Sensorless Control of a Modular Hybrid Inspection Robot for Small Diameter Complex Piping

Inspection robot for difficult and complex piping systems

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Introduction

 Pipelines and piping installations are a vital part of many marine and underwater installations. These piping systems are often hard to access and therefore hard to maintain and inspect. These systems experience extreme variations in pressure and temperature and endure vibrations, impacts, the buildup of sediment, exposure to corrosive saltwater, and possible radioactive conditions. An ideal example of such a system would be a nuclear submarine (pictorial left). US Navy subs have hundreds of miles of pipes of varying diameters, materials, and construction that serve to circulate water in their nuclear power systems and to maintain attitude control by adjusting a complex system of buoyancy tanks. To maintain continual readiness, these systems must be maintained at great cost. For these reasons a partially autonomous robotic inspection and maintenance system is desirable.

 Many current robotic pipe inspection systems are incapable of dealing with the complexity and variation found in an application such as a submersible buoyancy system. These systems are challenging to navigate for the reasons listed below:

- Small pipes
- Varying pipe diameters with rapid changes (weld seams, flanges)
- Varying pipe orientations
- Tee joints
- Minor obstructions

 A pipe inspection robot must navigate all of these challenges while delivering a sensor payload, something even current bio-inspired designs are not able to do. Recently, hybrid systems employing multiple integrated locomotion methods have been shown more capable. These systems have yet to be fully developed for highly complex and variable piping systems. This project is an attempt to achieve this capability in a small diameter piping system.

Sensorless control

 One consideration for thiscrawler robot is the minimization of sensors in the locomotion system to increase reliability by removing possible points of failure. As such our prototype uses an open-loop control system for its stepper motors. As stepper motors are not damaged by stalling, we detect when the motor has stalled to determine when it has reached the pipe wall. This is done by monitoring the back-EMF of the motor and using it to determine when motor motion should be stopped or reversed.

 The control system of the pipe crawler is relatively simple. An Arduino microcontroller manages both the Shape memory alloy springs and drive module locomotion based on external input from another computer. This computer then receives input from the crawler operator in addition to a front mounted camera and any attached sensors. All electrical signals are transferred via a robust tether system designed to allow the robot to be retrieved in case of failure (full block diagram can be found below).

Sensorless control

Robotic Crawler

USB Camera
Stepper Motors
SMA Spring Actuators

Legend:
Solid line: Power
Dashed line: Signal

Legend:

SMA Spring

Tether

12V Power Supply

Variable DC-DC Regulator
Motor Controllers

RAMPS V1.4 Board

TCM2130 Stepper Drivers

Control Box

Laptop

Proposed bio inspired inspection robot

Our inspection robot is a hybrid of bioinspired inchworm and traditional legged systems. Additionally, the design is modular and redundant, allowing for a wide variety of sensor, inspection, and repair modules. The current objective of this project is to develop a semi-autonomous pipe inspection robot based on this innovative locomotion system. The current robotic system is to be outfitted with a sensor module to search for and record various pipe anomalies such as corrosion, erosion, deposition, pitting, surface cracks, thermal cycling and joint failure (examples of corrosion/erosion and surface anomalies can be found to the middle and left bottom respectively). Additionally, work is continuing to develop machine learning and vision systems to automate various robot functions.

Locomotion

This pipe crawler system functions on a hybrid Legged and Inchworm inspired system. Via one stepper motor per module the legs can be extended or retracted while simultaneously increasing or decreasing the tension between modules by altering the module dimensions. This creates an additional force balance in the intermodule joints that upon release from the pipe wall advances the clamping point of that module. Through this process the clamping point of each module is continuously moved forward advancing the robot (see the below figure for cycle). This type of motion is relatively common in the natural world and is known as peristalsis.

This system also has the added benefit of being able to conform to multiple pipe diameters (shown in the figure to the left). This capability also allows the crawler to “step over” small obstructions on the pipe wall by contracting the legs of the relevant module.

In addition to an innovative drive system the crawler also uses an innovative steering system (found in the figure below). The main turning system of the pipe crawler functions via four shape memory alloy springs positioned between the front two modules. This system creates small flexible linear actuators that can orient the contracted first module in any direction. Additionally, each module of the pipe crawler is connected by springs that allow the system to navigate any turn that its individual modules can fit through. Through this system the crawler can reliably traverse any pipe junction that is within the crawlers turning radius and diameter range.