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Kinect-based System for Automated Control of Terrestrial Insect Biobots

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Abstract— **Centimeter scale mobile biobots offer unique advantages in uncertain environments. Our previous experimentation has demonstrated neural stimulation techniques in order to control the motion of Madagascar hissing cockroaches. These trials relied on stimulation by a human operator using a remote control. We have developed a Kinect-based system for computer operated automatic control of cockroaches. Using image processing techniques and a radio transmitter, this platform both detects the position of the roach biobot and sends stimulation commands to an implanted microcontroller-based receiver. The work presented here enables repeatable experimentation and allows precise quantification of the line following capabilities of the roach biobot. This system will help refine our model for the stimulation response of the insect and improve our ability to direct them in increasingly dynamic situations.**

I. INTRODUCTION AND BACKGROUND

Bio-inspired design has become increasingly popular in the domain of centimeter scale robotics. Researchers have recognized the highly optimized nature of biological systems, particularly those of insects, and have attempted to replicate their capabilities in synthetic robots [1-11]. However, there is still a long way to go before these man-made robots come close to the agility of an actual insect. A synthetic robot that can pick itself up after a fall is a feat of artificial intelligence and engineering, but many living insects manage this task with ease. An alternative to the synthetic approach is to harness living insects to create biological robots (biobots).

While this research has implications for any field that relies on centimeter scale robotics, it is of particular interest to first responders at disaster sites. In situations of a building collapse or the release of dangerous chemicals, first responders rely on robots and other sensors to keep humans out of harm's way [12]. However, current robots are typically larger, tethered, and lack the mobility and robustness of insect biobots. The use of a cyber-physical system to analyze a disaster site and seek out survivors offers a great benefit to public safety.

For our work, we have selected *Gromphadorhina portentosa* (Madagascar hissing cockroaches) because their large size and slow speed makes them easy to work with, and their long lifespan and agility makes them ideal for search and rescue operations [13]. Our previous experiments have demonstrated the ability to precisely control cockroach movement through wireless neurostimulation for path following purposes. We now present an experimental platform using the Microsoft Kinect [14] to automatically detect the insect and direct it along a specified path.

II. PLATFORM FOR AUTOMATED CONTROL

A quantitative platform to analyze insect locomotion is essential for precise, direct comparison between experimental groups. Previously, we relied on subjective measures based on visual observation to determine whether one trial was any better than another. Our previous trials also required a human operator to manually trigger neurostimulation through a remote control [13]. Now, we demonstrate a computer vision platform that serves three purposes: (1) to provide a test bed that limits insect motion and creates a repeatable testing environment, (2) to track the roaches using a Kinect camera and computer vision software, and (3) to automatically stimulate the insects to move in a particular direction for path following exercises. A diagram of the major components of this platform is shown in Figure 1.

A. Kinect Camera and Test Bed

The test bed consists of a 90×90 cm^2 container with 15 cm tall walls (Fig. 1). A PVC frame surrounding the test bed provides support for Kinect. The Kinect has both an RGB and an infrared depth camera, which allows experimentation in both light and dark conditions, when the insects are most active. Both cameras capture 640x480 frames at 30 fps.

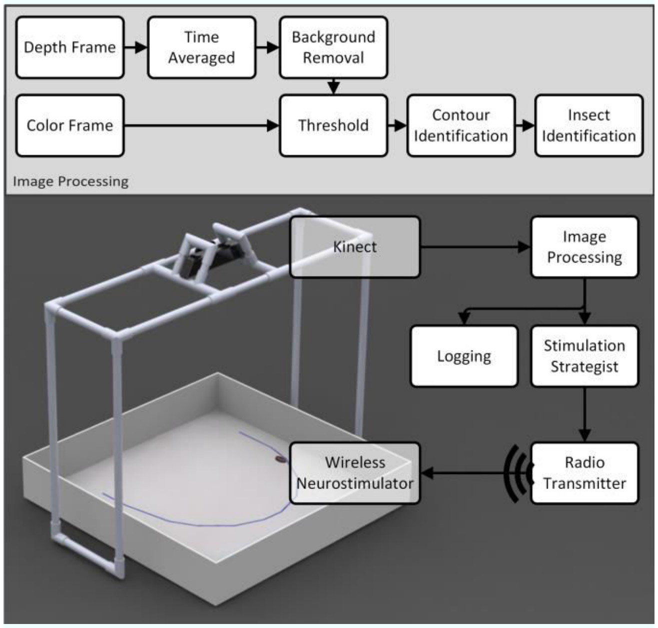

Figure 1. Components of Kinect-based automation system.

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B. Image Processing

Software was created to perform image processing on the live feed from the Kinect. Using the computer vision library, OpenCV, and the associated .NET wrapper, EmguCV, the insect is identified in the test bed in real-time. The processing algorithm first applies a Gaussian blur to the image to reduce noise and then thresholds the image to separate the dark roach from the light background.

