Design of a Bio-Inspired Crawler for Autonomous Pipe Inspection and Repair Using High Pressure Cold Spray

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ABSTRACT

In this paper, we describe design of a robotic pipe crawler for inspection and repair of remote to access internal piping systems. Current snake robots for pipe are primarily designed for inspection purposes and unreliable for conducting further operations including repair. This shortcoming is due to the limited load carrying capacity that impedes them from offering a holistic and viable inspection and repair approach. Towards achieving this goal, a collaborative effort has been formed among Advanced Intelligent Mechatronics Systems (AIMS) research laboratory and Advanced Materials Processing Technology Transition and Training Center (AMPTECH) of South Dakota School of Mines and Technology (SDSM&T). The objective is to design and develop a long-range tethered modular pipe crawler with high load capacity carrying capable of identifying and localizing the pipe damages using Non-Destructive Evaluation (NDE) and conducting repair through coating defected pipe areas via high pressure particle deposition also known as cold spray process.

A modular design concept is adopted in the design of crawler with four modules using a bio-inspired peristaltic movement for locomotion. Adoption of modular design concept along with high load carrying capacity allows the integration of two additional modules for carrying NDE and cold spray equipment, respectively. The current design allows navigation through 4 inch and above pipe diameters. To provides access for remote areas of piping system all modules are designed to satisfy dimensional requirement to pass 45 and 90-deg bends. Also, in order to maximize the pull force available for carrying the inspection and repair equipment, a self-locking mechanism is used in the design of the grippers. This paper describes the design considerations for maximum load carrying capacity and initial design efforts for the pipe robot. It highlights the break through innovations in the design of gripper mechanism using four-follower face cam mechanism and other novel features especially within NDE inspection and cold spray repair modules.

Keywords

Pipe Inspection, Robotic Crawler, Modular Design, Peristaltic Locomotion, Non-Destructive Evaluation, High Pressure Cold Spray, Visual Inspection.

1. INTRODUCTION

Research trends indicate that autonomous bio-inspired robotic systems are emerging in our daily lives as well as industrial applications [1-4]. The possibilities of bio-inspired robots are virtually endless for commercial entities and government agencies [5]. Snake robots are a subset of bio-inspired systems that are a class of hyper-redundant mechanisms that move by replicating interval shape-changes inspired by snakes and worms [6]. The narrow cross-section area of a snake robot and the extreme range-of-motion of the joints allow it to navigate many diverse environments, including pipes, channels, uneven ground, and internal hard-to-access areas [7]. This makes them applicable in a wide range of diverse operations, such as urban search-and-rescue in unknown and unstructured terrains of collapsed mines and disaster zones. For example, the use of inspection and rescue robots played an important role in emergency-response to the nuclear accident at Fukushima Daiichi nuclear power plant [8, 9]. Particularly, the harsh environments of nuclear applications demand a reliable and resilient robot. Snake robots are well-suited to pipe inspection applications due to their ability to actively locomote in a wide range of pipe diameters and configurations with a single mechanism. Due to these advantages, snake robots have a wide range of applications including pipe inspection [10]; automated search and rescue operations [11, 12]; visual and nondestructive inspections of city gas [13] and water mains [14], monitoring of power plants [15], nuclear facilities [16], and onshore oil and gas industries [17, 18].

South Dakota is ideally located, neighboring of some of the nation’s most oil and gas reach states including North Dakota, Wyoming, and Colorado, where pipelines are in widespread usage and pipe-inspection and repair is important. To establish pipe inspection and repair capabilities at the Advanced Intelligent Mechatronic Systems (AIMS) research laboratory of the South Dakota School of Mines and Technology (SDSM&T), several design challenges must be addressed particularly in pull force capacity. The same redundancy that provides snake robots with superior dexterity also poses significant challenges, particularly due to the limited load-carrying capability [19]. Two of these limitations that this current research is targeting to overcome are: a.) a lack of sufficient payload-carrying capability for repair equipment in long piping with multiple bending and variations in dimension and b.) an inability of nondestructive evaluation algorithms to cope with in-field inaccuracies of measurements and strict field deployment regulations. Specifically, the current research objectives are aimed to: 1.) develop and implement a novel bio-inspired mechanism for locomotion of robots to significantly increase the payload-carrying capacity, allowing it to carry equipment and conduct damage identification and mitigation and 2.) develop and implement state-of-the-art nondestructive evaluation algorithms for reliable autonomous in-pipe damage characterization.

