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PIPE CRAWLERS: VERSATILE ADAPTATIONS FOR REAL APPLICATIONS (U)

by

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INTRODUCTION

The purpose of a pipe crawler is two-fold. First, it provides a means of locomotion and control for accessing hard to reach locations in piping systems and secondly, it performs one or more tasks; anything from visual or ultrasonic inspection to object retrieval or weld repair.

Until a few years ago, most pipe crawlers were pushed or pulled through pipes with stiff extensions or rope; or crawled under their own power, primarily along horizontal stretches of pipe. Today there are a few crawlers capable of climbing a vertical section of pipe under their own power, and they are usually driven by one of two methods of locomotion. The first is the Continuous Motion method. It consists of a crawler that applies pressure to the pipe wall and propels itself along the pipe using either motor driven wheels, tractor treads, or some other means of continuous motion. The second method, the Stepper Motion, also referred to as the "inch-worm" motion, has quickly become the method of choice for industry. It is simply a six-step motion whereby a crawler uses a frictional means to grab the pipe wall with either the front or rear section of the crawler; then it uses the central body to propel the opposite section an incremental amount further down the pipe. (See Figure No.1).

With the advent of the inch-worm motion type of crawler and its capability for maneuvering around elbows and climbing vertical pipe, new applications for these "real" crawlers are now under development. The following section, "General Pipe Crawler Considerations", describes items to consider for most standard applications of pipe crawlers. The next section is the "Problem Statement", which describes a specific application of a pipe crawler. The third section, "Design Approach", describes how a purchased crawler was adapted and new equipment designed to solve the problem of interest. Finally, the "Conclusion" describes the status of the job.

GENERAL PIPE CRAWLER CONSIDERATIONS

Desired characteristics of a pipe crawler vary significantly from job to job depending upon the task to be accomplished. However, a few things are important to keep in mind in designing or purchasing a pipe crawler to increase the chances of successful performance.

1. The crawler should be light weight.
2. The tether should be light weight and low in friction to reduce the amount of drag during travel in the pipe, especially around elbows.
3. The pushing or pulling capability (payload) of the crawler should be matched to the particular job. However, a crawler with high capacity, whose reaction forces will not damage the piping system or the crawler, will be useful in many more applications.
4. The friction between the pipe wall and the crawler's gripping mechanism, usually the feet, should be as high as possible. This will aid travel, especially in vertical pipe. Beware of using material harder than the pipe, otherwise, the pipe may receive indentations or marks that may become the site of future problems. Also, avoid materials that are too soft which may wear quickly and leave undesired material in the pipe.
5. Control of crawler motion is important. It should allow passage through the straight leg of a "T" without the legs "hanging up" in the trunk of the "T". Speed control is also desirable. Slower speeds may help avoid difficult situations that arise.
6. Proper lighting and visual feedback should be utilized whenever possible. However, too much light or poor camera view ares not worth the added weight or complexity to the crawler.
7. The minimum bend radius or pipe diameter of an elbow that a crawler is to pass through should be calculated, or determined through testing, prior to field use.(See Figure No.2).
8. The minimum foot stroke length of a Stepper Motion crawler should be calculated or determined through testing, to determine passage through elbows. (See Figure No.3).

There are other items to consider that become individualized for non-repetitive jobs and do not warrant being identified here.

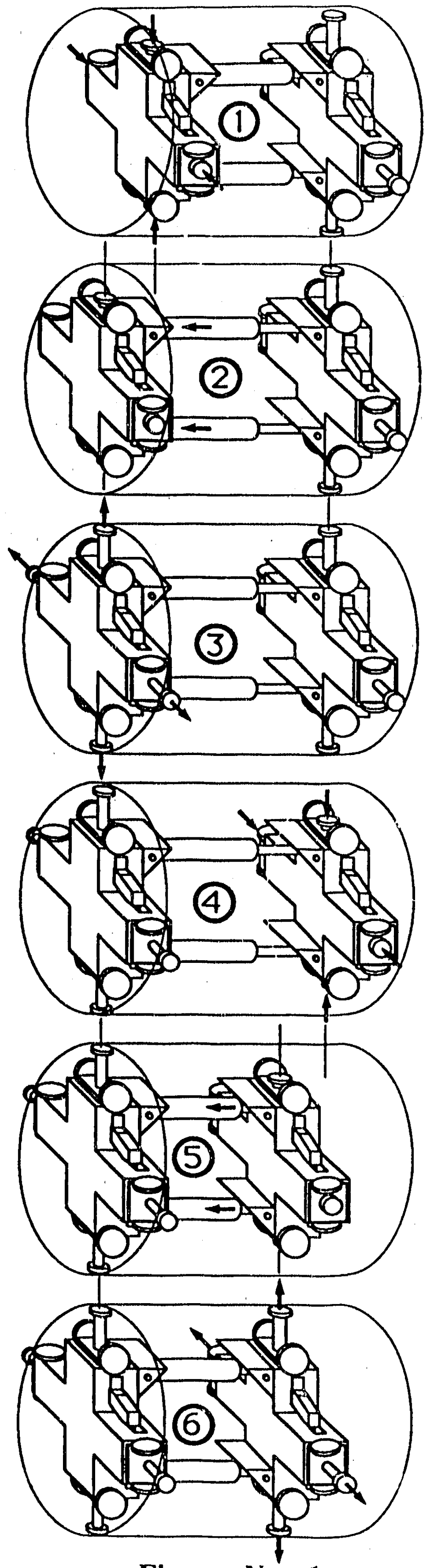


Figure No. 1
Stepper Motion

PROBLEM STATEMENT

Objective

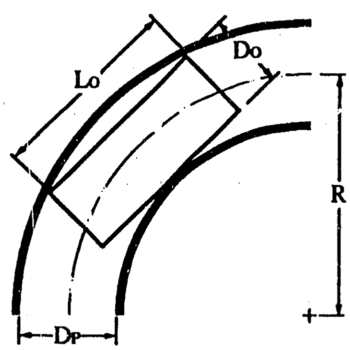
A problem encountered at the DOE Savannah River Site (SRS) requires the unique application of a pipe crawler. There exists a number of stainless steel pipes buried in concrete for which it is desired to ultrasonically inspect the heat affected zones of the welds for flaws or cracks. Thus, inspection of these welds must be performed from inside the pipe. In order for the crawler to reach this area of concern the piping system must be drained, a valve dropped out of line, and the crawler inserted into a 12-inch diameter pipe. (See Figure No.4). The crawler negotiates a 90° reducing elbow which changes diameter from 12 to 16 inches. The crawler then travels to another 90° elbow, turns into a vertical section, and then approaches the area of concern.

