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DEVELOPMENT OF TECHNOLOGY TO REMOTELY NAVIGATE VERTICAL PIPE ARRAYS

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ABSTRACT

Situations exist around the Savannah River Site (SRS) and the Department of Energy (DOE) complex where it is advantageous to remotely navigate vertical pipe arrays. Specific examples are waste tanks in the SRS Tank Farms, which contain horizontal cooling coils at the tank bottom, vertical cooling coils throughout and a limited number of access points or "risers". These factors limit accessibility to many parts of these tanks by conventional means.

Pipe Traveler technology has been developed to address these issues. The Pipe Traveler addresses these issues by using the vertical cooling coils as its medium of travel. The unit operates by grabbing a pipe using dual grippers located on either side of the equipment. Once securely attached to the pipe a drive wheel is extended to come in contact with the pipe. Rotation of the drive wheel causes the unit to rotate around the pipe. This action is continued until the second set of grippers is aligned with the next pipe. Extension pistons are actuated to extend the second set of grippers in contact with a second pipe. The second set of grippers is then actuated to grasp the pipe. The first set of grippers releases the original pipe and the process is repeated until the unit reaches its desired location. Once at the tool deployment location the desired tool may be used.

The current design has proven the concept of pipe-to-pipe navigation. Testing of the Pipe Traveler has proven its ability to transfer itself from one pipe to another.

A US Patent application has been filed for this technology by Savannah River Nuclear Solutions, the parent company of Savannah River National Laboratory.

Key Words: pipe, traveler, remote

1 INTRODUCTION

Situations exist around the SRS and the DOE complex where it is advantageous to remotely navigate vertical pipe 'forests'. Specific examples of this are the Type I, II, III & IIIA High Level Waste (HLW) at the SRS Tank Farms. These tanks contain 'forests' of vertical cooling coils originally used to remove heat from fissile products in the waste. The waste has since cooled and the cooling coils are no longer necessary. The mission of tank closure is now to remove the waste and fill the tanks with grout. To completely remove the waste it is necessary to deliver tools to various locations within the tank. An issue which complicates this is the limited number and locations of access points or "risers" in which to insert your tools. In addition, the horizontal cooling coils at the bottom of the tank make it difficult to put a crawler on the tank floor to deliver the tools to the desired locations. The Pipe Traveler addresses these issues by using the cooling coils as its medium to travel.

The Pipe Traveler was designed to navigate the HLW Tanks at SRS, therefore dictating the selection of the gripper diameter and extension length. However, this type of remote delivery platform may be useful in other places; specifically around the DOE complex for Decontamination & Demolition (D&D) operations where this type of environment may exist.

2 APPROACH

Grippers using idler rollers as the contact points and a drive wheel to contact the pipe are used to create the rotational motion around the pipe. The drive wheel is pressed against a pipe by a pneumatic cylinder and is powered by a stepper motor. Four linear slides are used to allow the system to extend while maintaining rigidity. The slides are actuated by two pneumatic extension cylinders. The overall system design is shown in Figure 1. Pipe Traveler Assembly

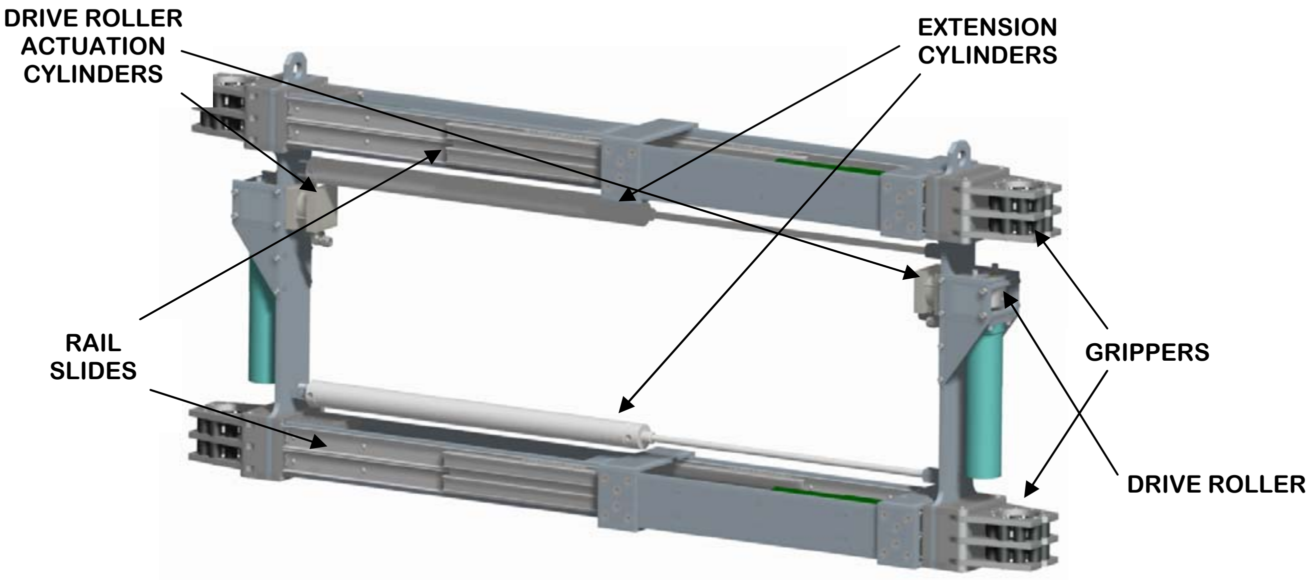
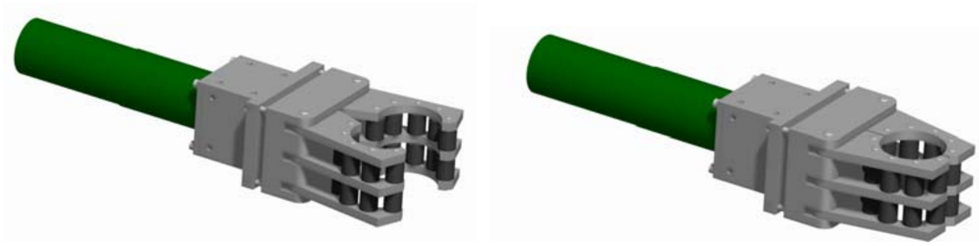