2. ANALYSIS

2.1 Dimensional Requirement of Modules

The maximum length and width of an individual module to move around bending segments of piping are related to each other. To find theses values first the maximum possible length of a rod L such that it could move around a corner with entrance diameter of A and exit diameter of B (shown in the Figure 1) is calculated. The length L should be minimized with in terms of the angle θ.

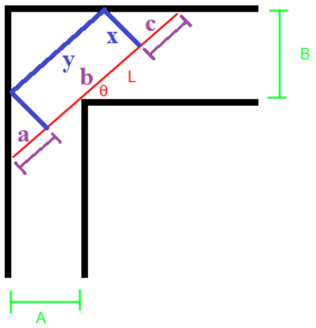

Figure 1. Maximum dimension of module feasible moving around a bending with variable corridor diameters

The length L could be formulated by being expressed in terms of the angle θ formed between the wall and the rod:

$$\boldsymbol{L = \min_{0 \le \theta \le \frac{\pi}{2}} \left(\frac{A}{\cos\theta} + \frac{B}{\sin\theta} \right)}$$

To minimize the length L in terms of the angle θ, the derivate $\frac{dL}{d\theta}$ is calculated and set equal by zero:

$$\boldsymbol{\frac{dL}{d\theta} = \frac{A\ \sin\theta}{\cos^2\theta} - \frac{B\ \cos\theta}{\sin^2\theta} = 0}$$

By doing so the angle θ is found as:

$$\boldsymbol{\theta = \arctan\left(\frac{B}{A}\right)^{\frac{1}{3}}}$$

By substituting θ back into the original equation for maximum length L will be obtained as follows:

$$\boldsymbol{L = \left(A^{2/3} + B^{2/3}\right)^{3/2}}$$

According to the geometry shown in the Figure 1 the dimensional requirement of a cylindrical module in terms of its diameter $\boldsymbol{x}$ and length y is found as:

$$\boldsymbol{L = x\tan\theta + y + \frac{x}{\tan\theta}}$$

This concludes that dimensions of the modules are related to each other and choosing one will dictate the other.

2.2 Cam Profile in Four-Follower Face Cam Mechanism

Inside the instrumentation module, a four-follower face cam mechanism is used to convert the rotational motion of stepper motor to translational motion of followers in the radial direction. This way, the NDE sensors that could be installed at the end of followers, will extend radially and contact internal surface of the pipe to engage in proper NDE operation. Design constraints for cams are [20]:

- The cam function must be continuous through the first and second derivatives of displacement across the entire interval of 360°.
- The jerk must be finite across the entire interval.

The simple harmonic cam profiles cause discontinuous acceleration and infinite jerks at the follower and therefore are considered bad cam design choices. In this study, the cycloidal cam profile is selected for as the cam profile and implemented for the grooves that guide the slider. The equation for a cycloidal cam has a cycloidal displacement as follows:

$$\boldsymbol{s = \frac{h}{\beta}\theta - \frac{h}{2\pi}\sin\frac{2\pi\theta}{\beta}}$$

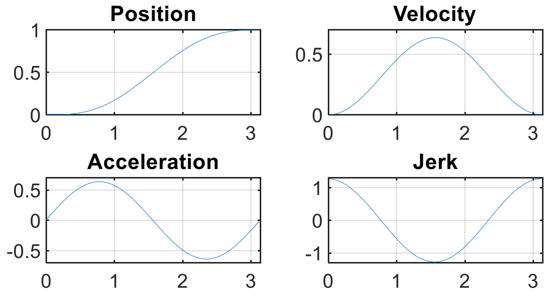

Figure 2. Cycloidal cam profile and motion parameters

The dynamic motion parameters of the follower for a cycloidal cam are shown in the Figure 2. The choice of this cam is a valid design decision since there are no discontinuity or infinite values observed in the acceleration and jerk diagrams.

2.3 Actuating force and gripping forces

In the design of the crawler, a stepping motor with an integrated threaded rod is used as a linear actuator. The lead screw with a traveling nut converts the rotational motion to linear motion and transmit the actuating force. The claws of gripper have the structure of slider-crank mechanisms with traveling nut as common slider. Although due to frictional losses the lead screws don't have a very high efficiency but generally they are self-locking. This feature is employed to hold loads in the modules and grippers and allows to release the motors. For this design, the

NEMA 17-size hybrid bipolar stepping motor with a built-in lead screw in place of the normal output is used. The specifications of the stepper motor with the lead screw is give in Table 1.