Other important constraints include a high radiation field that the crawler may have to operate in (up to 1x10E5 rad/hr), restrictions on materials which may contact the stainless steel pipe, and provisions for feedback and computer control. Materials must be low in chloride due to process piping system considerations. The feedback controls must provide repetitive location of the inspection equipment to the areas of concern, the center of the welds.

Special Requirements to Meet Objective

The following twelve constraints resulted from the description of the problem as well as a desire to develop a quality inspection device.

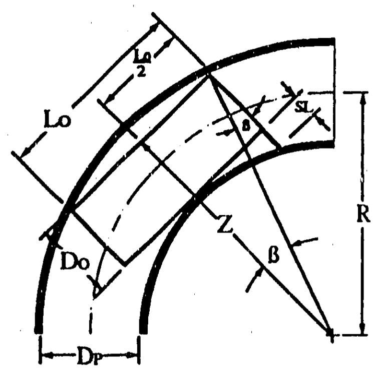
1. All equipment must be capable of entering the pipe to be inspected through a dropped valve.
2. The crawler must be self-propelled.
3. The crawler must be able to travel through 90° long radius elbows.
4. The crawler must be able to crawl up a vertical pipe for a minimum distance of 16 feet, stop, and maintain its position.
5. The crawler must be able to travel in a 12-or 16-inch pipe and change diameters "on the fly" to accommodate either.
6. The materials that contact the inside of the pipe must be compatible with the process piping system. This means that these parts should be limited to stainless steels, aluminum, or polymers low in both chloride content (less than 250 ppm) and other identified materials.
7. The crawler should have a radiation tolerance of 1x10E7 rad/hr.
8. Teleoperation is acceptable but telerobotic is preferred.
9. The ultrasonic (UT) scanning rate desired is 1 in./sec for both linear and rotational scans.



$R=(L_o{**}2)/\{8(D_P-D_o)\}-D_o/2$
Lo=Length of Object
Do=Diameter of Object
Dp=Inside Diameter of Pipe
R=Centerline Bend Radius of Pipe

See Reference No. 1

Figure No. 2
Minimum Bend Radius



$Z=R-(D_P/2)+D_o$
$\tan(\beta)=(L_o/2)/Z$
* $SL=D_P/\cos(\beta)-D_o$
Lo=Length of Object
Do=Diameter of Object
Dp=Inside Diameter of Pipe
R=Centerline Bend Radius of Pipe
SL=Stroke Length of Crawler Legs

* This equation is an approximation. For greater accuracy, the diameter of the foot and the radius of the pipe bend should be taken into account. It is also assumed that either Do and Lo or R has been optimized for a given Dp.

Figure No. 3
Minimum Stroke Length

10. The UT probe should be capable of scanning in any orientation.
11. A means of "coupling" the UT probe to the pipe wall for acceptable sound wave transmission must be provided.
12. Conditions conducive to implementing ALARA (As Low As Reasonably Achievable) for radiation exposure to personnel should be utilized.

DESIGN APPROACH

The problem described above was addressed in two parts. The first part was how to reach the area of concern, the circumferential pipe welds inside the concrete; and the second part was how to visually and ultrasonically inspect the heat affected zones of these welds. The program was then divided into two phases: the first was to have the pipe crawler be teleoperated; and the second to be telerobotic.

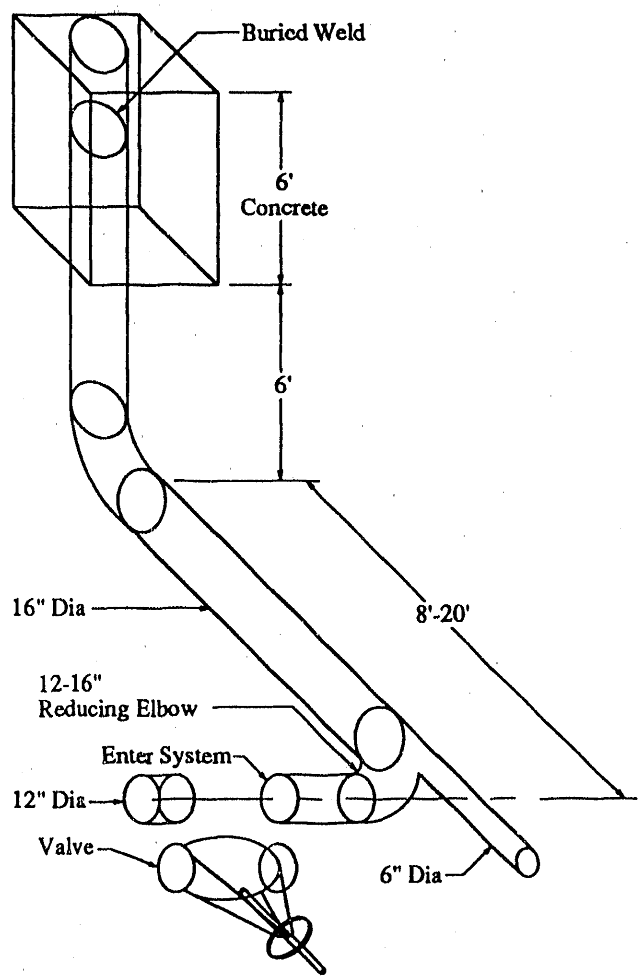


Figure No. 4
Piping Isometric

A limitation of many crawlers available on the market is the inability to remotely accommodate pipe diameter changes of more than two inches in the course of travel. As inspections of entire piping systems become common place, this feature of changing diameters will become more desirable. After a search of the market, it was decided to build the crawler in two functionally independent segments. A crawler was purchased from CTS Power Services Inc. and modified to provide the locomotion. This section of the crawler is referred to as the **tractor**. The other segment is a four degree of freedom, cylindrical coordinate device that was designed and built to perform the necessary ultrasonic inspections. It is positioned in front of the tractor and is referred to as the **instrument carriage**. Together these two sections are referred to as the **pipe crawler**. The controls for the pipe crawler are remote, attached by a 300-foot tether, and operated either manually or automatically. Below, divided into three subsections, are descriptions of the tractor, instrument carriage, and the controls.