Figure 1. Pipe Traveler Assembly

2.1 Mechanical Design

2.1.1 Gripper

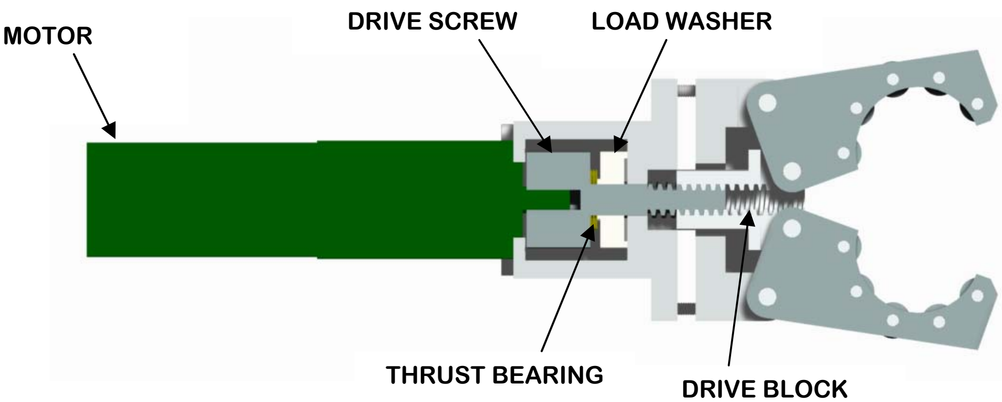
The gripper is used to allow the Pipe Traveler to clamp onto pipes, but still allow the unit to rotate around the pipe. This is achieved by using idler rollers located between fingers as the contact points on the pipe (See Figure 2). The idler rollers allow the grippers to support the weight of the Pipe Traveler while permitting rotation around a pipe. The gripping surface of the rollers is urethane rubber, which allows the grippers to accommodate imperfections in the pipes to be gripped.



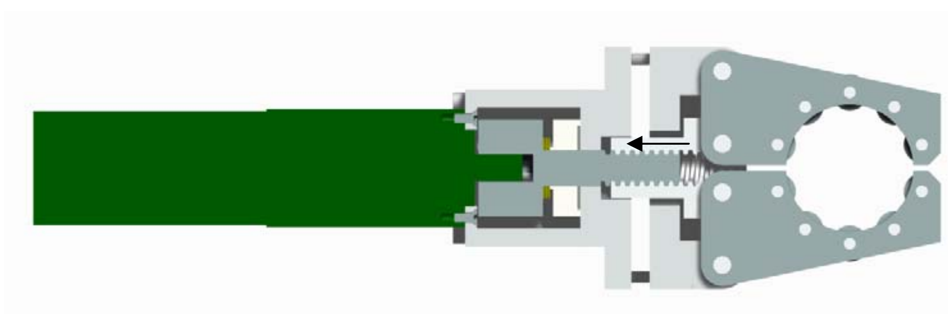
OPEN **CLOSED**

Figure 2. Gripper in Open & Closed Configurations

A 24V DC motor with encoder is used to supply the gripping force. When the gripper is initially open, the motor will actuate and cause the drive screw to rotate. As the drive screw rotates it threads into the drive block. Since the drive screw cannot move, the drive block is pulled toward it. As the block moves back, pins connected to the fingers are pulled back which closes the grippers (See Figure 3). When the gripper closes onto a pipe completely the torque supplied by the motor is turned into a linear force which is transferred through the thrust bearing to the load washer. The load washer is then able to provide force feedback to the motor to shut it off when the desired load on the pipe is obtained. An exploded view of the assembly can be seen in Figure 4.



Open



Closed

Figure 3. Gripper Cross Sections

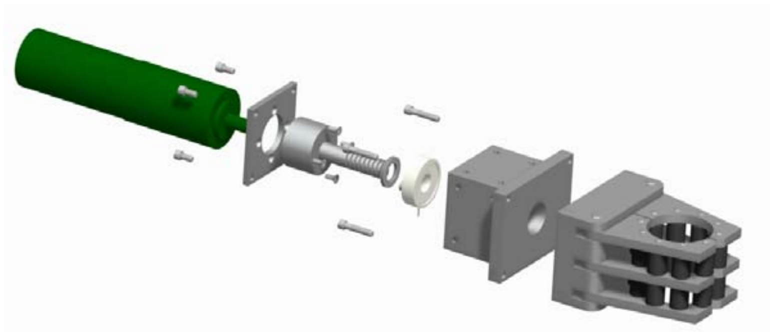


Figure 4. Gripper Exploded View

2.1.2 Extension System

An extension system is incorporated into the Pipe Traveler design to allow the second set of grippers to extend to the next pipe. Also, after a pipe is released, it is necessary for the pipe traveler to retract from a pipe before it rotates to another pipe. To provide the motive force for extension and retraction, two pneumatic cylinders are used (Figure 5). Four commercial linear slides are used to provide linear stability and support the large moment during extension.