For the depth feed, additional preprocessing is done to convert the depth image to a grayscale image. Because of imprecision in the depth camera and the need to detect depth differences on the order of 1 cm, each frame of the feed is temporally averaged with the past two frames. This averaged depth feed is compared to a snapshot of the empty test bed to determine raised regions of the image.

Contours are extracted from the image to identify potential roach locations. These are filtered by size, shape, and color. Temporal continuity is maintained by linking each roach with its closest neighbor from previous frames.

C. Stimulation Strategist

The software is given a predefined path, consisting of a set of waypoints, for the roach to follow. At regular intervals, the strategist compares the direction of the roach's current motion to the direction of the nearest waypoint. If these vectors differ by more than 25°, a decision is made to send a stimulation pulse to correct the deviation. This deviation threshold is based on previous experimentation with synthetic robots, but remains to be optimized for use with roach biobots. Both the frequency and duration of the pulses can be adjusted by the user. When the roach is within 4.5 cm of the current waypoint, the system moves to the next one and begins directing the roach toward it.

D. Radio Transmitter and Receiver

While this platform is compatible with a number of different transmitters, here we used a PIC microcontroller-based radio transmitter. The roach tracking software communicates with a National Instruments USB-6008 Data Acquisition Device (NIDAQ) [15] to interface with the transmission circuitry. Using a Serial Peripheral Interface Bus (SPI), the software programs a digital potentiometer. In conjunction with a PIC16F687 microcontroller [16] and an IA4220 FSK transmitter, this is used to send a pulse-modulated signal to the receiver on the roach.

The stimulation circuitry uses an IA4320 ISM Band FSK receiver along with a PIC16F630 microcontroller [17] to demodulate the incoming signal. Pulse width modulated (PWM) stimulation signals are sent to either the right or left antenna. This stimulation circuitry is housed on a "backpack" placed on the insect as shown in Figure 2.

Stimulation is achieved by surgically removing a portion of the flagellum and implanting 200 µm-diameter wire into each antenna. An additional insertion is made in the thorax of the insect to serve as a ground electrode. Stimulation takes the form of a monophasic 3.5 V pulse across the antenna and ground electrodes. The actual voltage drop across the tissue-electrode interface is less than 0.7 V to prevent tissue damage and oxygen evolution that would damage the interface [13].

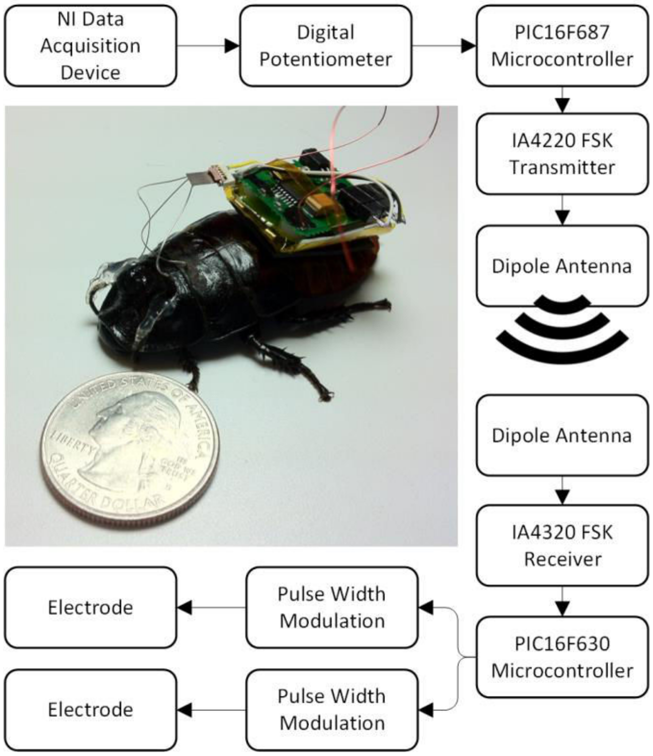

Figure 2. Components of radio transmission between PC and stimulation circuitry on insect. (Inset) *Gromphadorhina portentosa* with stimulation backpack and battery.

III. EXPERIMENTAL EVALUATION

A. Evaluation Procedure

For this path following exercise, a semielliptical path, consisting of 13 waypoints, was used as the target path. These exercises were performed in both the clockwise (cw) and counterclockwise (ccw) directions along the path. For each trial, the roach was placed just before the start of the path in the test bed, facing in the direction of the first waypoint. The computer vision system automatically detected the roach and began directing it along the path.

