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Burst Stimulation for Enhanced Locomotion Control of Terrestrial Cyborg Insects

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Abstract— **Terrestrial cyborg insects are biohybrid systems integrating living insects as mobile platforms. The insects' locomotion is controlled by the electrical stimulation of their sensory, muscular, or neural systems, in which continuous pulse trains are usually chosen as the stimulation waveform. Although this waveform is easy to generate and can elicit graded responses from the insects, its locomotion control efficiency has not been consistent among existing literature. This study demonstrates an improvement in locomotion control by using a new stimulation protocol, named Burst Stimulation, to stimulate a cyborg beetle's antennae (*Zophobas morio*). Modulating the continuous pulse train into multiple bursts enhanced the beetle's turning responses. At the same stimulation intensity (amplitude, pulse width, and active duration), the Burst Stimulation improved the turning angle by up to 50% compared to the continuous waveform. Moreover, the beetle's graded response was preserved. Increasing the stimulation frequency from 10 Hz to 40 Hz raised the turning rate by 40 deg/s. In addition, the initial implementation of this protocol in the feedback control-based navigation achieved a success rate of 81%, suggesting its potential use to optimize further the autonomous navigation of terrestrial cyborg insects.**

I. INTRODUCTION

Bio-inspired mobile robots are developed by learning from living organisms' naturally evolved morphology and locomotion [1, 2]. However, it is still challenging for these robots to match their natural counterparts. As a potential alternative, biohybrid systems attempt to close this gap by incorporating living materials with fabricated components inside single entities, thus allowing them to possess both organic and artificial advantages [3, 4]. Such incorporation has helped researchers to overcome several challenging engineering tasks (e.g., manufacturing millimeter-scale actuators [5]), facilitating novel ideas (like biosensors [6], biosyncretic robots [7]), or benefiting contemporary studies (for example, animal-robot interactions [8]). In the case of artificial insect-scale land robots, biohybrid systems could play the role of an advanced alternative in the form of terrestrial insect-machine hybrid systems or cyborg insects.

These cyborgs consist of ambulatory living insects as mobile flatforms and miniature electronic devices/backpacks as central control units [9-13]. The cyborgs could be deliberately controlled to perform specific tasks, such as exploring complex environments like post-disaster sites [14]. Meanwhile, they still preserve essential natural characteristics of the insects, for instance, durable exoskeleton and muscles, flexible joints, proficient locomotion across complex terrains, and various organic sensors/receptors [14-19]. Also, their locomotion control was reported to consume power negligibly [10, 20]. Thus, these cyborgs could be a potential miniature and low-cost solution for complex terrain navigations, like search-and-rescue missions [14, 21].

The locomotion of these terrestrial cyborg insects could be controlled by electrically stimulating their sensory/muscular systems [9, 10, 12, 20]. Various stimulation methods were developed to diversify controllable motions and insect species. For instance, giant flower beetles' terrestrial and inflight motions could be manipulated by coordinately stimulating their thoracic muscles (*Mecynorrhina torquata*) [10, 22]. Reproducing the insects' natural behaviors, such as evasive and obstacle-avoidance responses, by the electrical stimulation of specific sensory organs, e.g., cerci, elytra, and antennae, in darkling beetles (*Zophobas morios*) and cockroaches (*Gromphadorhina portentosa*), could induce distinct motions, like acceleration, directional sideways walk, and left/right turn [9, 13, 14, 20, 23]. In addition, these motions could be graded by adjusting the stimulation parameters [10, 13, 20, 24].

Navigations of these cyborgs were also demonstrated. Manual path-following control was performed in several studies [9, 25]. Simple automatic navigation systems were then built to study the insects' behaviors [26] or display the backpacks' functionalities [21]. Despite the insects' physiological distinction, these systems usually employed a fixed stimulus across different individual insects, causing unreliable navigation [21, 26]. An efficient feedback control-based system was then introduced with significant improvements in the navigation's reliability and accuracy by regulating the stimulation signal according to the insects' instantaneous status [27]. Practical navigations were also demonstrated by incorporating the insects' natural behaviors with artificially designed control rules. For example, a predictive feedback navigation algorithm was reported to enable cyborg insects to maneuver across unknown environments while searching for lives [14].