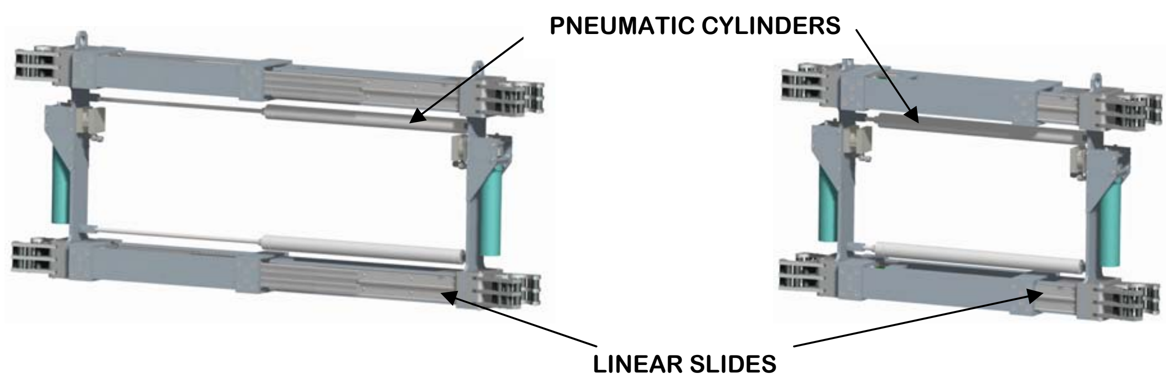


Figure 5. Pipe Traveler Extended & Contracted

2.1.3 Rotation System

The rotation mechanism operates by using a pneumatic cylinder to push a drive wheel against the pipe. The large bore cylinder is used to apply a contact force on the pipe for rotation. The drive wheel is powered with a stepper motor. When the motor is actuated, friction between the wheel and the pipe causes the wheel to drive itself around the pipe. This motion rotates the entire Pipe Traveler around the pipe until the unit is aligned with the next pipe. Gussets are used to support the drive wheel cage which houses the drive wheel. The drive wheel cage slides along support ridges along the inside of the gussets. A gusset brace allows the gussets to transfer the moment applied to the Pipe Traveler when the drive wheel is actuated. These components and can be seen in Figure 6 & Figure 7.