The analysis platform allows variation of the stimulation parameters as well as the frequency at which the strategist checks the position of cockroach. These trials used a fixed stimulus duration of 200 ms and a PWM duty cycle of 100%. Longer stimulation times generally led to a more pronounced turn by the insect. The position of the insect with respect to the waypoint was checked every 500 ms, resulting in a minimum inter-pulse duration of 500 ms. This duration was chosen to most closely mimic the manual stimulation technique described in [13]. A shorter duration tended to improve the ability of the system to make the roach follow the line. However, if this duration is too short, the next stimulus could preempt the desired reaction from the original stimulus.

B. Experimental Results and Analysis

Out of approximately 100 trials performed with four different insects, 27 trials reached at least 11 of the 13 waypoints. Of these, a set of ten successful trials was selected randomly for further analysis. In five of these trials, the roaches completed the path in the cw direction and in the other five trials, the ccw direction.

Figure 3 shows the location of the roach at various points along the path for a typical trial (see the video [18]). Without stimulation, the roach typically moved in a straight path. Upon application of the stimulation, the roach paused and turned in the appropriate direction. The average reaction time before a turn was 80 ms.

To quantify the success of these trials, the average orthogonal deviation from the desired path was computed. This metric was computed by dividing the area between the actual and target paths by the length of the target path. This procedure is described in (1). D(x,y) represents the orthogonal distance from a point on the roaches path, S, to the target path, P.

$$\frac{\int D(x,y)ds}{\int dp} \qquad (1)$$

Due to the discrete nature of the data, the area must be approximated using a trapezoidal approach as in (2). The jth waypoint is represented by w_j.

$$\frac{\sum(D(x_i,y_i)+D(x_{i+1},y_{i+1}))\frac{\Delta s}{2}}{\sum|w_j-w_{j+1}|} \qquad (2)$$

The average deviation from the path for these 10 trials was 2.85 cm with a standard deviation of 0.70 cm. There was no significant difference in the path deviation between the trials that followed cw and ccw directions.

The paths traveled by the insects in all ten of these trials are shown in Figure 4. The red lines indicate trials where the roach was directed in a cw direction around the path, and the blue lines indicate the ccw direction.

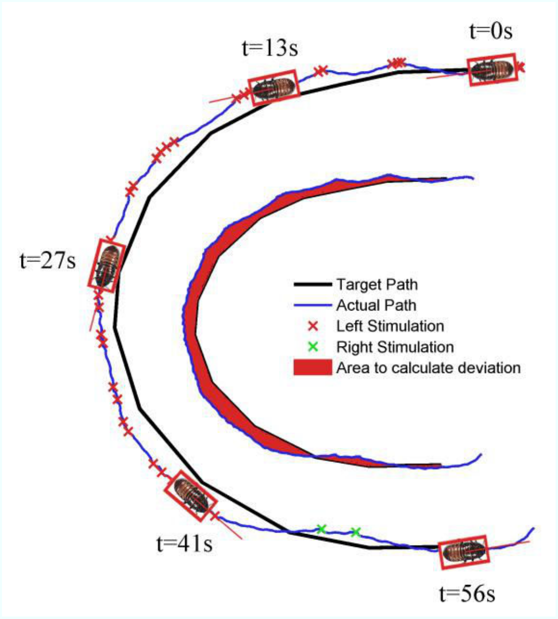

Figure 3. Path taken by roach in a typical trial (see the video [18]). (Inset) The same trial with the area between the actual and target paths shaded. This is used to compute the average deviation from the path.

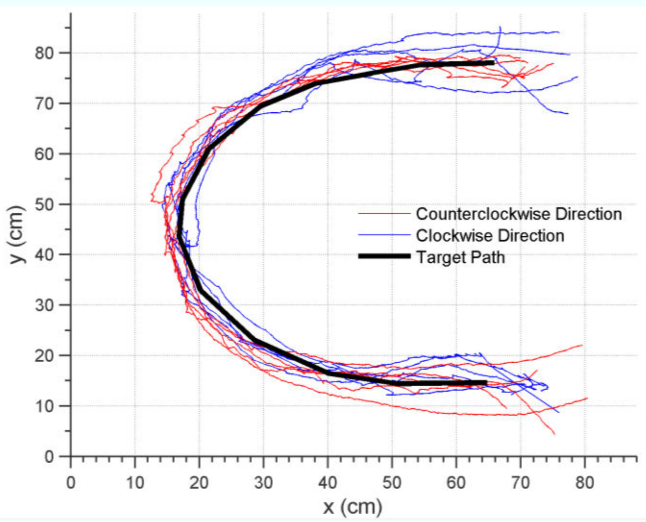

Figure 4. Paths taken by the insect in ten successful trials. The black line indicates the target path. The red lines represent roaches that traveled in the counterclockwise direction (from top to bottom) and blue lines represent roaches that traveled in the clockwise direction (from bottom to top).