In these studies, the continuous rectangular wave (or pulse train) was commonly used as the stimulation waveform [9, 11, 20]. Not only could this waveform induce the insects' locomotion, but it also offers a graded control by adjusting its parameters. For example, increasing its frequency and pulse width tended to elicit bigger turning angles when stimulating the antennae of darkling beetles and cockroaches, respectively (*Zophobas morios*, *Gromphadorhina portentosa*) [13, 24]. The leg's contraction/extraction speed of giant flower beetles could also be altered with the stimulation

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frequency (*Mecynorrhina torquata*) [10]. Such a feature favored the use of this waveform in developing feedback systems to control the cyborgs' motions, for example, path-following navigation [27], leg movement [10, 28], and walking gait [29].

Although it was widely implemented, this waveform's efficiency was reported differently across existing studies. Its parameters to maximize the insects' reactions were varied between reports despite being implemented for the same species [9, 21, 26]. Despite an effort to compare these works and optimize the stimulation protocol [11], the result was demonstrated manually, questioning its performance in automatic control. This waveform's efficiency was also discussed in other cyborg animals. The studies on inflight and aquatic steering of giant flower beetles (*Mecynorrhina torquata*) and catfishes (*Clarias gariepinus*), for instance, suggested that using stimulation signals in the form of multiple bursts instead of a long continuous pulse train could enhance the control outcome [30, 31]. I.e., the stimulated subjects were reported to have a higher control success rate and more natural-like reactions [30, 31]. However, the effect of such a burst-shaped stimulation on the locomotion control of terrestrial cyborg insects remained unclear.

Herein, this study demonstrates a significant enhancement in the locomotion control of an ambulatory cyborg beetle (*Zophobas morios*, Fig. 1A) when using the burst-shaped signal for its antennae stimulation. The beetle's response to this signal was up to 50% more profound than the continuous pulse train despite using the same stimulation intensity (i.e., amplitude, pulse width, and active duration). In addition, such a response still retained its graded manner, which would be applicable to developing efficient feedback control-based navigations for the cyborg beetle. Although further investigation is needed to fully evaluate the performance of this protocol in the beetle's autonomous navigation, it resulted in a success rate of ~81% with an error of half of the beetle's body length when tested with a feedback navigation system [27], which employed a simple proportional controller as its core and utilized a fixed gain of 0.5.

II. MATERIALS AND METHODS

A. Animals and Ethical Statement

Zophobas morios (~0.4-0.6 g, ~2-2.5 cm), a darkling beetle species, was selected for this study (Fig. 1A). Being relatively small, light, and possessing various controllable motions [13, 20], this species was suitable for cyborg insect studies. They were reared inside compartments of an animal housing system (~9000 cm^3/compartment, NexGen® Mouse 500, Allen Town®). Water, carrots, and vegetables were provided biweekly. Temperature and relative humidity were maintained at 25 ˚C and 60%, respectively. Although adult beetles can live up to 6 months [32], only 1-2 months old individuals were studied to minimize the aging impact [33].

Despite the lack of a standard ethical regulation for invertebrate and biohybrid research [34, 35], this study attempted to provide the beetles with appropriate treatments and good living conditions. The used temperature, humidity, and nutrition followed published instructions [13, 32]. The compartments were cleaned weekly to maintain hygiene and limited to 20 beetles/compartment to ensure spacious territories. Clean air was supplied by the housing system. After experiments, electrodes were removed from the beetles. The post-experimental beetles shared the same living conditions as the intact ones. Despite if the beetles feel pain still being discussed [36], the study anesthetized them before implanting/removing the electrodes as if they did.

