Structural Vibration for Robotic Communication and Sensing on One-Dimensional Structures

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Abstract: Structural vibrations in waveguide structures are examined as a means of communication and sensing for networks of robots. Inspired by the observation that insects may use structural vibrations to communicate and to detect features of their environment, a centimeter-scale mobile robot equipped with a piezoelectic vibration-sensing element was constructed. Preliminary communication and sensing techniques are demonstrated through experimental results.

Keywords: Structural Vibration, Communication, Sensing, Bio-Inspired Robotics

1 INTRODUCTION

Creatures in nature transmit and receive information at high speeds using structure-borne vibration. Up to 70 % of insect species may use substrate vibration of some form to communicate [1]. In particular, many species of caterpillar communicate by producing and responding to sounds and substrate vibrations [2, 3].

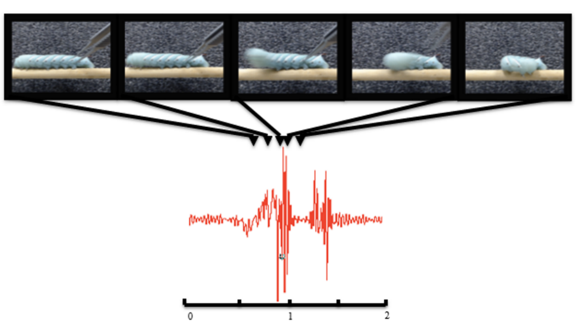

Figure 1: *Manduca sexta* caterpillar on a wooden dowel exhibiting a strike reflex (top) and the resultant transverse vibration at the substrate (bottom).

Although Manduca caterpillars do not live in communities, they do produce trains of clicks (3 s trains, dominant frequency around 30 kHz) as part of their defensive behavior [4]. A vibratory response generated by striking behavior is illustrated in Fig. 1. Some species can discriminate substrate vibrations produced by abiotic influences (rain, wind), conspecifics, and predators [5, 6]. A recent phylogenetic and morphological study suggested that ritualized vibratory signals (produced by anal scraping) originated from walking behavior [7]. One possibility, not yet explored, is that, before vibration detection was used for active communication, it evolved for evaluating the mechanical properties of the environment. Surface texture, stiffness and slip can all be detected through oscillations in shear force (vibrations) [8, 9, 10].

A vibration communication and sensing system is proposed for mobile robots. This system would have advantages over RF communication in situations of limited spectrum and signal interference. Such *mechanocommunication* is also covert by excluding mechanically isolated devices from "listening." Vibrations can also be used to sense properties of the environment due to reflections at branch points or terminal points in the structure.

One-dimensional branching structures such as cables, structural trusses, pipes, and tracks, as well as natural structures like trees, are of particular interest for this application. Such structures are common both in nature and in human construction, and are important environments for robots tasked with inspection, material transportation, and surveillance tasks. The one-dimensional nature assures vibrations do not spread geometrically, potentially allowing for long range communication and sensing. The dispersive properties of bending waves in the vibrating structure can be exploited to give additional information about the environment that might not be available for nondispersive waves, such as longitudinal pressure waves.

Little prior work has been done on the use of structural vibrations for communication and sensing in robotics. In one instance, surface waves were used successfully for communication between robots on a common plate substrate using cross-correlation methods [11]. However, due to the two-dimensional substrate, this system lends itself only to close proximity distributed communication methods because the vibrations die out quickly due to both geometric spreading and absorption.

Localization on a plate substrate was achieved by measuring the variation of Time of Arrival (TOA) at each leg of a six legged scorpion robot with similar range limitations [12]. A similar strategy, Time Delay of Arrival (TDOA), was implemented for a microphone array mounted on a robot for localizing sound [13]. Microphones are also used in recent work in tactile sensing skins for robots, which utilize sensor node networks embedded in a flexible substrate to localize objects and characterize textures [14].

In another piece of prior work, acoustic reflectometry was used to remotely map complex tunnel networks, detecting distances to turns, turn types, and closures [15]; this application has more similarities to the method proposed here.

2 PLATFORM

A vibration-sensing mobile robot and track were constructed to develop the proposed communication and sensing schemes.

2.1 Test Environment

A simple test environment that a robot could traverse robustly and with low energy loss through damping, was needed. A track design was selected with three carbon fiber rails; two of the rails are for the robot to attach to and one rail allowing vibration transmission. The track was constructed in the shape of a closed loop, with the ability to add branches later (Fig. 2).

