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.

BACKGROUND

Some species of caterpillars can discriminate substrate vibrations produced by abiotic influences (rain, wind), conspecifics, and predators [1,2]. A recent phylogenetic and morphological study suggested that ritualized vibratory signals (produced by anal scraping) originated from walking behavior [3]. 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) [4,5,6]. A preliminary investigation of the kinematic adaptation exhibited in *Manduca sexta*'s crawling gait in the presence of substrate vibration, is shown in Fig. 1.

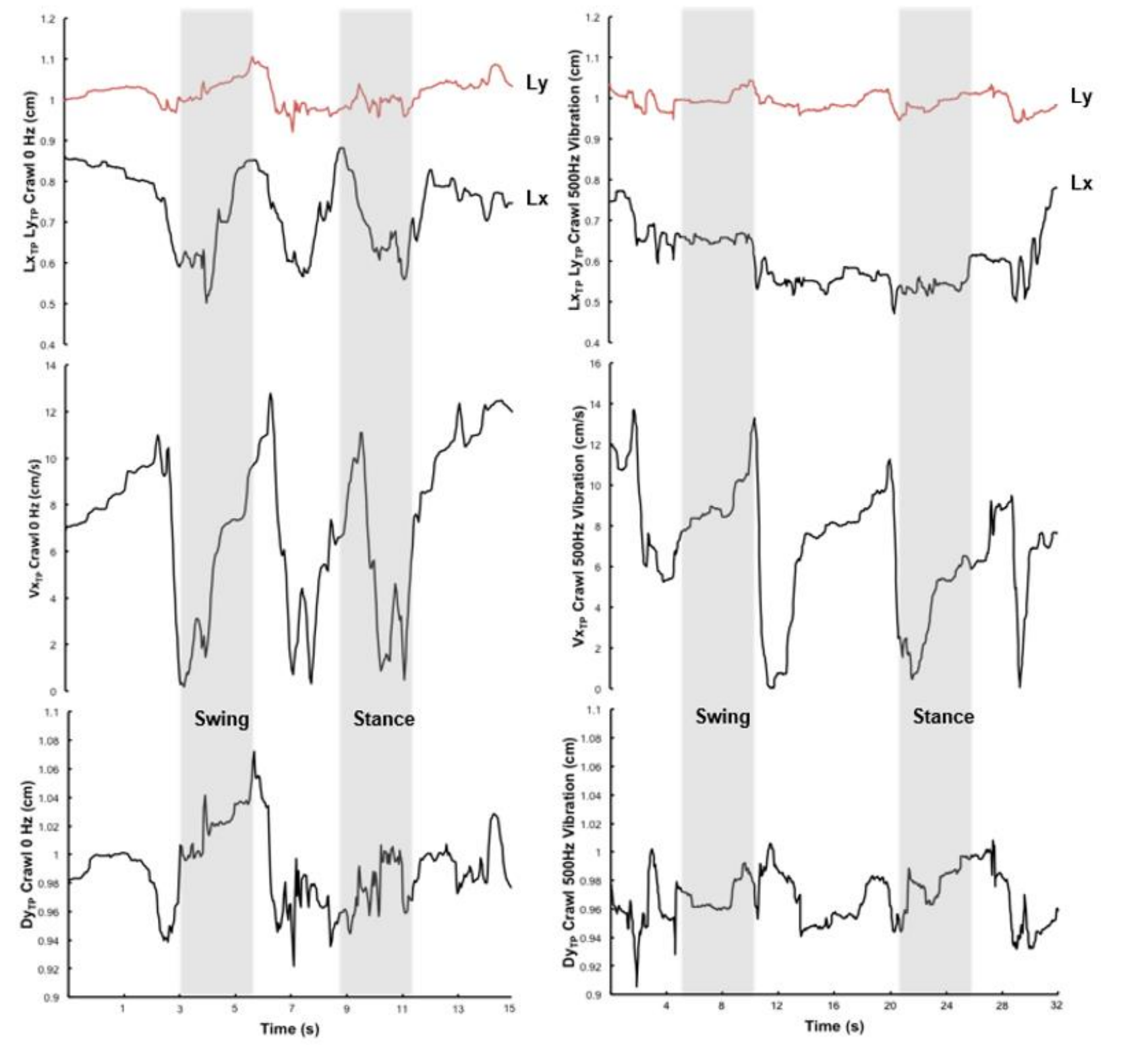

Figure 1. *Manduca sexta* crawling behavior kinematics on a stationary substrate (left), and 500 Hz vibrating substrate (right).