Tractor

The purchased crawler operates using the Stepper Motion described earlier and crawls at a rate of one foot per minute. It meets five of the twelve special requirements (SR) and five of the eight general pipe crawler considerations (GC):

- Enters the system at a dropped valve (#1 SR)
- Self-propelled (#2 SR)
- Negotiates long radius 90° elbows (#3 SR)
- Crawls up vertical pipe (#4 SR)
- Teleoperated (#8 SR)
- Light weight (#1 GC)
- High payload (#3 GC)
- Controlled motion (#5 GC)
- Min. bend radius acceptable (#7 GC)
- Min. foot stroke length acceptable (#8 GC)

The CTS crawler (See Figure No.5) was modified to accommodate either 12-or 16-inch pipe during travel. The legs of the crawler were redesigned and fabricated from two-inch-square,aluminum tubing which houses pneumatic cylinders inside a polymeric bushing (See Figure No.6). In the normal (12-in.) state, the feet operate the same as the purchased crawler. Expansion of the legs on the enhanced tractor occurs with the use of a mechanism added to the center of this new leg assembly. When this mechanism is actuated, the legs extend radially and the tractor may now crawl in a larger diameter (16-in.) pipe. (See Figure No.7). This extension mechanism is used in both the front and rear leg sections of the tractor.

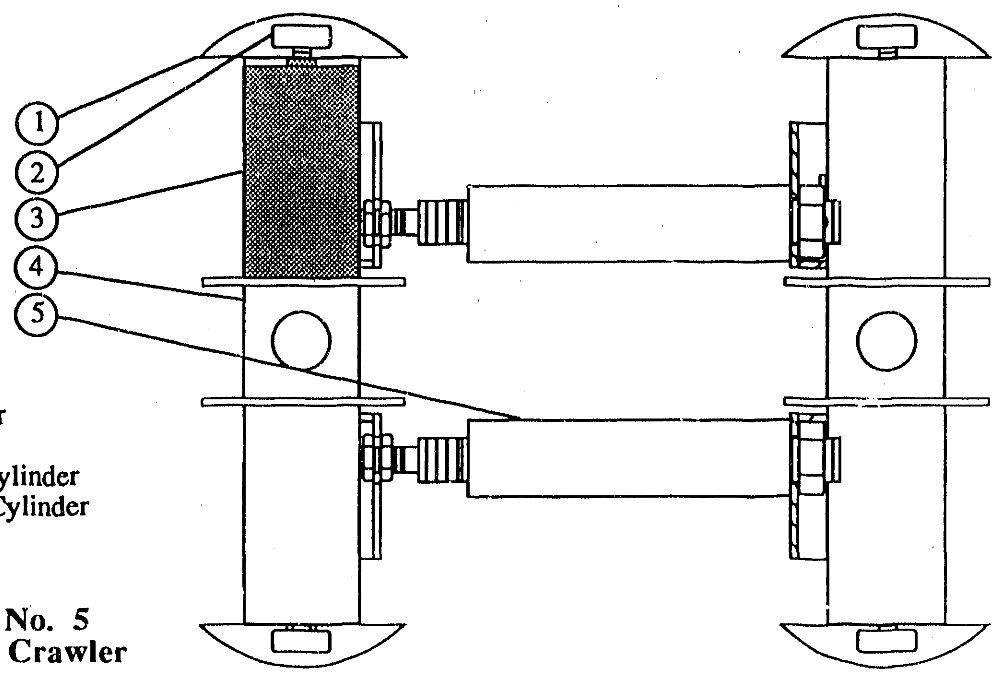
An important consideration that resulted from this leg expansion mechanism is that two different air pressures are now necessary to operate the tractor. This results from the transmission of forces from the legs to the expansion mechanism being 45° to each other. Additionally, the ratio of effective areas of foot cylinders to the leg expansion cylinders adds to the imbalance. Thus a resulting minimum of 3.18 times the air pressure of the foot cylinders is required to operate the expansion cylinder in order to keep the legs expanded while the feet crawl inside a 16 inch pipe. (See Figure No.8). Otherwise, the reactive forces transmitted from the pipe wall through two adjacent feet and legs would collapse the leg expansion mechanism.

To enable the tractor to move along more freely inside the pipe, three additional modifications were made. (See Figures No.5 and No.6). First, stainless steel wheels were substituted for the sled runners to help reduce the drag. Second, the metal feet were replaced with rubber ones. This doubled the load that the tractor could pull at a given operating air pressure. Finally, the pneumatic valves in the control box were replaced with light weight miniatures and relocated to the tractor. This reduced the number of pneumatic lines from six to two thus reducing the weight and drag of the tether. The enhancements described above allow the crawler to meet three special requirements and two general considerations:

- Material constraints (#6 SR)
- Radiation tolerance (#7 SR)
- Diameter changes (#5 SR)
- Reduced tether weight & friction (#2 GC)
- Maximum feet friction (#4 GC)

Instrument Carriage

The other half of the pipe crawler is referred to as the instrument carriage. It is a four degree of freedom, cylindrical coordinate device that performs nondestructive testing of circumferential welds inside a pipe. The instrument carriage consists of two sections: the body and the arm. (See Figure No.9). The body has two sets of legs in the shape of a cross that house pneumatic cylinders that accommodate pipe diameter changes from 12 to 16 inches. On the end of the cylinder shafts one inch diameter stainless steel ball transfers are mounted that allow the carriage to roll freely in the pipe. Between the front and rear legs is a three shaft drive train on which the carriage arm travels.