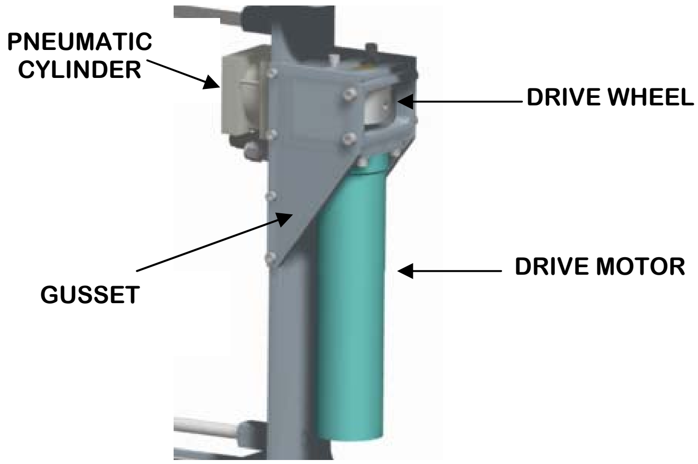


Figure 6. Rotation Mechanism

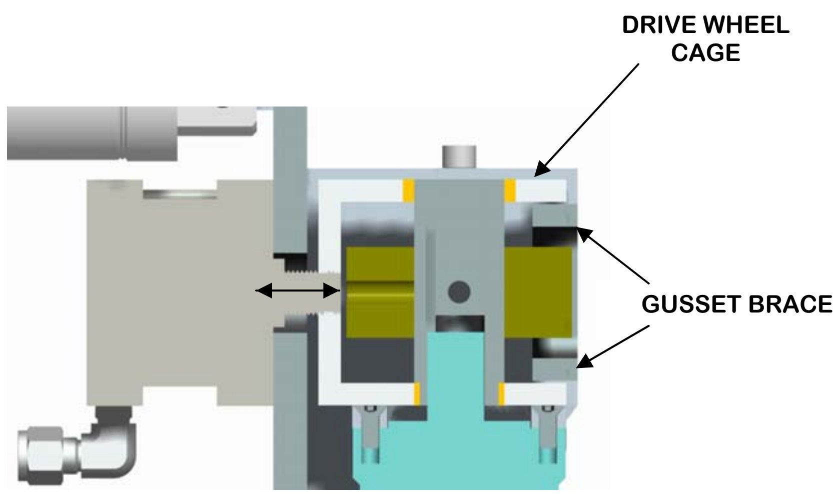


Figure 7. Rotation Mechanism Cross Section

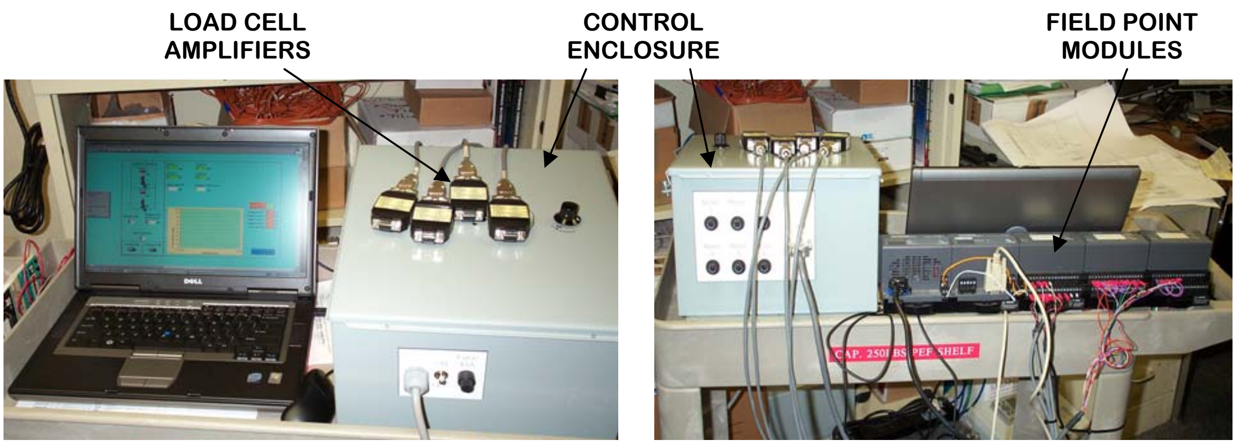
2.1.4 Pneumatic Controls

The pneumatic cylinders are controlled using 4-way 2-position manual valves. A manual return valve is used to control the drive wheel actuation so that the air pressure would continue to be applied until the operator decided to disengage the wheel. The extension cylinders are controlled with a momentary valve to provide the operator with finer control of the extension. The extension cylinders have a single control valve and the drive wheel cylinders have a single control valve since there is no situation where independent control would be required. The same air supply is used for both valves / air cylinders sets. To slow the velocity of extension cylinder actuation, the lines to the extension cylinders are throttled using needle valves to limit the rate which the air can enter the cylinder.

2.2 Electrical/Software Design

2.2.1 Pipe Traveler Remote Controls

A control enclosure, shown in Figure 8(a), is designed to permit remote control of the four individual gripper motors and the two rotation motors of the pipe traveler. It contains four servo controllers for the gripper motors and two stepper controllers for the rotation motors. A Field Point platform, shown in Figure 8(b), is used to provide a user interface between the control enclosure and a laptop computer. Amplifier transducers, placed in series with the gripper load cells, convert the load cell voltage signal to a 4-20 mA loop current to minimize electrical noise. The 4 – 20 mA signal is connected to the analog input module of the field point to permit remote measurement of the gripper force.



a) Control enclosure with amplifier transducers   b) Control enclosure and field point modules

Figure 8. Electronic Controls

2.2.2 Software for Control of the Pipe Traveler

Software was developed using LabView to remotely control the operation of the pipe traveler. The software provides a user interface for actuating the pipe traveler grippers and rotational motors. Three modules were written to handle the different Pipe Traveler systems (Gripper Force, Gripper Control and Arm Control).

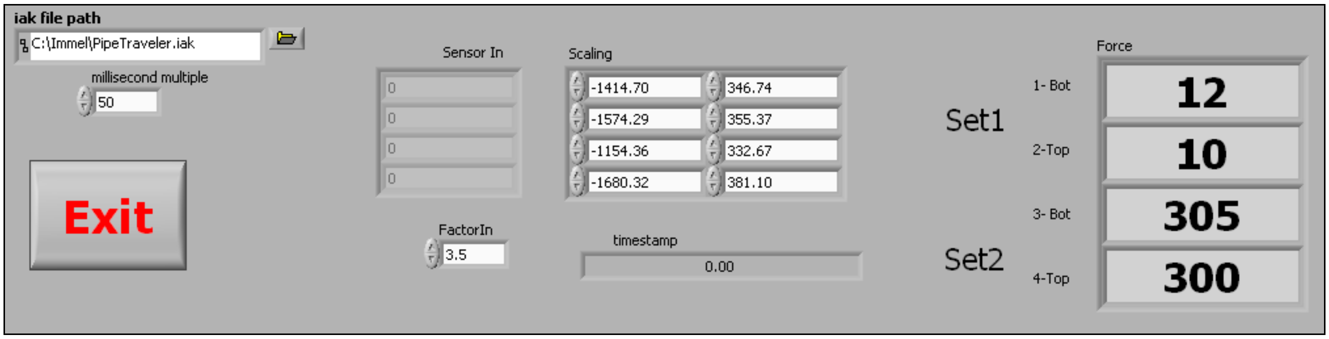


Figure 9. Force Monitor User Interface

The gripping force of each gripper is monitored by the Gripper Force module, which reads milliamp inputs from the gripper load cells and converts them to lbf (Figure 9). The conversion is determined from gripper geometry and static analysis. The force values are exported to other LabView modules as inputs.