In the field of robotics the only applications of vibration-based communication and sensing used Rayleigh (surface) waves on flat (2D) substrates for inter-robot communication and localization [7,8]. Geometric spreading and absorption limit the range of this approach; the magnitude decays with the square root of distance from the source. Waveguide (1D) structures, which mitigate these losses and have the potential for longer range transmission, were selected as the target structures for this research. Branching structures such as cables, trusses, pipes, and tracks are of particular in this investigation, for applications in inspection, material transportation, or even surveillance.

ROBOT PLATFORM

A small (12 x 5 x 6 cm) mobile robotic platform, shown in Fig. 2, was constructed to test structural vibration-based communication and sensing strategies in a test environment structure. The platform navigates the structure using two motorized wheels and a PID controller to keep the wheels engaged. The platform uses the Texas Instruments eZ430-RF2500 target board. A piezoelectric bimorph beam is cantilevered underneath the platform to interface with test environment and detect any structural vibrations. A charge amplifier circuit conditions the output from the piezoelectric beam so it can be sampled by the microcontroller.

The test structure is similar to a track, with two rails to engage the robot's drive wheels, and one for vibration transmission – see Fig. 3. Carbon fiber rails make up the structure's rails. The high elastic modulus (275 GPa) carbon fiber contributes to a high wavespeed, for fast propagation. Additionally, the relatively low intrinsic damping of the material is ideal for transmitting mechanical energy with low loss, and the long slender rod geometry mitigates geometric spreading in the structure.