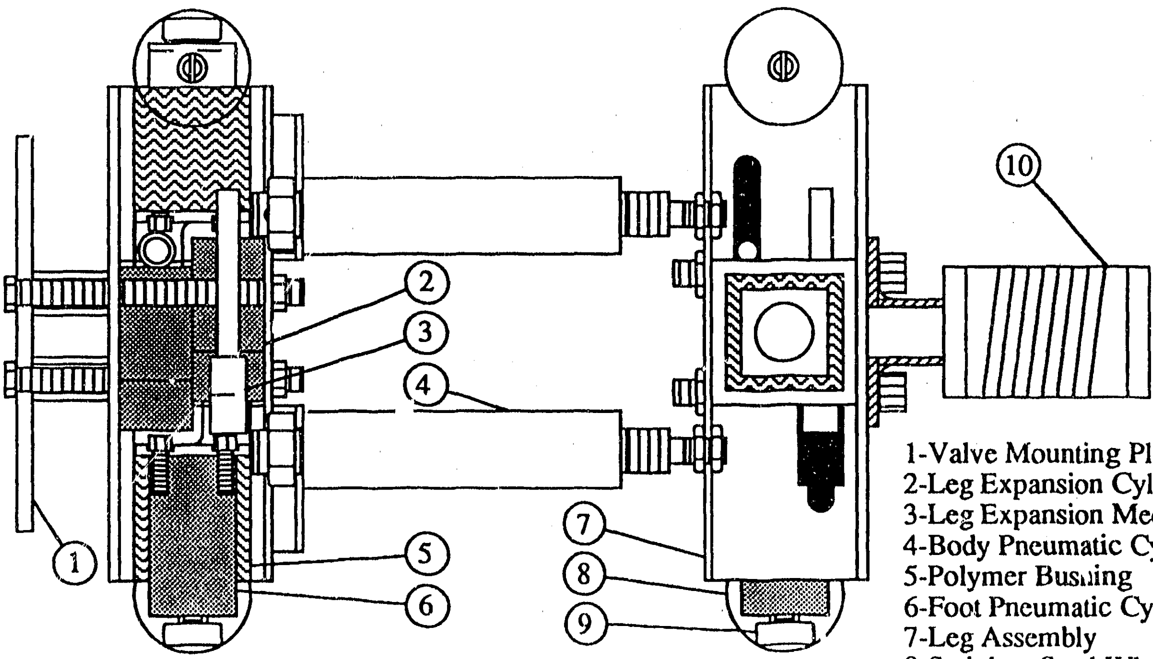
1-Metal Sled Runner
2-Metal Foot
3-Foot Pneumatic Cylinder
4-Body Pneumatic Cylinder
5-Leg Assembly

Figure No. 5
CTS Pipe Crawler

The shafts are mounted in a triangular pattern to add rigidity to the carriage. This helps to prevent the body from twisting such that the arm may still travel axially. One shaft is a ball screw that is driven by a high torque planetary gear motor. It is used to move the arm in the axial direction and travels from two to four inches at speeds of 0 to 0.52 inches per second. The second shaft provides stability between the legs and also acts as a guide for the arm to ride along in the axial direction. The third shaft is a rotating splined linear bearing shaft that also has a high torque motor attached to the end of it. The bearing slide has a gear mounted on it which is used to drive an internal ring gear mounted on the arm.

The ring gear surrounds the three shafts which theoretically allows the arm to rotate about the shafts continuously. The speed of rotation ranges from 0 to 17.4 rpm. This is equivalent to a scan rate of 0 to 13.7 in/sec for a 16 inch diameter pipe. The entire drive train is capable of transmitting a maximum arm rotation torque from 0.6 to 60 foot-pounds and a linear force of 0 to 300 pounds depending on which gear motors are utilized. This range of power transmission allows the use of the instrument carriage for low torque applications such as ultrasonic scanning or high torque tasks such as grinding or heavy object removal. Both the axial and rotational motions have position feedback by way of high pitched gears and rotational potentiometers. Miniature switches are used to limit the range of motion and protect the equipment from over-travel damage.

The arm is designed to allow the user to attach any number of interchangeable devices for use inside the pipe. Attached to the rotating housing is a mechanism to provide radial motion to the pipe wall. It is comprised of two pneumatic cylinders mounted in parallel to the rotating housing. With an excess of available stroke, they are operated at low pressure (5-20 psig) to allow compliance of the probes to the pipe wall. This proves to be necessary since most pipe is not perfectly round nor can the center of rotation of the instrument carriage be repeatedly aligned with the center of a pipe. A rectangular plate mounted on the arm serves as a platform for the inspection devices. In this instance a small planetary gear motor is mounted to the plate and geared to a potentiometer for position feedback. This motor provides 380° of spin to a gimble that both supports and provides additional yaw and pitch compliance for the UT probe.



1-Valve Mounting Plate
2-Leg Expansion Cylinder
3-Leg Expansion Mechanism
4-Body Pneumatic Cylinder
5-Polymer Bushing
6-Foot Pneumatic Cylinder
7-Leg Assembly
8-Stainless Steel Wheel
9-Rubber Foot
10-Flexible Beam Coupling

Figure No. 6
Enhanced Crawler: Tractor

The UT probe that is mounted in the gimble houses both a straight through transducer to look for material laminations and a 45° shear wave transducer to inspect for transgranular or intergranular cracks. These two transducers are packaged as one unit and have a small hole in its mount where couplant is pumped to the surface of the probe. This couplant is a water soluble gel that allows for good contact between the probe and the pipe wall; insuring good sound transmission. Mounted next to the UT spin mechanism is a spring loaded eddy current probe. This probe is a redundant aide in the location of the welds. It does so by sensing the changes in the magnetic properties of a metal.