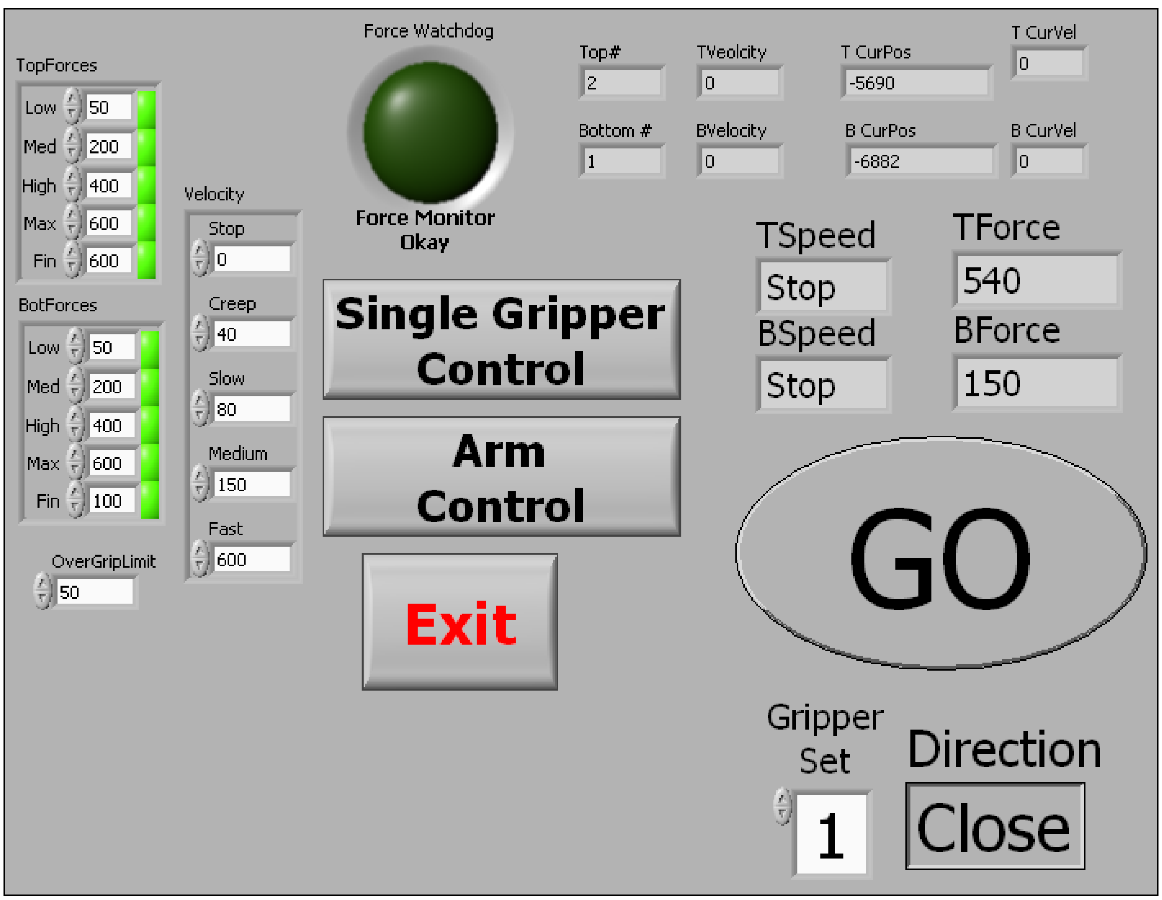


Figure 10. Gripper Control User Interface

The Gripper Control module was developed to configure and control the grippers (Figure 10). This module receives force input from the Gripper Force module and motor speed input from the motor encoders and uses this information to control gripper motion. As the gripper force increases toward the setpoint, the gripper speed is incrementally reduced until it stops at the setpoint (+/- 50 lbf). If the force monitoring has faulted, gripper motion is inhibited. The grippers are operated as a set consisting of the top and bottom gripper on each end of the Pipe Traveler. The gripper force setpoints and corresponding motor speeds can be configured for each individual gripper.

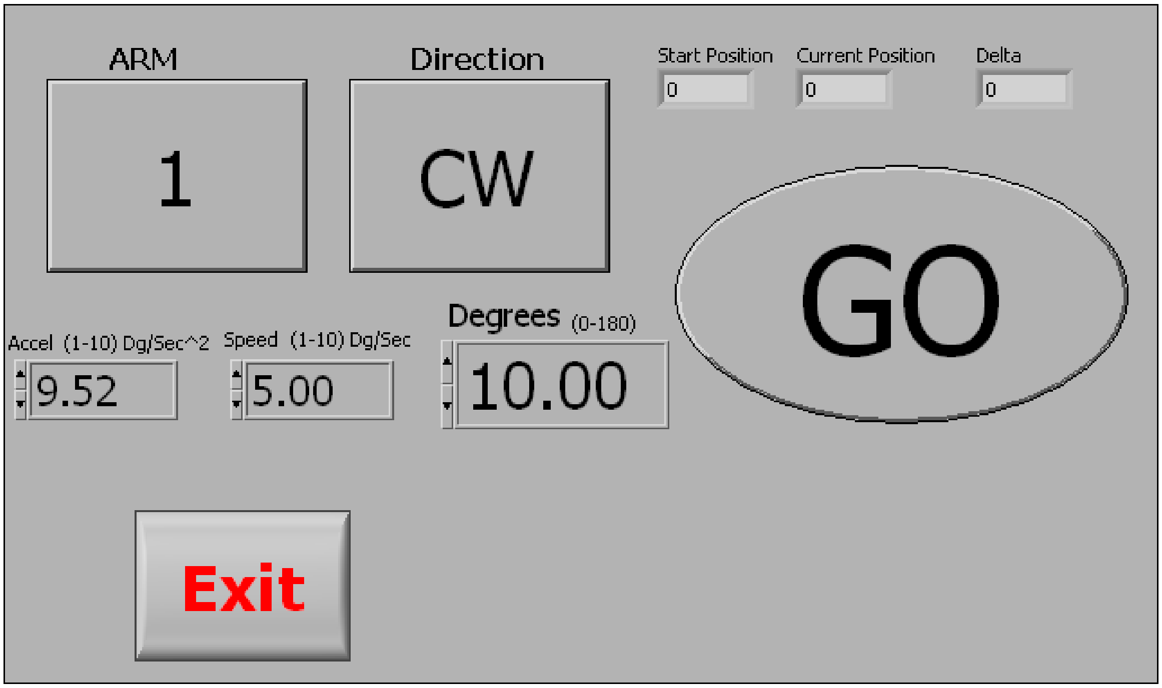


Figure 11. Arm Control User Interface

The Arm Control module was developed to configure and control the rotational motion of the Pipe Traveler (Figure 11). For normal operation the appropriate arm, direction, acceleration, speed and degrees controls are set. These settings correspond with functions that dictate the motion of the stepper motor (arm) selected.