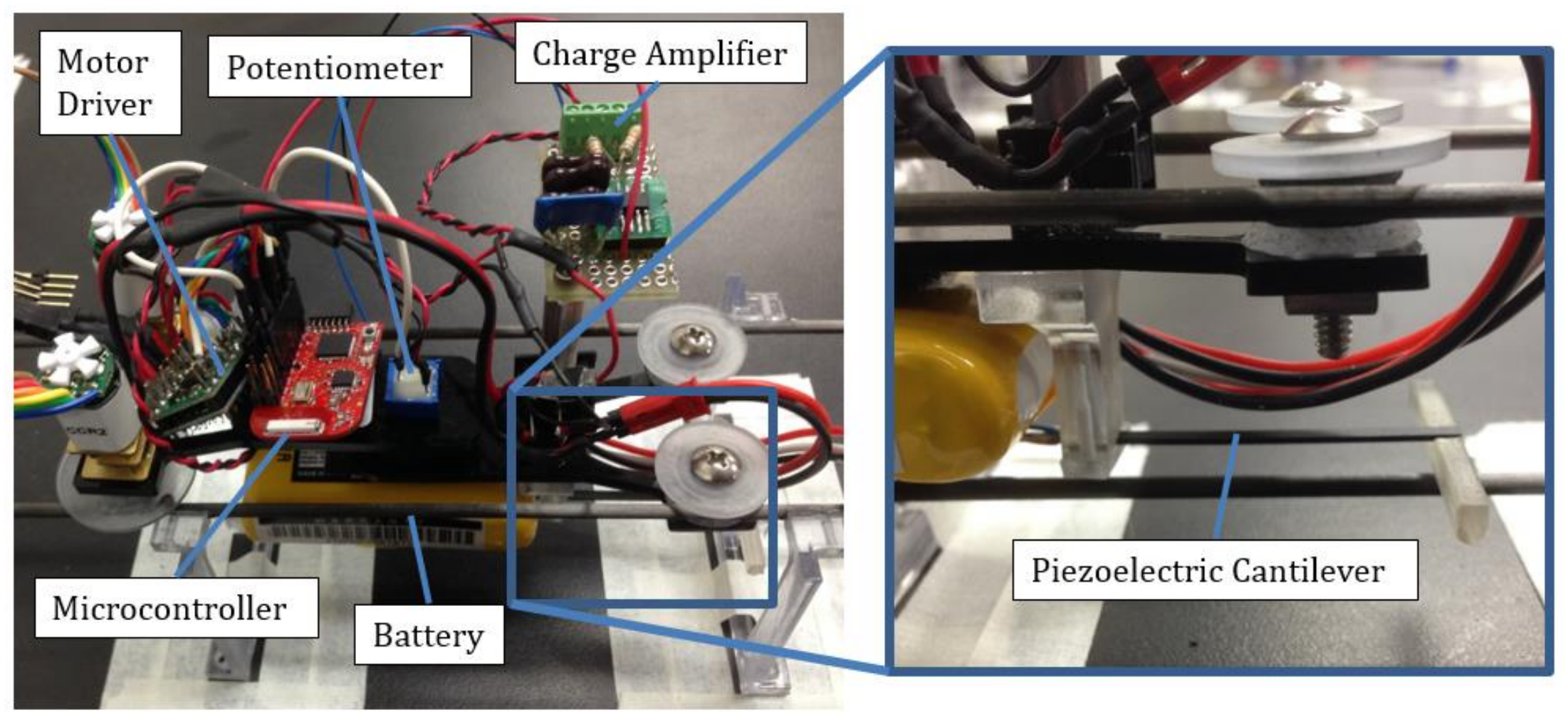

Figure 2. The robot platform (left), and a zoomed-in view of the piezoelectric sensing element (right).