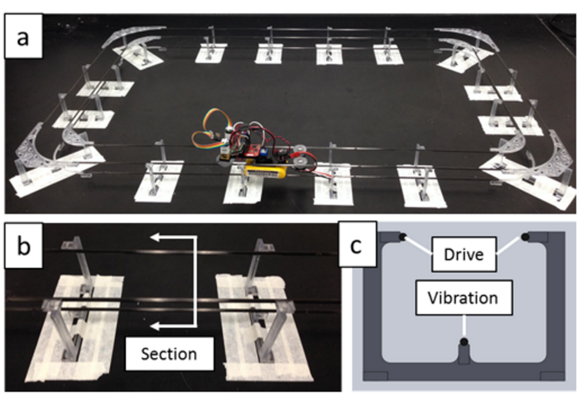

Figure 2: Robot navigating track (a), a close-up of the three-rail structure (b), and a section view along the track (c).

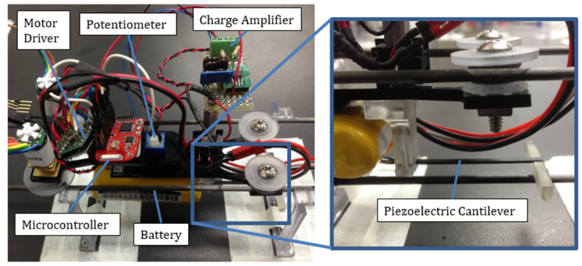

Figure 3: The placement of components on the robot (left) and a zoomed-in view of the piezoelectric transducer interface with the track (right).

2.2 Robot

The small (12 x 5 x 6 cm) robotic platform was developed to traverse the track environment and to sense vibration propagated through the bottom rail. A four-wheeled design was chosen, with the two front wheels driven by small geared motors, as shown in Fig. 3. Like wheels on a train, grooves in the wheels maintain alignment between the wheels and rails. In order to negotiate turns, the robot is split into two symmetric segments; which are pinned about an axis and give it a single degree of freedom.

Piezoelectric cantilevers mounted underneath the robot enable it to induce and sense vibration of the bottom track rail. These cantilevers are ideal for this application because they can be configured both as an actuator or sensor, have high sensitivity, and kilohertz bandwidth. Similar elements were successfully used to detect vibration in a robot scorpion [12].

Substantial analytical modeling has been conducted to predict the interaction of the piezoelectric transducers with straight segments of the carbon fiber track. This modeling has enabled the development of some preliminary communication and sensing schemes.

3 Communication

A simple example communication protocol was created for proof-of-concept. Fixed-frequency bursts of varying cycle lengths are transmitted to the track using a piezoelectric cantilever mounted directly to the track. A robot placed on the track uses a simple algorithm to listen for a burst and move forward depending on the duration of the detected burst - see Fig. 4. The dispersive nature of the beam makes single-frequency and amplitude modulation techniques attractive for potential communication protocols.

4 Sensing

A preliminary sensing scheme - separate from the robotic platform - was also tested to measure distance between actuator and sensor using standing waves.

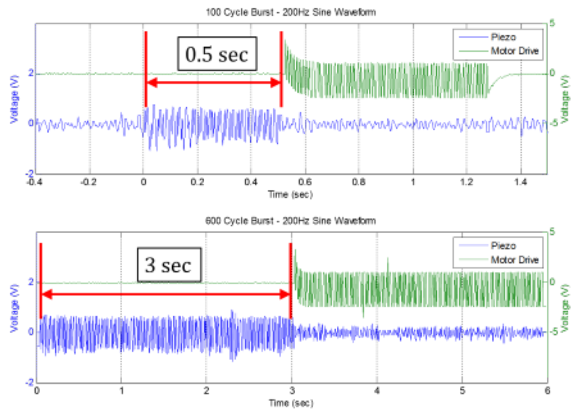

Figure 4: Sine wave burst detection: short drive command triggered by 100 cycle burst (top), a long drive command triggered by 600 cycle burst(bottom).

In a standing wave regime of a single frequency, the phase toggles between zero and 180 degrees at wave nodes. If the phase is interpreted as a binary code, for two simultaneously driven frequencies, this gives a 2-bit output with position resolution determined by the half wavelength of the shortest wave. This scheme was tested on a cantilevered acrylic beam driven by an electromagnetic shaker, and using a laser doppler vibrometer (LDV) to track the response at multiple points along the beam.

5 Conclusion

A vibration-sensing robot was built which can demonstrate a simple communication scheme. Additionally, a distance measurement technique is presented. Future work will further develop these techniques and apply them to multiple robots on a common structure.

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