2.3 Testing

2.3.1 Bench Testing

Bench tests were performed to ensure the Pipe Traveler grippers were working correctly before placing the Pipe Traveler on vertical pipes. The first test performed was a gripper strength test. In this test a load cell was placed between a split cylinder which was then compressed by the gripper (Figure 12). The test showed that each gripper is able to apply over 1000 lbf to the pipes, which was more than adequate for the application.

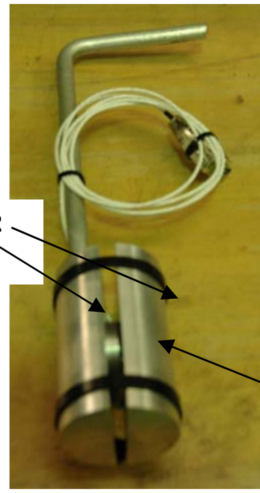


Figure 12. Compression Load Tester

Another bench test was performed to see how well the drive wheel was able to rotate a pipe when the grippers were applied. To conduct this test a pipe was placed in both grippers and gripped with varying forces. It was determined that when at least 250 lbf of gripper force was applied, the pipe was able to be easily rotated using 90 psi air on the drive wheel cylinder.

2.3.2 Functional Testing

The Pipe Traveler was functionally tested using a pipe ‘forest’ mock-up. This mock-up was constructed of four pipes four feet apart and connected on the top and bottom by frames. When performing the test, the Pipe Traveler was lowered in by a hoist and lowered into the pipe ‘forest’ mock-up. The Pipe Traveler was then attached to one of the pipes. Initially 300 lbf/gripper was applied to the pipe. After the unit was attached to the pipe the hoist was slowly lowered until the load was completely supported by the grippers. The unit was disconnected from the hoist. Next, the rotational capability of the unit was tested. During initial testing, the drive wheel was able to rotate the unit intermittently. Slippage between the drive wheel and the pipe was observed, as evidenced by smearing of the pipe where the drive roller contacted it. Photos of the testing can be seen in Figure 13 thru Figure 17.

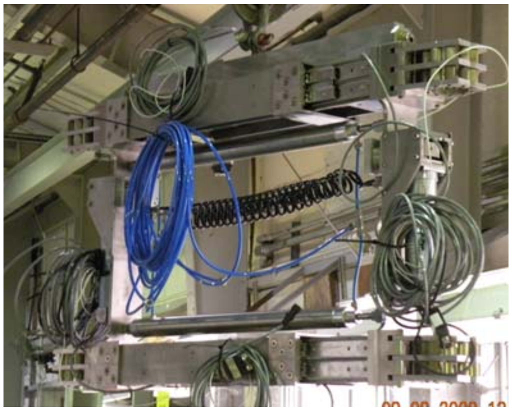


Figure 13. Pipe Traveler Supported by Hoist

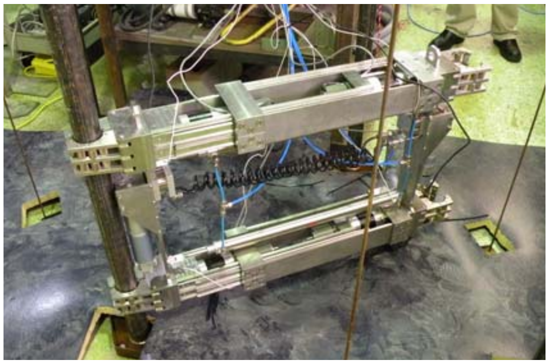


Figure 14. Pipe Traveler Attached to Pipe

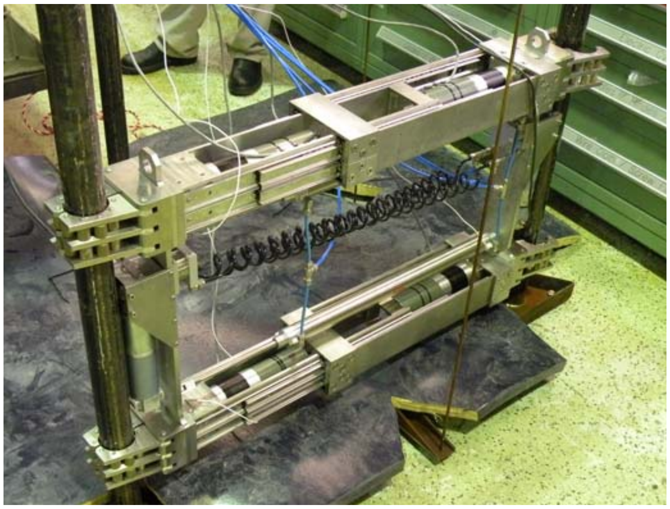


Figure 15. Pipe Traveler Extended to Second Pipe

Figure 16. Pipe Traveler Gripping Pipe

Figure 17. Pipe Traveler after Pipe Transfer

During initial testing of the Pipe Traveler, the drive wheels were not able to produce consistent rotation around the pipes of the mockup. Improvements were needed in control of both the gripper motors and the drive wheel motors. Encoders were added to the gripper motors to allow more precise control of gripper force. The LabView program was modified to communicate with the encoders. Since these modifications were completed, the grippers are now able to grip consistently within 50 lb of the desired force. During testing it was determined that independent control of each gripper was needed, so this feature was also added (see Figure 18). This allowed testing of various gripping force scenarios, during which it was determined that a top gripper force of 600 lbf and a bottom gripper force of 100 lbf produced the most consistent rotational performance. When the grippers were programmed to stop at these load values, it was observed that the bottom gripper would sometimes be slightly misaligned with the pipe and would therefore reach 100 lbf without being completely closed around the pipe. To compensate for this, both grippers were programmed to reach 600 lbf and then the bottom gripper retracts until 100 lbf is reached. Manual gripper control was also added to permit control of the grippers independent of load cell force.