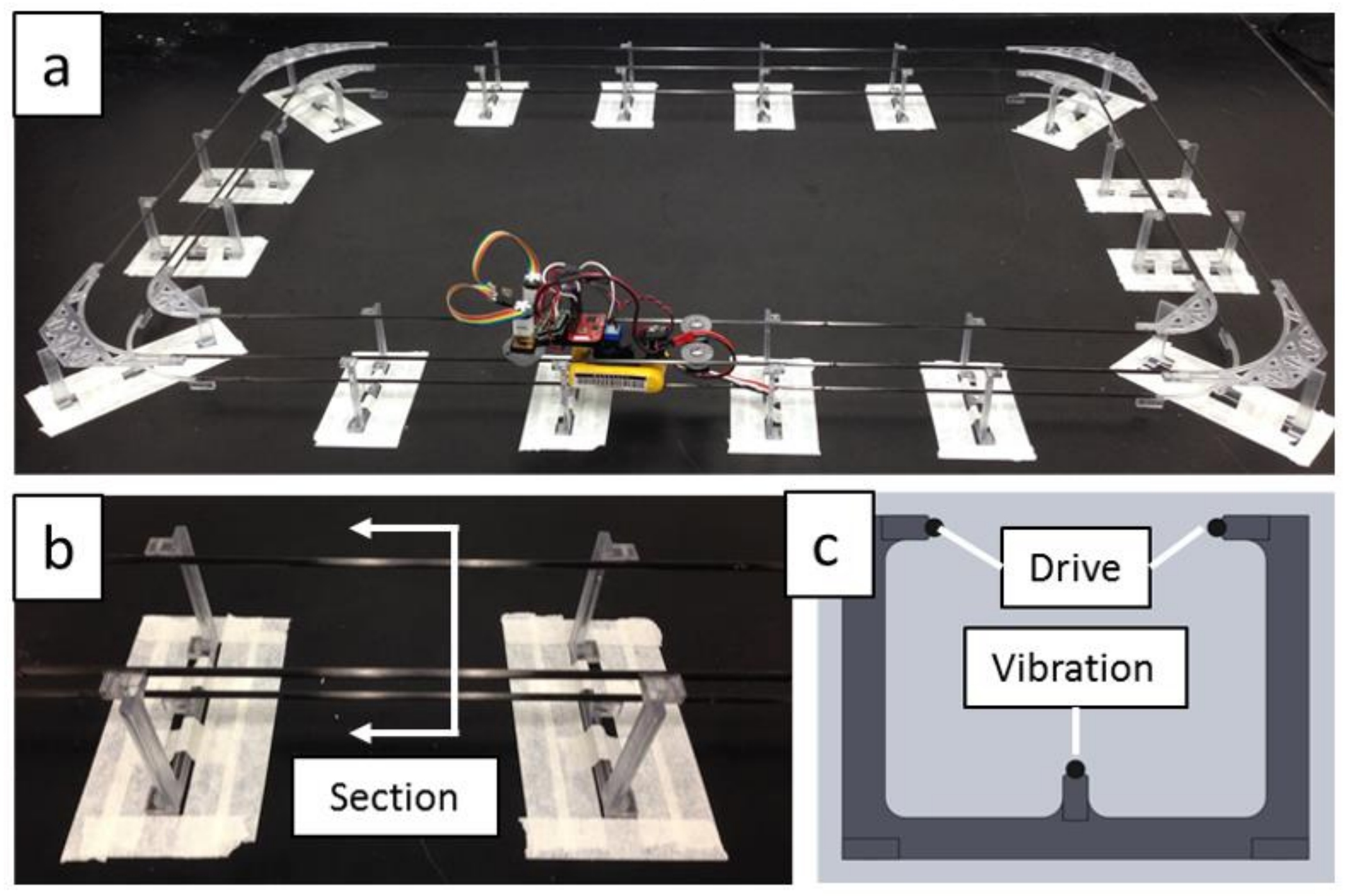

Figure 3. The test environment structure (a), a zoomed-in view of the structure (b), and a section view (c).

MODELING

A system-level model of the vibration TX/RX system was to understand the interaction between robot and environment. An analytical model was built based on the dynamic Euler-Bernoulli relation, giving an equation of motion of a carbon fiber rod subject to a periodic forcing $F_0e^{j\omega t}$ and appropriate loading configuration.

$$EI\frac{\partial^4 u}{\partial x^4} + \rho A\frac{\partial^2 u}{\partial t^2} = q(t)$$