Also mounted on the arm platform is a small (approx. 1-in. dia. x 3-in. long) color CCD camera that aides the inspection. Lights are mounted on the legs of the instrument carriage. Remote "eyes" can save many problems from occurring during an inspection. The primary purpose of this camera is to view the probes and the area of concern that is being inspected. Up to three other cameras may be mounted on the instrument carriage or tractor to aide travel and inspection.

The instrument carriage and the tractor are connected together with a stainless steel flexible beam coupling that is capable of transmitting the high forces encountered when maneuvering through an elbow. It is important to have a coupling that is flexible enough to allow the two halves of the crawler to "bend" in relation to each other yet stiff enough to transmit the linear forces of travel from the tractor around a bend to the instrument carriage in order to continue its travel through an elbow. (See Figure No.10) This capability is even more important when passing through an elbow in the vertical direction since both friction and gravity are resisting the motion.

Except for automatic control, all other requirements and considerations for the crawler were met as described by the system above:

- 12-16 in. adaptability (#5 SR)
- material compatibility (#6 SR)
- radiation tolerance (#7 SR)
- Teleoperation (#8 SR)
- Scanning rate (#9 SR)*
- Probe orientation (#10 SR)
- Probe coupling to pipe wall (#11 SR)
- ALARA (#12 SR)
- Camera & lights (#6 GC)

* The maximum linear scanning rate is 0.524 in./sec, but this rate does not affect the quality of the data acquired although it does slow down the rate of data acquisition.

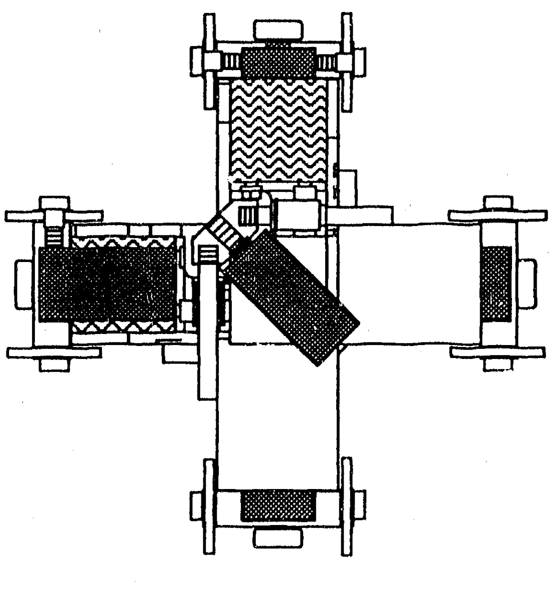
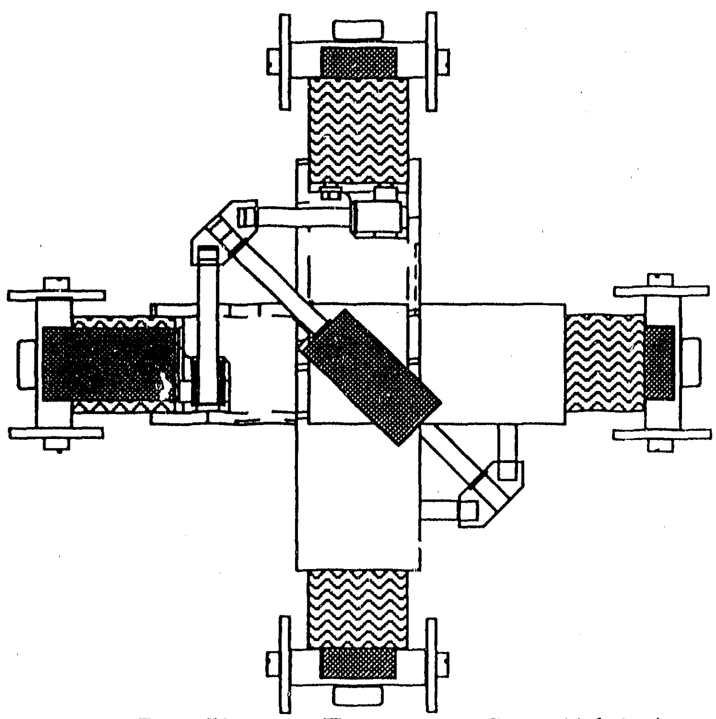
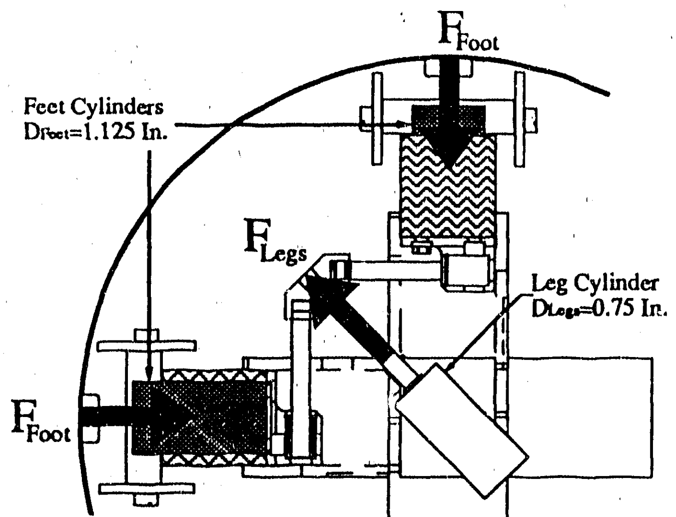


Figure No. 7

End View: Normal State(12 in.)



End View: Expanded State(16 in.)



$F_{Legs}=2(\cos 45°)F_{Foot}$

$F_{Foot}=P_{Foot}A_{Foot}$

$F_{Legs}=P_{Legs}A_{Legs}$

$P_{Legs}A_{Legs}=2(\cos 45°)P_{Foot}A_{Foot}$

$P_{Legs}/P_{Foot}=2(\cos 45°)A_{Foot}/A_{Legs}$

$P_{Legs}/P_{Foot}=1.414\{D_{Foot}**2/D_{Legs}**2\}$

$P_{Legs}/P_{Foot}=1.414\{1.125**2/0.75**2\}$

$P_{Legs}/P_{Foot}=3.182$

F=Reactive Forces on Feet
A=Effective Area of Cylinders
D=Effective Diameter of Cylinders
P=Air Pressure in Cylinders

Figure No. 8
Force Diagram

The remaining requirement of the pipe crawler's capability is robotic control. Feedback on positioning and speed is important in accomplishing this. The following subsection describes how the teleoperated controls for the pipe crawler were accomplished and how automatic control of the system was handled.