Table 1. Specifications of stepper motor with the lead screw

Stepper Motor	**Type**	NEMA 17-size
	Dimensions	42.3 mm square × 38 mm
	Steps per revolution	200 (1.8° step angle)
	Linear step size	40 µm (1.6 mil) per full step
	Current rating	1.68 A per coil
	Voltage rating	2.8 V
	Holding torque	3.7 kg-cm (51 oz-in)
Leadscrew	**ISO**	Tr 8 × 8 (P2)
	Shaft type	threaded rod
	Number of leads	4
	Original length	18 cm
	Acme thread form	trapezoidal
	Diameter (d)	8 mm
	Lead (l)	8 mm
	Pitch (p)	2 mm

The linear actuating force could be found from the formula for torque T required to lift or lower a load F. This calculation can be conducted by knowing the parameters of lead screw:

$$T_{L/R} = \frac{F\, d_m}{2}\left(\frac{\mp l + \pi\, f\, d_m \sec(\alpha_n)}{\pi\, d_m - f\, l \sec(\alpha_n)}\right) + T_c$$

Where indeces L and R indicate lowering and raising torques, respectively. f is coefficient of friction between stainless steel threaded rod and copper alloy travelling nut and is equal to 0.15. The mean diameter d_m and the normal pressure angle are found as:

$$d_m = d - \frac{p}{2} = 7mm$$

$$\alpha_n = tan^{-1}(\tan(\alpha) * \cos(\theta))$$

Where α is the half of the thread angle considering that the Acme type has a 29° thread angle. The lead angle θ is found from:

$$\tan(\theta) = \frac{l}{p\, d_m}$$

Knowing the maximum torque provided by the stepper motor being 37 kg-mm, a total actuating force of 188.94 Newtons (19.26 kg) is attained from the above formula. To find the overall pull force of the robot, a static analysis needs to be conducted to obtain the reaction force at the contact point of each claw with the pipe:

$$\sum M_O = 0$$

$$F = \frac{B\, b \sin(\alpha + \beta)}{L\,(\sin(\beta) + \mu \cos(\beta))}$$

Where α and β depend on the geometry (see Figure 3) and could be calculated from:

$$r2 + L\cos(\beta) = R$$

$$r1 + a\cos(\alpha) + c\ \cos(\beta) = R$$

B is the portion of the actuating force transmitted to each claw and depends on the number of claw:

$$B = \frac{F/n}{\sin(\alpha)}$$

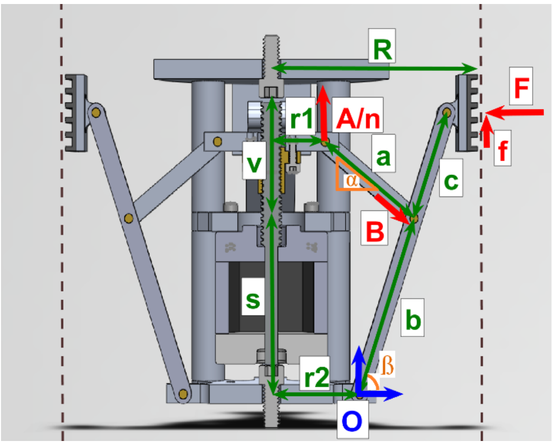

Figure 3. Pull force analysis based on the actuating force

The overall pull force is generated from effects of friction forces at the contact pads and depend on the coefficient of friction (Figure 4).

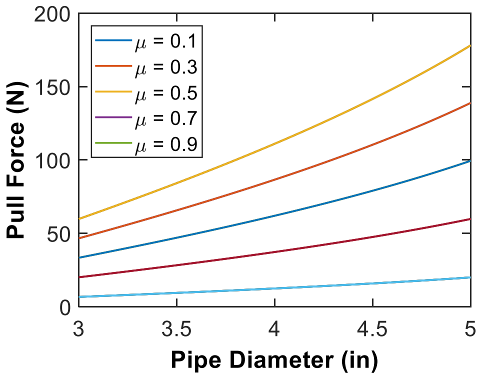

Figure 4. Pull force versus pipe diameter for various coefficient of friction between the pipe and claws

3. DESIGN

This research is comprised of three distinct yet complementing tasks each defined within development of certain modules of the pipe crawler.