$$F_0 = k_t V_{app}$$

$$k_t = \frac{-3d_{31}Ebh}{4L}$$

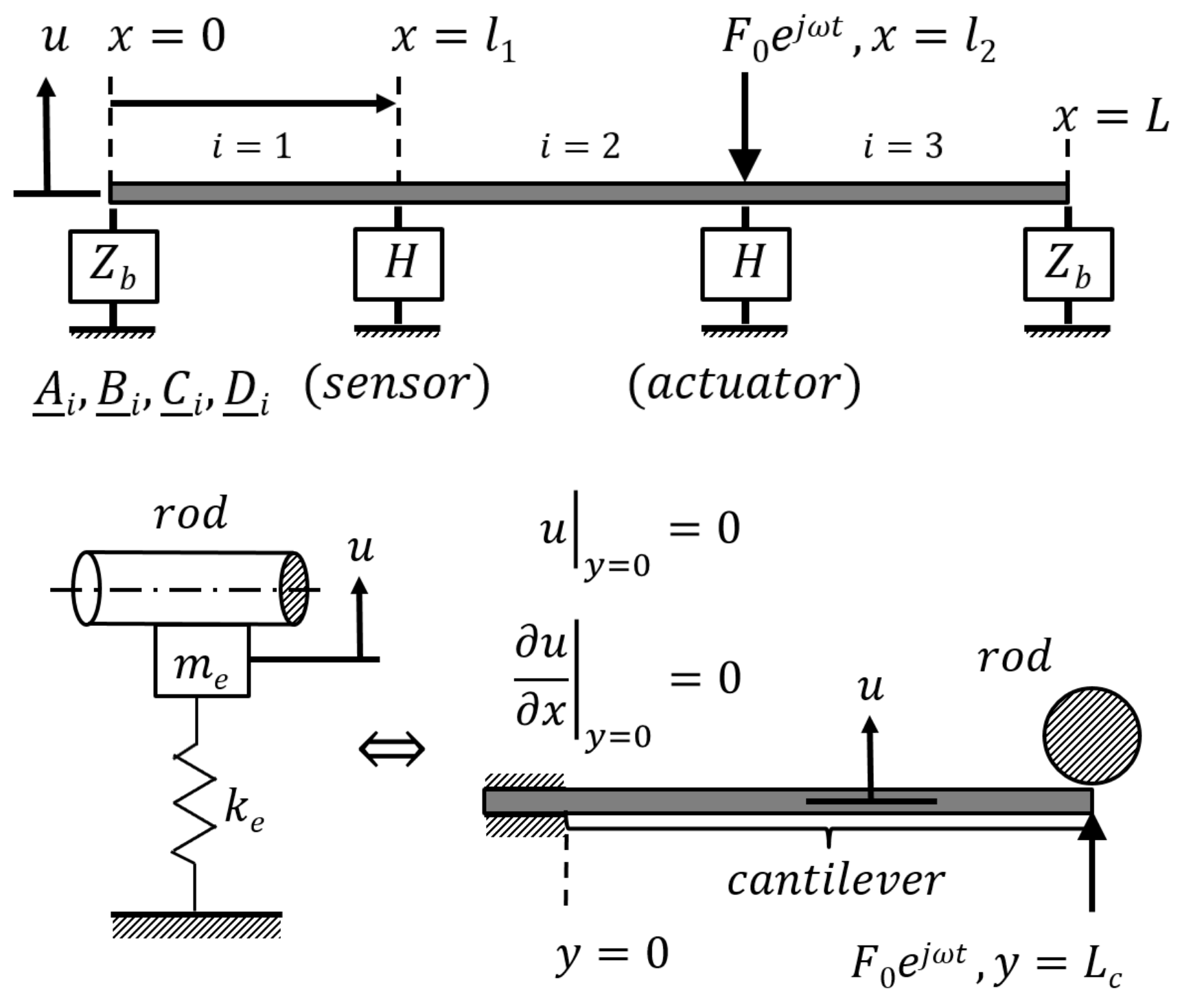

Figure 4. The piezoelectric cantilever modeled as a mass-spring system.

A numerical model was built to combine these elements, in addition to the electrical dynamics of the actuation and sensing electronics. The result matches the behavior of experimental data well.

SENSING

A preliminary sensing scheme - separate from the robotic platform - was also tested to measure distance between actuator and sensor using standing waves. 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 90 cm 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, shown in Fig. 5. This case only achieves a 11 cm/bit spatial resolution, but it is simple to imagine using eight frequency components (instead of two) to increase the resolution to 0.35 cm/bit. Bandwidth is the limiting factor of this scheme, as Fig. 5 shows, the next fundamental frequency is four times the previous.

$$BW = f_0(4^{N-1} - 1) \qquad R = L/N^2$$

COMMUNICATION

A proof-of-concept communication scheme to transmit commands between robots was developed using fixed frequency bursts. The robot listens for the bursts generated by a piezoelectric actuator mounted to the structure and measures the duration; different durations bursts correspond to different commands, as shown in Figure 8. A software high-pass filter makes the communication scheme robust to low frequency disturbances (such as bumping the table the structure is on).