Controls

PIPE CRAWLER

The robotic control of the pipe crawler consisted of two design phases: teleoperated ultrasonic inspection capability and computer controlled (telerobotic) ultrasonic inspections. Initial implementation of a teleoperated control system allowed troubleshooting and design enhancements to be performed in conjunction with the development of a computer control system, which required only minor hardware and software development.

The system was designed to allow remote operation of the pipe crawler at a distance of 300 feet to aid with ALARA as well as long pipe inspections. A portable equipment cabinet was equipped with a tractor control chassis, an instrument carriage control chassis, two video monitors, a video recorder, and an audio communication system. An additional cabinet contains ultrasonic and eddy current data acquisition systems. (See Figure No.11).

The tractor control chassis was developed by adapting the existing CTS tractor controls into a 19 inch chassis, including a new front panel that incorporates user-friendly feedback. The programmable logic controller (PLC) supplied by CTS was mounted in the chassis along with smaller power supplies. The front panel was equipped with an air pressure regulator, switches, and LED indicators to notify the operator of the tractor feet and body positions. Air lines inside the chassis were minimized by replacing existing pneumatic valves (previously located inside the chassis) with miniature versions mounted on the tractor. Sequencing of the valves to perform Stepper Motion can be performed automatically through the PLC, or manually via switches on the front panel. In addition to the LED indicators, video cameras mounted on the tractor and instrument carriage aid the operator in positioning the equipment.

INSTRUMENT CARRIAGE

The instrument carriage is propelled through the pipe by the tractor. Once a weld is located by the camera or one of the probes, the UT probe can be positioned by hardware located in the instrument carriage control chassis. Three of four axes on the instrument carriage are electrically controlled by closed loop servo systems. These axes provide rotation around the circumference of the pipe, axial motion along the pipe wall, and rotational (spin) positioning of the ultrasonic transducer. The fourth degree-of-freedom, pipe wall compliance, is controlled pneumatically.

During teleoperated control of the robotic arm, the operator interfaces with the front panel of the instrument carriage control chassis. Manipulation of a three-axis joystick controls positioning of the ultrasonic or eddy current probe. This joystick invokes movement of the sensors in a manner that simulates an inspector's

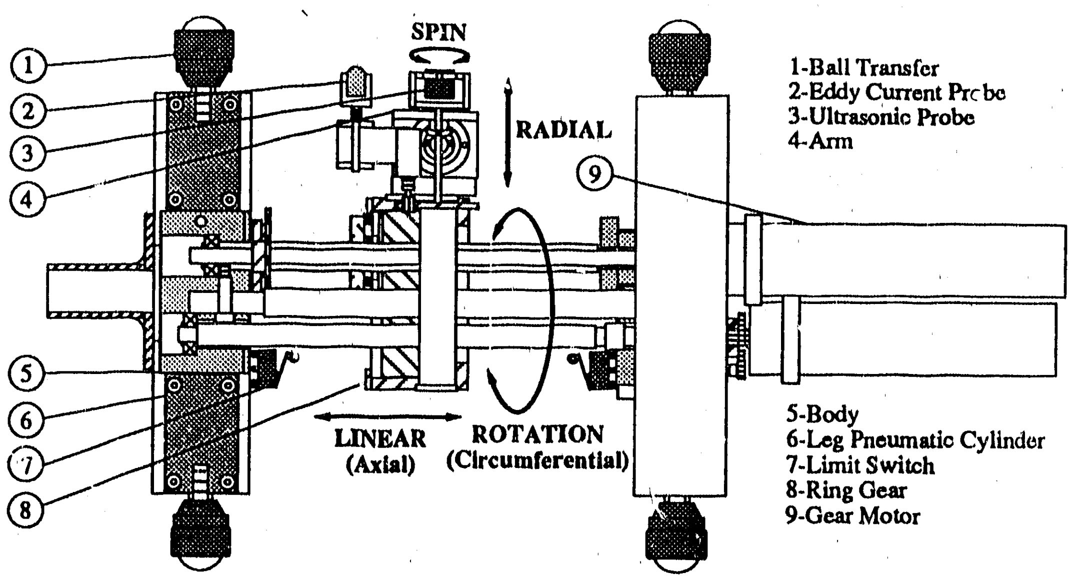


Figure No. 9
Instrument Carriage

hand movements during a hand-held weld inspection. A pressure regulator mounted on the control panel can be adjusted to provide adequate pipe wall compliance for the sensors.

Position feedback for the three electrically controlled axes is supplied by rotational potentiometers. An electronic level sensor (a pendulum potentiometer) has been mounted on the instrument carriage to provide a vertical reference in horizontal pipe and a means for calibrating the arm rotation feedback. With the aid of a mechanical cam and two limit switches, arm rotation is limited to 400° and start-up status of its location is provided from any unknown position. This position information is converted to engineering units and displayed by digital panel meters during operation.

The instrument carriage chassis contains motor drivers and electronics necessary to drive the arm and process feedback information. Three pulse width modulated (PWM) servo amplifiers drive brushless DC motors to provide speed control from creep to full speed. Tachometers are used to enhance low speed control of the axial and rotational axes. Inputs from the three-axis joystick are amplified to supply a reference input to the PWM servo amplifiers. A dead band circuit prevents motor creep when the joystick is in the "rest" position. An "enable" input on the servo amplifier accepts the dead band signal and inhibits current output to the motor.

Additional "enable" inputs on the PWM servo amplifiers are used to disable motion as the arm reaches the extent of its travel. Limit switches mounted on the instrument carriage prevent arm movement beyond preset boundaries. Information from these switches is processed by a logic circuit and used to determine when any of the three axes should be disabled; at which time an LED on the control panel is illuminated. For example, rotation of the arm is continuous without a physical hard stop. For this axis, a circuit is used to decode both potentiometer position feedback and limit switch status to disable arm rotation.