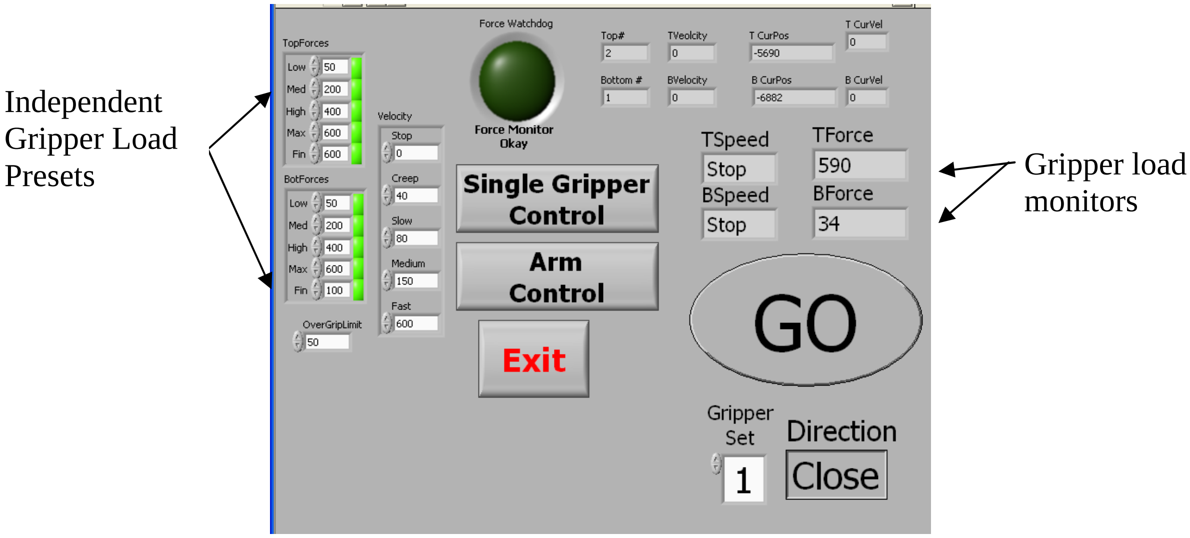


Figure 18. Enhanced User Interface

For improved speed control of the drive wheels, the original DC drive motors were replaced with stepper motors and the LabView program was modified to communicate with the stepper motors. The DC motor previously used did not allow for acceleration adjustments and the velocity could only be reduced by reducing the input voltage, which in turn reduced the output torque of the motor. The stepper motor allows control of drive wheel acceleration and velocity, reducing slippage between the drive wheel and the pipe. Figure 19 shows the user interface for the improved drive wheel controls.

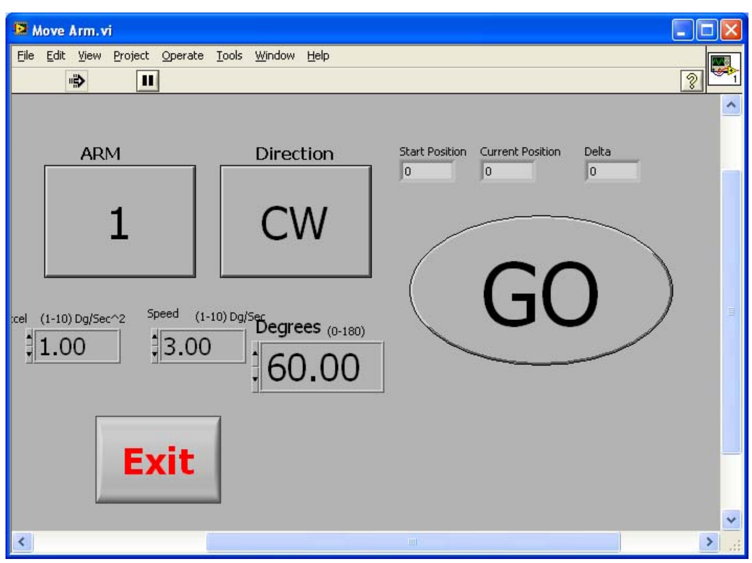


Figure 19. Enhanced Drive Wheel Controls

In addition to improving control of the grippers and drive wheels, multiple combinations of gripper roller and drive wheel materials were tested.

The drive wheels tested were:

1. 70 durometer urethane wheel with metal hub.
2. Steel wheel with 1/16" thick rubber outer layer.
3. Knurled, hardened 440C stainless steel wheel.

The gripper rollers tested were:

1. 70 durometer urethane roller with with bronze hub.
2. Knurled, hardened 440C stainless steel roller.
3. Smooth, hardened 17-4 stainless steel roller.

While testing the various gripper roller and drive wheel combinations, the drive wheel pneumatic cylinder air pressure was increased to the maximum allowable pressure of the pneumatic components to increase the normal force of the drive wheel against the pipe. The combination that produced the most consistent rotation was the knurled drive wheel with the urethane gripper rollers. The knurled drive wheel roughened the surface of the pipe until it gained traction and the rubber gripper rollers allowed compliance to pipe imperfections.