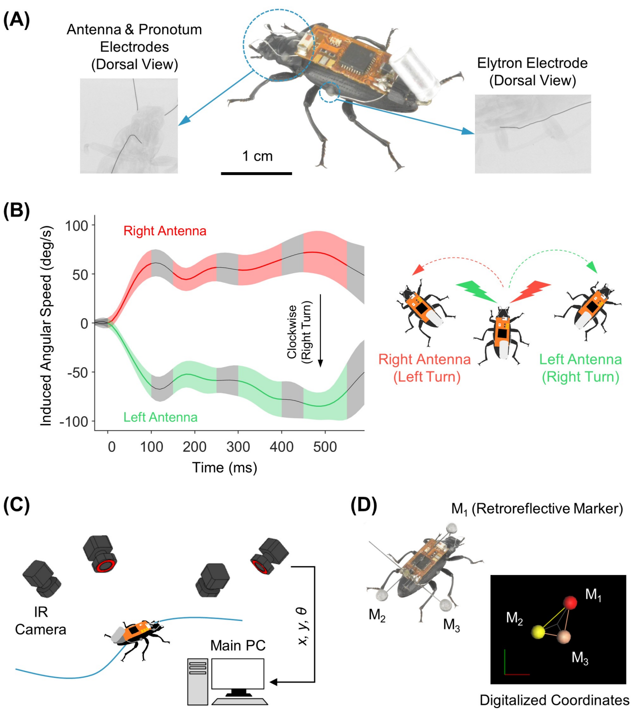

Fig. 1. Overview of the terrestrial cyborg beetle. (A) It consists of a darkling beetle with a wireless stimulator mounted on the elytra. The stimulator and battery weigh ~0.5 g. Inserts are X-ray images of the implants. (B) Representative data of the beetle's response to its antennae stimulation under Burst Stimulation. The beetle turns away from the stimulated antenna. Its angular speed promptly rises once the stimulus is applied. The red/green color represents the stimulation period of the right/left antenna. The black color denotes the stimulation-free duration. Data are shown as mean ± standard deviation (i.e., colored curves and shadow regions, respectively). (C) – (D) The motion capture system. The beetle's location data (x, y, θ) is tracked by four infrared (IR) cameras and fed to a central PC. Three retroreflective markers (~5 mg, 3 mm radius) enable this motion-tracking process. Their coordinate is digitalized and used to work out the location data.

B. Implantation and Wireless Backpack Stimulator

The detailed implantation procedure was described in previous works [13, 20, 27]. The beetle was first anesthetized using CO_2. Four working electrodes were then implanted into the beetle's antennae and elytra to elicit directional turns and forward accelerations, respectively (Figs. 1A-1B). The common electrode was implanted into the beetle's pronotum (Fig. 1A). All electrodes were secured with beeswax. The beetles then rested for an hour before the experiments. An electronic backpack (15×5 mm^2, Fig. 1A) was mounted on the back of the beetle using double-sided tape [27]. The backpack possessed a wireless control range of ~10 m using the microcontroller CC2650 of TI. It also supported eight stimulation channels with flexibly adjustable parameters, e.g., frequency. The backpack was powered by a rechargeable lithium-ion battery (3.7 V, 8 mA).

