate to within 0.25 inches and had a standard deviation for each positioning motion of under 0.25 inches. Qualitatively the robot performed all three required motions, these were the angular, radial, and vertical maneuvers. All test criteria passed. The averages and standard deviations of all positioning efforts can be compared in the Tables 1-2 below.

Table 1: Nozzle Known Coordinates

Nozzle Coordinate System				
Nozzle #	***r***	**Θ**	***h***	**Color Designation**
1	0.0	0	2.3	Blue
2	6.0	30	3.6	Red
3	6.0	150	3.6	Green
4	9.0	45	5.0	Yellow
5	3.0	180	2.8	Purple
6	9.0	270	5.0	Orange
7	6.0	210	3.6	Gray
8	9.0	90	5.0	Black
9	6.0	330	3.6	Brown
10	9.0	315	5.0	Teal

Table 2: Data Analysis for Individual Positioning's

Data Analysis for Individual Positionings			
Nozzle Number	**Respective Coordinate**	**Average**	**Standard Deviation**
Nozzle 1	Angular	0.12	0.09
	Radial	0.14	0.08
	Vertical	2.21	0.15
Nozzle 2	Angular	29.99	0.12
	Radial	6.05	0.13
	Vertical	3.52	0.13
Nozzle 3	Angular	150.02	0.13
	Radial	6.08	0.11
	Vertical	3.60	0.11
Nozzle 4	Angular	45.05	0.13
	Radial	9.01	0.11
	Vertical	5.06	0.11
Nozzle 5	Angular	180.03	0.11
	Radial	2.98	0.12
	Vertical	2.73	0.12
Nozzle 6	Angular	270.02	0.14
	Radial	9.03	0.11
	Vertical	5.08	0.12
Nozzle 7	Angular	210.03	0.17
	Radial	5.97	0.12
	Vertical	3.61	0.12
Nozzle 8	Angular	90.00	0.14
	Radial	9.02	0.12
	Vertical	4.98	0.16
Nozzle 9	Angular	330.00	0.11
	Radial	5.91	0.11
	Vertical	3.58	0.14
Nozzle 10	Angular	315.05	0.10
	Radial	8.94	0.17
	Vertical	4.99	0.15

5. DISCUSSION

Results showed that the QS model had the ability to position itself accurately and precisely within .25-inch of the nozzle location. The system also showed the manufacturability of the system to our sponsoring company IHIswt. The model passed other test that were essential to the functionality of the test. Table 3 below show other test that were passed.

Item Number	Feature to be Tested	Specification Refernece in Appendix X	Testing or Verification Procedure	Compliance Status (Pass/Fail)
01	Accuracy in Positioning	1.01	Test T_0001	PASS
02	Precision in Positioning	1.02	Test T_0002	PASS
03	360-Degree Rotation	1.03	Visual Verification	PASS
04	Radial Drive System	1.04	Visual Verification	PASS
05	Vertical Drive System	1.05	Visual Verification	PASS
06	10 Positioning Loops	1.06	Visual Verification	PASS
07	Rotational Limit Switch	1.07	Visual Verification	PASS
08	Radial Limit Switch #1	1.08	Visual Verification	PASS
09	Radial Limit Switch #2	1.09	Visual Verification	PASS
10	Vertical Limit Switch	1.10	Visual Verification	PASS
11	RSS Spatial Envelope	2.01	Yard stick	PASS
12	RSS Weight	2.02	Common Scale	PASS
13	RSS Power Requirements	2.03	Multimeter Reading	PASS
14	Structural Components Composition	2.04	Material Data Sheet (NO CERTS)	PASS
15	Non-Structural Component Composition	2.05	Material Data Sheet (NO CERTS)	PASS
16	Hardware Material Composition	2.06	Material Data Sheet (NO CERTS)	PASS

With these results one can conclude that system could work on an autonomous level and position on its own. The only limitation to this work is that the nozzle location would have to be exactly located from the drawings provided of the pressurized water reactor. Our QS system also has the ability to manually control the steps of each motor and make adjustments when in position. This allows the end user to make minor adjustments when doing the inspection.

6. CONCLUSION AND FUTURE WORK

The robot was proven a success on both quantitative and qualitative levels. Quantitatively the robot is accurate to within 0.25 inches and has a standard deviation for each positioning motion of under 0.25 inches. Qualitatively the robot performs all three required motions, these are the angular, radial, and vertical maneuvers. All test criteria pass and the product is ready for shipment to IHIswt.

Future work for the QS model could consist on a more developed software that will allow the input of coordinates instead of having to determine the number of steps needed to reach a certain nozzle within the reactor. In a pressurized water reactor there are welds that can be scanned for example the meridional scan. This weld run across from one end of the lower head to the other side. The system could improve on height adjustments and would allow the system to scan this welds with a simple change of the end effector.

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REFERENCES

[1] Manufacturing, B&B. "Belt Length Calculator." Timing Belt Calculator - Belt Length Calculator | B&B Manufacturing. N.p., n.d. Web. 07 Dec. 2016.

[2] Grbl. "Grbl/grbl." GitHub. N.p., n.d. Web. 15 Dec. 2016. <https://github.com/grbl/grbl/wiki>.