3.1 Bio-Inspired Locomotion

First task is to develop and implement a novel bio-inspired mechanism for the locomotion of a robot and to significantly increase the payload-carrying capacity, allowing it to carry and conduct damage identification and mitigation equipment; The objective of this study is to develop a robotic field deployable inspection and repair crawler with nondestructive evaluation capability. Sure method adopted from structural health monitoring community [21-26] will be deployed for addressing primarily pipe inspection needs. The bio-inspired peristaltic locomotion previously has been effectively utilized in developing customized robotic crawlers for hazardous and remote areas of nuclear waste storage piping and tanks at the DOE-EM Hanford Site [27-29].

To provide collaborative robotic support for human personnel performing inaccessible inspection and repair tasks from internal pipe and tank areas, there is a need for inspection robotic tools that can identify the location, type, and extent of internal defects. The crawler will perform both inspection and repair of pipes and identify the defective location. For this inspection, SDSM&T will be designing a pipe crawler, a bio-inspired snake robot that uses the peristaltic movement for locomotion. A preliminary design of locomotion module that has been developed using the lead screw stepper motors in shown in Figure 5.

Figure 5. Preliminary design of pipe crawler for locomotion modules and grippers

3.2 Non-Destructive Evaluation and instrumentation module

Second task is to implement state-of-the-art nondestructive evaluation algorithms for reliable autonomous in-pipe damage detection and characterization. The new robot will have a modular design with the use of interchangeable cylindrical modules connected with a pair of universal joints. The forward motion of the robot is generated by using peristaltic movements via compact cylindrical linear actuators and two gripping mechanisms. A front camera module will provide a live video feedback. In addition, a separate instrumentation module will conduct NDE inspection of the internal circumferential surface of the piping. The team is considering deploying a four-follower face cam mechanism shown in Figure 6 to convert the rotational motion of a motor to linear motion of followers.

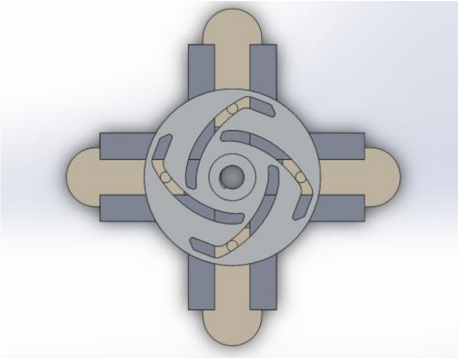

Figure 6. Four-follower face cam mechanism, the NDE transducers will be installed at the end of followers

Therefore, by extending NDE transducers to contact the 4. inch diameter pipe and conduct thickness and corrosion measurements. Integration of additional sensors including radiation motioning is also be possible, allowing conduct required measurements according to inspection mission. The nondestructive evaluation process is fully automated, and a tether will enclose the communication and power lines. The instrumentation module will be compatible with the requirements of nuclear environment inspection procedures and may include NDE capabilities such as visual, ultrasound, EMAT, laser-depth, or non-contact thickness measurements. A rendering graph of the instrumentation module is shown in Figure 7.

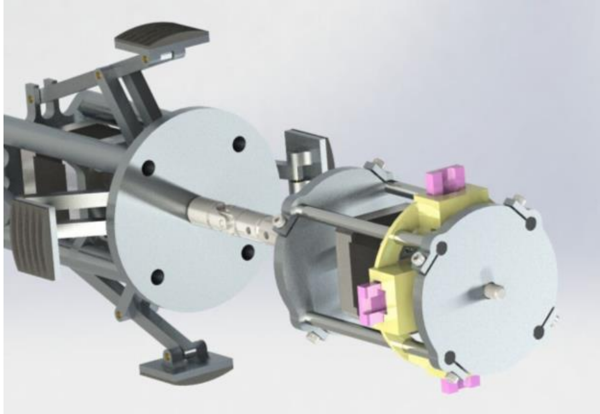

Figure 7. Four bar face-cam mechanism integrated to the instrumentation module

3.3 Maintenance and Damage Mitigation using Cold Spray

Third task is to deploy the cold spray process which is schematically shown in Figure 8. This process, also known to as supersonic particle deposition, is a high-energy solid-state coating and powder consolidation process. Cold spray uses an electrically heated high-pressure carrier gas, such as nitrogen or helium, to accelerate metal powders through a supersonic nozzle above a critical velocity for particle adhesion. The bonding occurs when a combination of mechanical interlocking and metallurgical bonding from re-crystallization at highly strained particle interfaces. Cold Spray can create mixtures of metallic and nonmetallic particulates to form a coating or free-standing structure by means of ballistic impingement upon a substrate. The

Cold Spray process is applicable to corrosion-resistant coatings, dimensional restoration and repair, wear-resistant coatings, and electromagnetic interference (EMI) shielding.