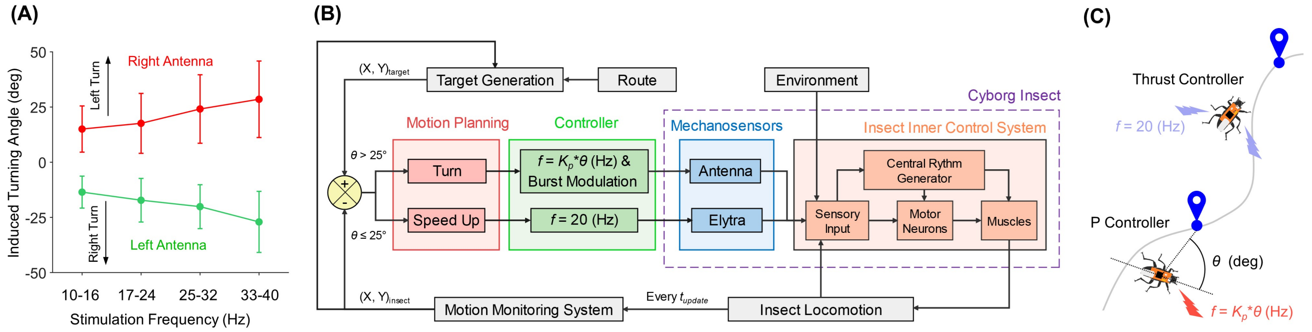

Fig. 2. Overview of the feedback control-based autonomous navigation system. (A) The graded response of the beetle to its antennae stimulation under Continuous Stimulation (53 ≤ stimuli ≤ 182 per frequency group) [27]. Higher stimulation frequencies likely induce larger turning angles (or faster turning speeds). Data are shown as mean ± standard deviation. (B) – (C) Diagram of the feedback system & depiction of the two controllers, respectively. The navigation commands, i.e., steering or accelerating, are determined through the beetle's location data. The angle θ is the orientation error between the beetle and its current target (i.e., blue dots). The P controller regulates the antennae stimulation frequency to steer the beetle ($f = K_p * \theta$), whereas the thrust controller accelerates it by executing the elytra stimulation. The antennae signal is modulated to generate the Burst Stimulation. Besides these electrical control inputs, the beetle possesses a complex internal control system. This system constantly gathers surrounding & proprioceptive information to adjust the beetle's locomotion, thus producing a robust and skillful maneuvering process [18, 40]. The location data is monitored by a motion capture system and fed to the navigation system periodically every t_{update} second.

C. *Electrical Stimulation*

The elytra were stimulated using a fixed rectangular stimulus having 2.5 V amplitude, 20 Hz frequency, 200 ms duration, and 50% duty cycle to obtain significant responses from the beetle [20, 27]. A similar continuous pulse train was employed for the antennae stimulation. Its amplitude, pulse width, and duration were set as 2.5 V, 2 ms, and 400 ms, respectively [13, 27]. In the antennae stimulation, the stimulation frequency was regulated by the feedback control system. The regulation range was 10-40 Hz to grade the induced angular speed proportionally (Fig. 2A) [13].

Besides this conventional stimulation protocol used for the antennae stimulation [9, 13], named "Continuous Stimulation," a new protocol, "Burst Stimulation," was proposed. This signal consisted of four stimuli (or bursts), separated by 50-ms-long stimulation-free periods. Each burst lasted 100 ms. Except for their waveform, the other parameters were identical between the two protocols, i.e., 2.5 V amplitude, 2 ms pulse width, and 10-40 Hz frequency (governed by the feedback control system). From a signal processing perspective, the new stimulation was established by modulating the original stimulus with a low-frequency carrier signal, i.e., ~6.7 Hz frequency and 66% duty cycle (i.e., 100 ms). Despite their structural differences, the active charging period (or the stimulation intensity) that the two protocols applied to the beetle were unaltered, i.e., 400 ms.

D. *Feedback Control-Based Autonomous Navigation System*

The control system periodically monitored the beetle's position and orientation (the angle θ, Fig. 2C), then regulated the stimulation accordingly [27]. The monitoring period was denoted as t_{update}, or update interval. The system consisted of two controllers, activated depending on the relative position between the beetle and its navigation target [27]. When the beetle faced the target ($\theta \leq 25$ deg), a thrust controller would accelerate the beetle via its elytra stimulation (Figs. 2B-2C). Otherwise, a proportional controller, or P controller, would steer the beetle to correct its orientation using the antennae stimulation (Figs. 2B-2C). The P controller would adjust the stimulation frequency correspondingly to the beetle's orientation, i.e., $f = K_p * \theta$, where f was the stimulation frequency, and K_p was the proportional gain (Fig. 2). The feedback system enabled the autonomous maneuver of the cyborg beetle along arbitrary, predetermined paths [27]. This path-following task was done in a carrot-chasing fashion (Fig. 2C, Movie 1 [27]). Several temporal targets the beetle navigated toward would be generated along the path. When the beetle approached a target, a new one would be established. This pursuing processing was repeated until the beetle reached the ultimate destination.

E. *Experiment Setup*

The experiment was set up to collect the beetle's locomotory behaviors under the Burst Stimulation and test this protocol's feasibility in the beetle's autonomous navigation, like that reported in this study's preceding work with "Continuous Stimulation" [27]. The feedback system navigated the beetle to follow a predetermined sine curve, $y = 170(2\pi x/850)$ (mm), from the origin to the destination. A navigation trial would be terminated if the beetle reached the destination, left the experimental region (120 × 60 cm^2), or the experimental time exceeded 5 minutes, whichever came first. A successful/failed trial was counted if the destination arrival occurred before/after the termination. The destination and origin were swapped between two consecutive trials to avoid potential biases. Each beetle was experimented with 12 trials and allowed to rest for 5 mins after each trial.