The improved motor controls and gripper/drive wheel material combinations improved the rotational performance of the Pipe Traveler. On the mockup of four pipes used for testing, this configuration produced consistent rotation on one of the pipes given a specific gripper force setting. However, rotation was not consistently achieved when attempting to rotate around other mockup pipes.

Slippage of the drive wheel on the pipe caused the inconsistent rotational motion observed during initial testing. In order to provide additional normal force between the drive wheel and pipe, the 2" diameter drive wheel pneumatic cylinder was replaced with a 3" cylinder. When using the 3" cylinder (Figure 20) was able to consistently rotate from pipe to pipe with minimal slippage.

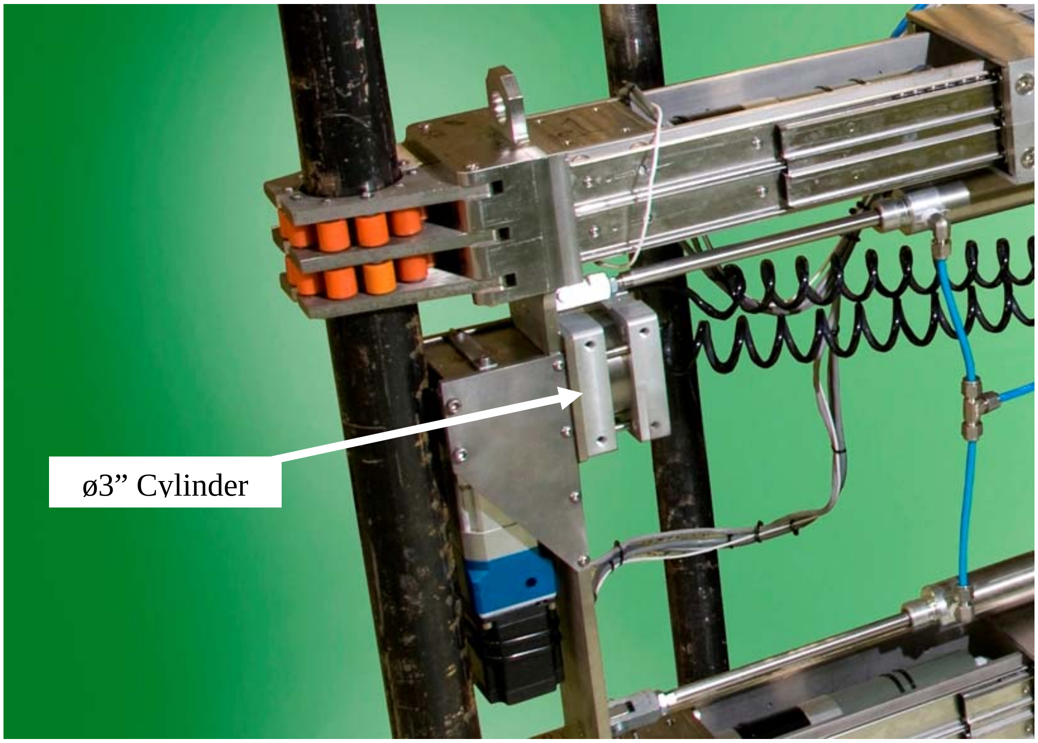


Figure 20. 3" Diameter Drive Wheel Pneumatic Cylinder

3 RESULTS

Extensive testing of the Pipe Traveler led to a number of design modifications. In order to improve control of the gripping force, encoders were added to the gripper motors. In order to improve control of the drive wheel motion, the drive wheel DC motors were replaced with stepper motors. The software was optimized to utilize these motor control improvements. A number of different gripper roller configurations were tested, leading to the use of rubber gripper rollers and knurled steel drive rollers. In order to increase the normal force against the pipe, the diameter of the drive wheel pneumatic cylinder was increased from 2” to 3”. The ø3” cylinder provided adequate normal force when supplied with at least 90 psig air. In addition to the design improvements, testing indicated that the rotational performance was optimized by setting the top gripper force at 600 lbf and the bottom gripper force at 100 lbf. After all of these design improvements and operational parameters were implemented, the Pipe Traveler was able to consistently transfer itself from pipe to pipe within the pipe mockup.

4 CONCLUSIONS

While the basic function of the Pipe Traveler has been proven, a number of additional features would be needed to make the system field deployable.

The Pipe Traveler in its current form assumes a vertical pipe is readily accessible. In a waste tank or possibly other applications, deployment techniques and equipment must be developed to position the Pipe Traveler so that it can attach to the initial pipe. Techniques and equipment may also be needed for removal from a tank or other facility.

Tether and cable management would be another critical improvement to the system. During testing, tether drag inhibited Pipe Traveler motion more than the weight of the Pipe Traveler. One option for reducing tether weight and size would be to mount the controls on the Pipe Traveler. The pneumatic controls could be replaced by solenoid valves and a small onboard compressor so that no pneumatic lines are needed in the tether. Given these changes, the tether could consist of a single electrical cable with power and communication lines and a safety cable. Other options for tether management should also be considered. Techniques for minimizing tether drag must also be developed.

No effort has been made to minimize the weight of the Pipe Traveler. Reducing the weight of the Pipe Traveler mechanism would make it more flexible in terms of the payloads it could deploy.

Vertical motion of the Pipe Traveler would be desirable in many applications. Vertical motion could be performed in an “inch-worm” fashion by using the top grippers to pull up the bottom, and to then use the bottom grippers to push up the top. The reverse would be true to climb down the pipes. The current system was designed with points in mind to incorporate a vertical climbing system of this fashion.

A US Patent application has been filed for this technology by Savannah River Nuclear Solutions, the parent company of Savannah River National Laboratory.

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