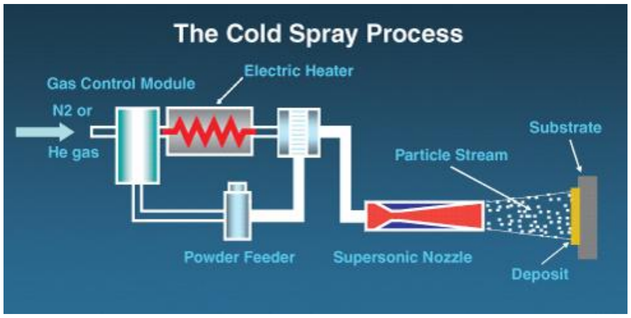

Figure 8. Schematic of the Cold Spray Process [30]

Cold Spray is in the family of thermal spray processes; however, it has the lowest overall temperatures and highest velocities of the thermal spray family. As a result, cold spray coatings are deposited in the solid state and possess the highest strengths of any thermal spray process. Cold spray coatings cause almost no microstructural changes in the powder materials deposited except for extreme plastic deformation, and it does not increase the oxide content in the coating over the base oxygen level present in the starting powder. The modular design approach, along with improved load-carrying capacity, will allow incorporating additional additive repair technologies. Upon diagnosis of pipe damage by instrumentation module the repair module will deploy a coating using cold spray material deposition process [30] compatible with the requirements of nuclear environments. The repair module will integrate the high-pressure metal deposition applicator for temporary-damage mitigation developed by collaborating research partner. A cold spray applicator installed on a robotic arm at AMP center of SDSM&T is shown in Figure 9.

Figure 9. High pressure metal deposition applicator on a robotic manipulator at AMP lab of SDSM&T

The robotic inspection tools will be connected to the user through a tether comprised of power and control lines; a cable management system will automatically supply and retrieve the tether. The system will also be able to help with localizing the robot and identifying the extent of damage inside pipes and tanks with the desired accuracy and conduct the repair process accordingly. During the design and development process, the team will communicate with research partner to effectively establish the components of design according to government Technology Readiness Levels (TRL) and nuclear deployment requirements. A full assembly rendering of the robot is show in Figure 10.

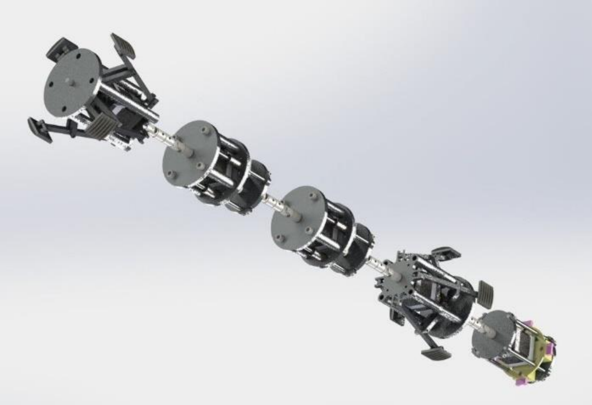

Figure 10. Assembly rendering of current design of robot

4. Conclusion and Future Work

The design and architecture of a novel modular pipe inspection and repair robot is presented. In the process of designing of the pipe crawler influential parameters for maximizing pull force and functionality were considered including torque, module size and NDE sensor requirements. The results are a design with high pull force output yet small module dimension and weight. In addition, integration of a four-follower face cam mechanism in the instrumentation module allows the NDE sensors to make contact between with the internal pipe wall and measure the characteristics of the pipe interior surface condition. We believe that the current modular design will lead to a robust inspection robot and as the next step the design team will be building and testing a prototype of robot were several areas for improvement areas will be identified and implemented.

The repair module will be designed and incorporated to the robot via close communication with our collaborating research team who are specialized at additive repair processes. This collaboration will be significantly facilitated through our access to high pressure cold sprayed deposition facilities of AMP center at SDSM&T. The instrumentation module has space for several additional sensors among which the radiation sensor has already been build and tested. Finally, the integration of a module for a visual inspection and measuring pull force are being evaluated.

5. ACKNOWLEDGMENTS

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