COMPUTER CONTROL HARDWARE

The present electrical design allows the development of a VMEbus host computer system to coincide with design enhancements and testing of a manually controlled operational system. A Motorola MVME147 CPU with a 20 MHz 68030 processor and a Galil 3-axis motion control board will operate the robotic arm in both teleoperated and automatic scanning modes. This host computer system will also communicate over RS-232 interfaces to a graphics monitor, an Amdata Intraspect/98 data acquisition system (which will process the ultrasonic data), and a Failure Analysis Assoc./SmartEDDY eddy current data acquisition system.

The 3-axis motion control board monitors position information and user inputs. It also issues velocity commands to the PWM servo amplifiers in response to commands from the processor board. All communication between the processor board and the motion control board occurs over the VMEbus. As a safety mechanism, limit switch "disable" commands to the servo amplifiers will continue to be performed by hardware. However, software limits will be used to prevent an axis from reaching any of the limit switches.

The use of a computer in this system allows repeatable weld examinations by providing scanning strokes of specified lengths in the heat affected zone of a weld. Scanning patterns can be performed automatically through software and position information can be supplied to the data acquisition system throughout the scan. During this process, the operator must be aware of critical system parameters and be able to alter or terminate a scan at any time. The following section describes how these goals are achieved through software.

COMPUTER CONTROL SOFTWARE

The software system consists of four major tasks: user interface, robot control, UT/ET system interface, and graphics display. A large area of shared memory has been allocated to store data required by more than one task. The USER task is the interface between the computer and the operator. It accepts keyboard inputs from the user's response to menu choices on the graphics terminal, and notifies the user of error messages and other information. The ROBOT task interfaces with the Galil motion control board. It issues velocity commands and continually monitors position information. This information is used to update the data in the shared memory segment. A GRAPHICS task updates the graphics terminal three times a second with position information accessed from shared memory. A UT/ET task allows the host computer to communicate position information, control signals, and error status to the ultrasonic and eddy current data acquisition systems.

Robot operators interface with a menu-driven graphics terminal and initiate automated actions through a keyboard. Selection of the teleoperated mode enables the 3-axis joystick, and allows the operator to position the arm in any orientation. Additionally, automatic scanning mode may be selected to perform a number of predefined scanning patterns. The graphics terminal displays an animated version of the arm position as it moves within the pipe. Position

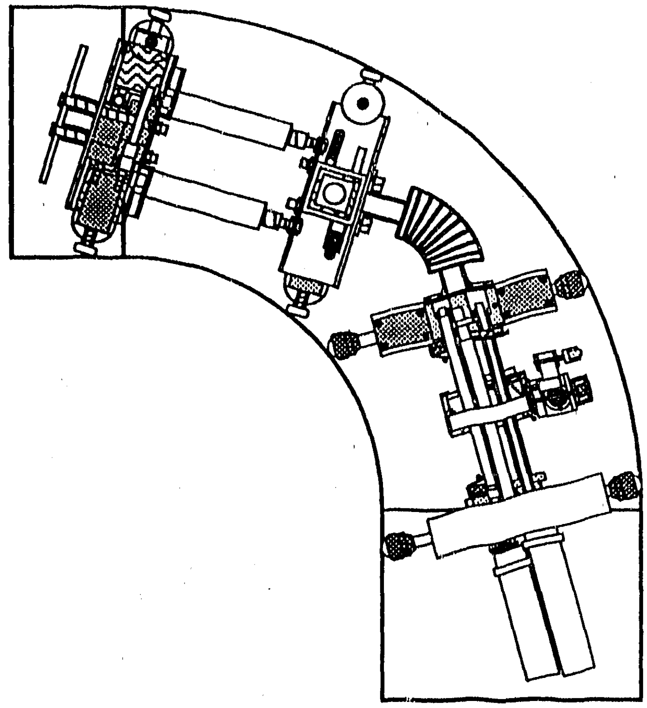


Figure No. 10
Travel Through Elbow

feedback data is displayed in a window format, while limit switch status and error messages are displayed in another window. Computer controlled movement of the arm is best described through the following examples.

Teleoperated positioning of the arm is invoked by the operator through a keyboard selection. After receiving this input, the processor board begins monitoring the joystick input data. When an input is recognized, a move command is sent by the processor board to the motion control board, which in turn outputs a velocity command to the appropriate PWM servo amplifier(s). The processor board continues to monitor the joystick input and position feedback. As the joystick input changes, the processor board sends new commands to the motion control board. Throughout this process, the processor board is refreshing the graphics terminal display three times a second. During the teleoperated mode, the operator may position the arm without restrictions until a limit switch disables an axis.

During automated scanning, a true closed loop servo system exists. In other words, the computer issues velocity commands to the servo amplifiers in response to position feedback