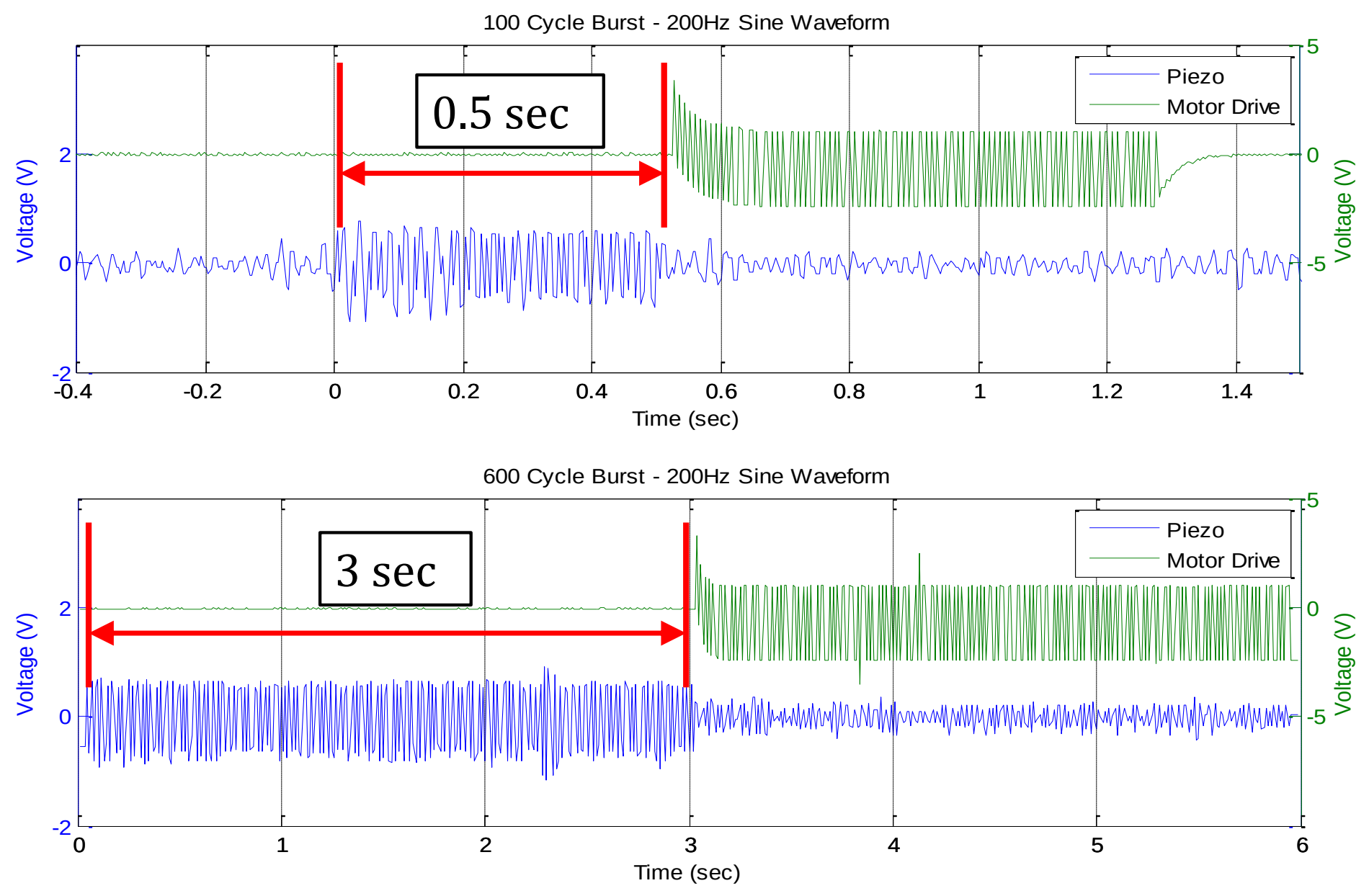

Figure 8. The robot detects 200 Hz bursts: a 100 cycle burst triggers motors to drive for 0.75 s (top), and a 600 cycle burst triggers motors to drive for 3 s (bottom).