The navigation was carried out under a loosely tethered condition to extend the experiment period (Movie 1) [27]. A 1.5 m-long copper wire (44 AWG, Remington Industries) was employed to transmit electrical signals from the stimulator to the cyborg beetle. The feedback control-based navigation program (written in MATLAB®) was embedded into a main PC connecting to the stimulator. The beetle's motion was monitored and fed to the program via a 3D motion capture system (Vicon®, 100 fps) [10] (Figs. 1C-1D). Also, this data was logged for post-experiment analysis. The feedback system was evaluated under various combinations of the two control parameters (t_{update} = 1.0 and 1.5 s) and K_p = 0.5. The locomotory responses elicited by the Burst Stimulation and its usage in the feedback control-based navigation of the beetle were then analyzed.

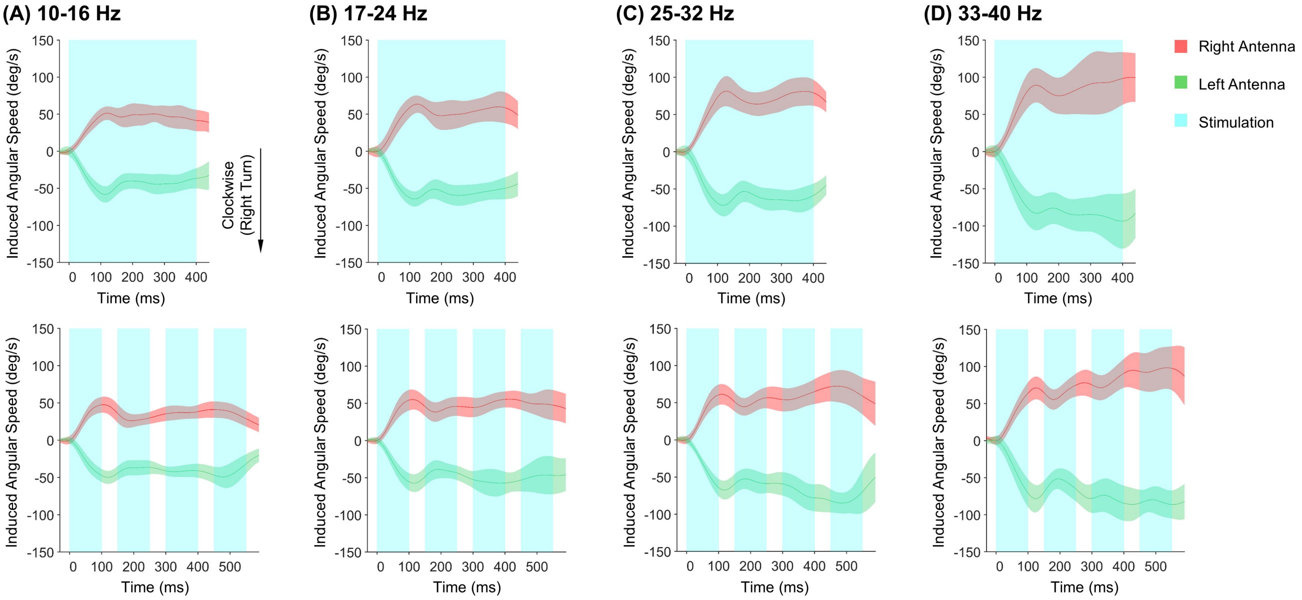

Fig. 3. Profile of the angular speed induced by the two stimulation protocols. Under Continuous Stimulation (*Top Figures*), the induced angular speed tends to reduce after its first peak (53 ≤ stimuli ≤ 182 per frequency group) [27]. Meanwhile, under Burst Stimulation (*Bottom Figures*), this peak tends to recover in the subsequent bursts after appearing at the first burst (80 ≤ stimuli ≤ 170 per frequency group). In both stimulation protocols, the peak's value tends to increase in tandem with the stimulation frequency, reflecting the graded response of the beetle to the stimulation. The stimulation intensity is identical for both stimulation protocols, which is 400-ms duration of actively stimulating the beetle's antennae (indicated by cyan color). The angular speed is displayed as mean ± standard deviation, i.e., colored curves and shaded regions.

The ambient conditions remained similar across the experimented beetles. The room temperature and relative humidity were set at 25 °C and 60%, respectively. The experiments were conducted between 9 am to 12 pm or from 6 pm to 9 pm. Unexpected stimulations like visual and olfactory cues were minimized by fixing the lighting condition at 500 F and prohibiting the consumption of foods, beverages, and chemicals during the experiments.