Additional post-processing was performed on the data. For each turn induced by stimulation, two parameters were computed: (1) the net angular change due to a stimulus and (2) the angular velocity just after the start of the stimulus response. An analysis of these stimulation effects will aid in constructing an adaptive stimulation strategy. The turn angle induced by a stimulus is a simple metric that indicates the stimulation's effectiveness. Understanding the angular velocity at each turn provides more information that will be used in optimizing stimulation parameters.

The angular change was computed by taking the difference between the angle of the roach at the start of the stimulus and maximum angle it traveled before the next stimulus. The mean angular change was 11.8° in the direction of the stimulus. The distribution of these turn angles is shown in Figure 5. A negative angular change suggests that after a stimulus, the net direction of the roach opposed the stimulus direction. This occurred in only 2.9% of the 410 stimulations performed over these ten trials.

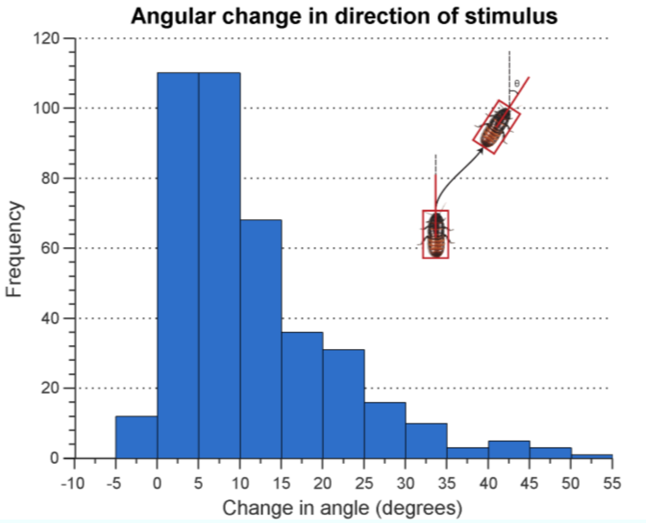

Figure 5. Histogram showing the distribution of angular changes due to a stimulus.

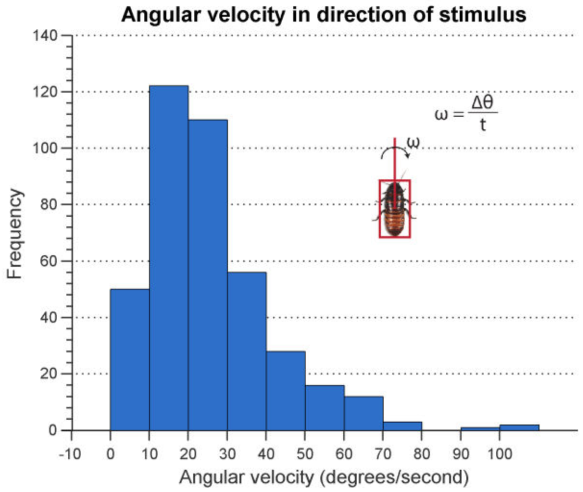

Figure 6. Histogram showing the distribution of angular velocities just after a stimulus.

The angular velocity, ω, of the roach just after the stimulus was computed by taking the change in angle divided by the reaction time. An analysis of the angular velocity just after the insect responds to the stimulation reveals a mean velocity of 23.1° per second. Only 2.4% of stimulations resulted in an angular velocity in the wrong direction.

IV. DISCUSSION AND CONCLUSION

The results presented here demonstrate the validity and effectiveness of our experimental platform for analyzing the motion of roach biobots and shows promise for achieving precise automation. The data from these trials suggests that each stimulus elicits an 11.8° turn from the roach. The average angular velocity after a stimulus was 23.1° per second.

This platform represents the first step in constructing a model of insect movement and stimulation response. It is hoped that such a quantitative model will help inform the stimulation strategist and optimize stimulation parameters. A precise estimate of the effects of each stimulus will allow us to stimulate more efficiently and reduce the likelihood of the insect's habituation to the stimulus. A prediction of the natural motion of the insect in a particular environment should help us time the stimulus application for maximum efficiency.

A quantitative analysis of an insect's stimulation response is important in optimizing the efficacy of the stimulation technique. We have demonstrated the first steps of this analysis by automating the stimulation process with our Kinect based platform, removing human factors, and conducting a preliminary analysis on the nature of the stimulation response. For this study, we performed our experiments without optimizing the surgical procedure and stimulation parameters such as number of waypoints or pulse duration. This resulted with a lower success rate and relatively larger distribution of angular change and velocity as seen in Fig. 5 and 6. Many experimental factors also seemed to affect the response of the roaches in these trials, including time of day, time since the surgical insertion, ambient light levels, and proximity to the walls of the test bed. Fortunately, this platform will allow us to conduct future studies that pinpoint and control these sources of uncertainty.

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