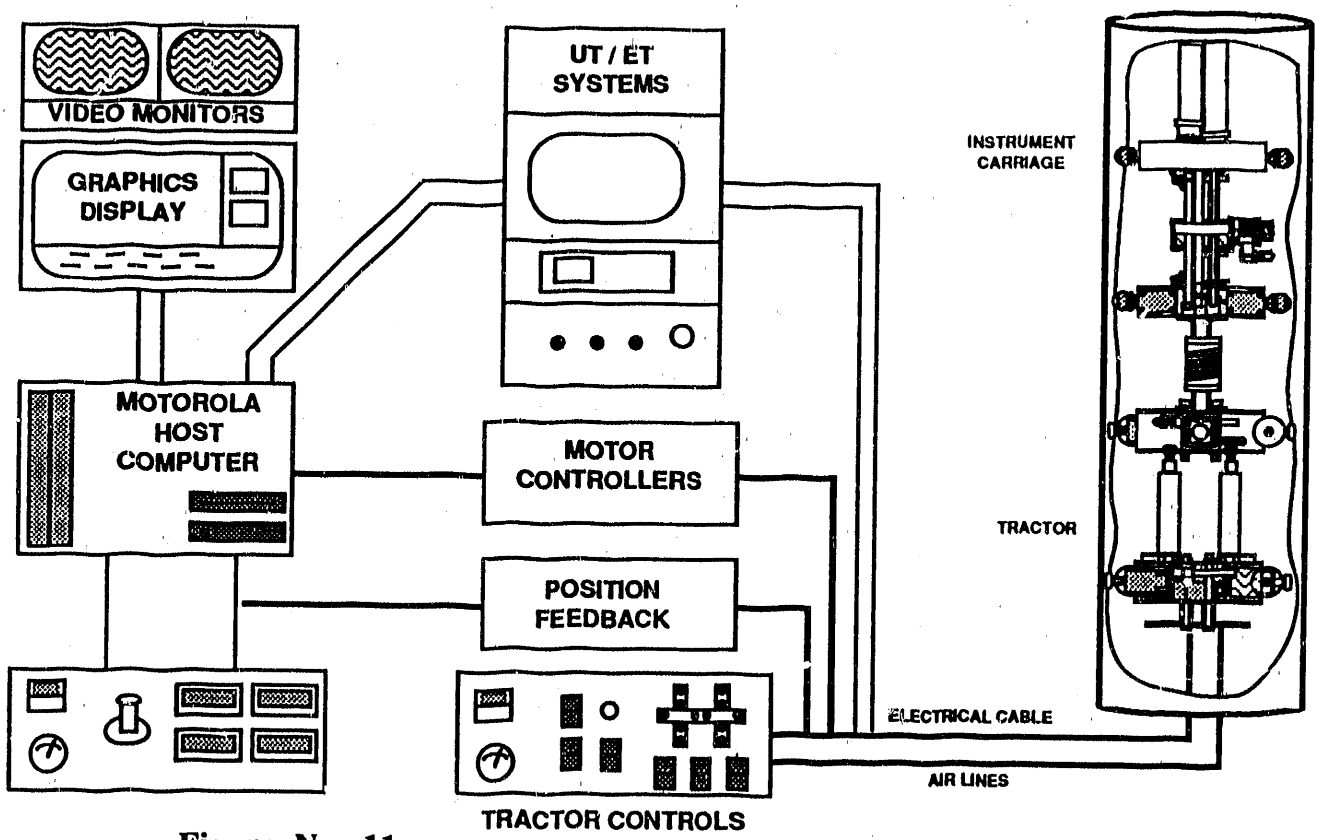


Figure No. 11
Control Diagram

information. During an actual inspection of a circumferential weld, a raster pattern is traced in the heat affected zone of a weld. (See Figure No. 12 and Reference No. 2). This pattern consists of two movement commands issued by the processor board: "move to SZ" and "scan to SZ", where S and Z refer to movements in the circumferential and axial directions along the pipe wall, respectively. During a "scan" command, the host computer passes position information to the data acquisition system and prompts it to take data bursts at specified intervals.

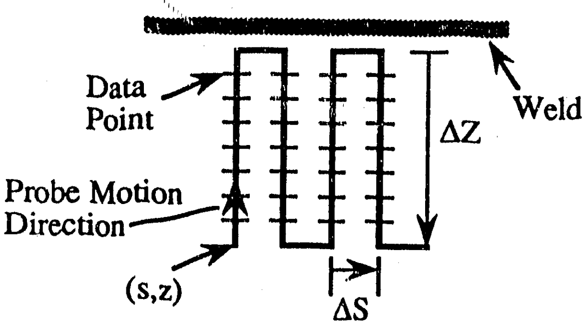


Figure No. 12
Raster Scan

A "move to SZ" is issued to position the transducer for the next data scan parallel to the weld. During this movement, the processor board does not communicate with the data acquisition system. The motion control board responds to a "move to SZ" by calculating a trapezoidal velocity profile and issuing a velocity command to the servo amplifier based on this profile. A velocity command will continue to be issued by the motion control board until the probe reaches the desired "SZ" coordinates. When the processor board realizes that the probe has reached the desired position, it will issue a "scan" command.

During a "scan to SZ" command, the processor board must communicate with both the motion control board and the data acquisition system. The motion control board is issued a "move to SZ" command as described earlier. It responds by calculating a velocity profile and initiating movement of the arm. The data acquisition system is informed of the initial "SZ" position and the "go to SZ" location over an RS-232 interface. As the arm moves axially along the pipe, the processor board monitors the position information and commands the data acquisition system to take data bursts at specified intervals. The "take data" commands, along with the initial position information, allows the data acquisition system to map the characteristics of the weld on its graphics display. A series of "move" and "scan" commands continues until the probe has encompassed the entire heat affected zone along the circumference of the pipe.

CONCLUSION

A crawler has been successfully demonstrated at SRS that can change diameters in transit for a range of 12-18 inches for horizontal travel and 12-16 inches for elbows; and inspect the heat affected zone of circumferential welds using ultrasonics.

The status of this equipment is that it has been tested in a mock-up of the piping that will be inspected. The crawler reaches the area of concern and can take ultrasonic scans in the teleoperated mode. All twelve of the "Special Requirements" and eight "General Pipe Crawler Considerations" were met and work is currently in progress to convert to a telerobotic mode of operation. The equipment will be qualified on known test marks inside the mock-up. After training and qualification of inspection personnel, the equipment will be ready to go to the field.

As the miniaturization of electro-mechanical devices progresses, pipe crawlers will be utilized to a much greater extent for many new applications. The design of the above pipe crawler was intended for the crawler to be adaptable to more than just the problem described in this paper. For this reason, the tractor and instrument carriage were modified and designed respectively as two stand-alone units. By doing this, the tractor may also be used for visual inspections, pulling objects through pipes, or other new applications. Similarly, the instrument carriage may be modified to accept a grinding head, a gripper tool, or possibly even a welder. Adaptations such as these are usually thought of first for use of a pipe crawler. Considerations for new applications, and thus new crawlers, will build upon the above demonstrated technologies.

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