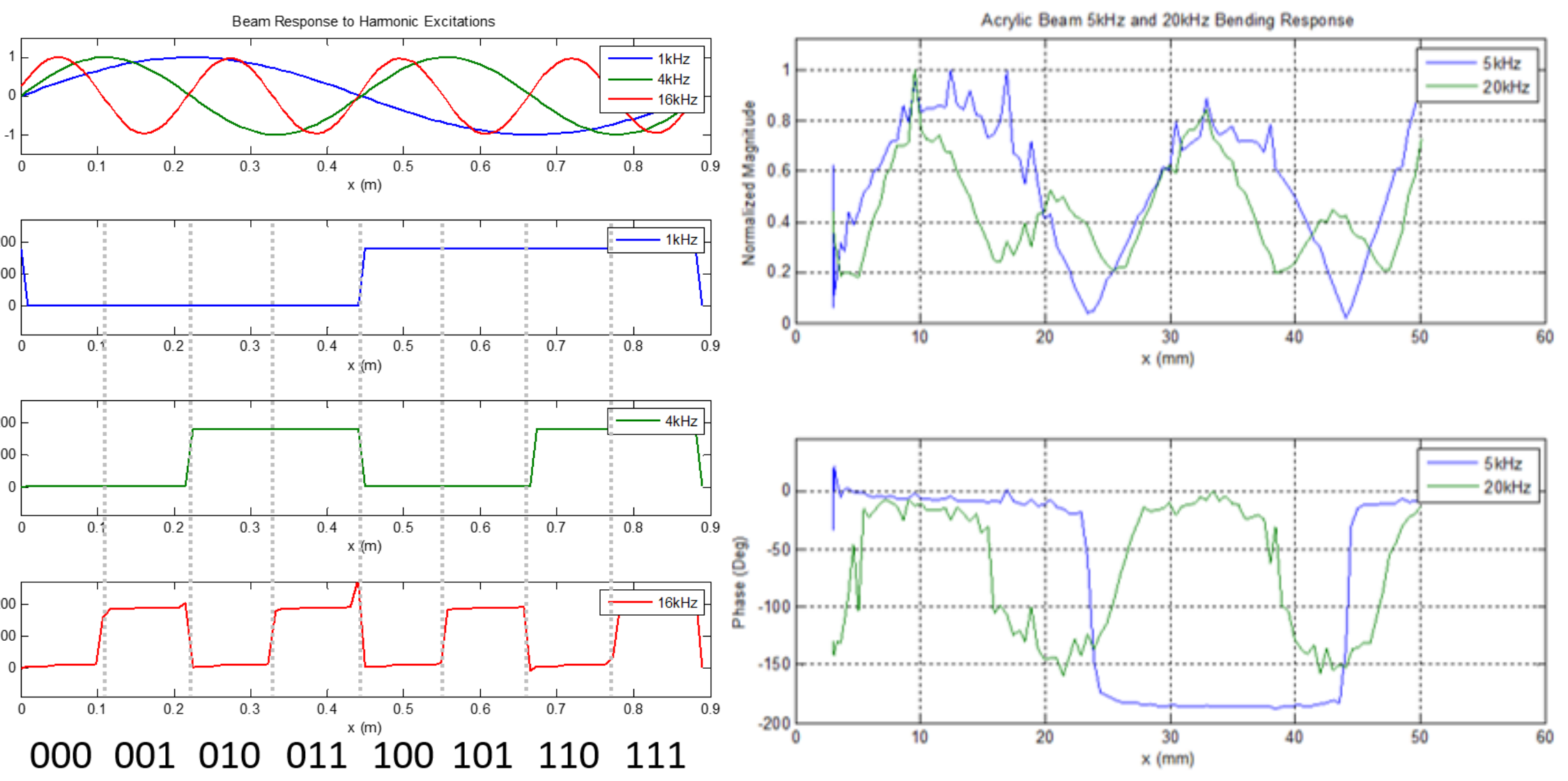

Figure 5. The simulated distance measurement scheme for a three frequencies (left), and the experimental results for two frequencies (right).

FUTURE WORK

In future work, sensing strategies for detecting track features will be developed. Multiple robot agents will be constructed to explore vibration-based distributed sensing and control schemes. The range limitations of inter-robot communication will also be explored.

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