F. *Data Analysis*

The logged location data was passed through a moving mean filter (0.1-s sliding window) for noise removal. The outcome was used to reconstruct the beetle's response to stimulations and its instantaneous linear speed during the navigation. This speed was sampled at 2 Hz and defined as the average speed within a 100-ms window. Right turns were assigned negative values and vice versa. The beetle's responses to its antennae stimulation were categorized into four frequency groups, including 10-16 Hz, 17-24 Hz, 25-32 Hz, and 33-40 Hz. Responses falling outside the range of $\pm 2.7\sigma$, where σ was the standard deviation of each group, were excluded as outliers. Student's t-test ($\alpha = 5\%$) was employed for comparisons. Spearman's correlation test ($\alpha = 5\%$) was used to examine the graded response of the beetle's locomotion. The navigation outcome was evaluated via four factors [27]. "Success rate," i.e., reliability, was defined as the ratio of successful trials. "Tracking error," i.e., navigation accuracy, was calculated by dividing the region formed by the actual trajectory and the sine curve by the latter's length [26]. "Navigation time" and "control effort" were the control time and the number of stimuli delivered to attain successful navigations. 7/60 trials containing more than 15 consecutive stimuli at one antenna were removed to avoid biases caused by habituation and/or tissue damage [37, 38].

III. RESULTS AND DISCUSSION

A. *Burst Stimulation for Enhancing Locomotory Responses*

The beetle's response to its antennae stimulation under Continuous Stimulation was reconstructed from the data collected in a preceding work [27]. The turning response was graded by the stimulation frequency (Spearman's correlation test, $\rho > 0.31$, $P < 0.001$, $df > 329$, Fig. 2A) [13]. E.g., the average induced turning angle increased by ~14 deg when the stimulation frequency was switched from 10-16 Hz to 33-40 Hz in the left antenna stimulation (Fig. 2A). Besides, the elicited angular speed of all four frequency groups shared a similar profile (Fig. 3). This speed promptly rose once the stimulus was triggered. Then, it reached the first peak after ~100 ms and tended to fluctuate around a lower saturated level afterward. The peak was found to reduce at least ~10% after 50 ms. For instance, when the left antenna was stimulated at 25-32 Hz, the angular speed initially peaked at around -72 deg/s and then dropped to approximately -55 deg/s (~25%) after 50 ms (the "minus" sign indicates the turning direction). In addition, this peak increased with the stimulation frequency (Fig. 3), resembling the graded response of the antennae stimulation (Fig. 2A). For example, in the right antenna stimulation, the average peak of 10-16 Hz was ~51 deg/s, whereas that of 25-32 Hz was ~81 deg/s.

Such a profile implied that a more efficient turning response could be obtained if the peak's magnitude was maintained throughout the stimulus. An intuitive idea was breaking the 400-ms-long continuous stimulus into multiple 100-ms-long stimuli (or bursts) to maximize the number of peaks. Also, existing studies suggested shortening the stimulus to minimize damage to the beetle's tissue and limit its reaction degradation [11, 38, 39]. Furthermore, modulating a continuous stimulus into multiple bursts could potentially elicit more natural-like responses or increase the control success rate [30, 31]. Thus, the Burst Stimulation was designed and examined via the feedback control system (K_p = 0.50, t_{update} = 1.0 s, 1.5 s). Herein, the stimulation-free period between two consecutive bursts was set at 50 ms, expecting to recover the peak from a minimal drop of 10%, which occurred under the Continuous Stimulation (Fig. 3).

The data analysis suggested that the angular displacement induced by this new protocol was generally more profound than the Continuous Stimulation, indicating an improvement in the beetle's locomotory response (Figs. 4A-4B, t-test, P < 0.01, df > 200). In specific, the induced turning angle under the Burst Stimulation was larger than that of the Continuous Stimulation by up to 50%. For instance, in the left antenna stimulation, this signal steered the beetle to an average angle of ~30 deg, which was ~10 deg larger than that obtained from the conventional protocol (25-32 Hz, Fig. 4B). While improving the beetle's turning reaction, the Burst Stimulation retained its graded ability via the stimulation frequency, suggesting this signal's potential use in the feedback control of terrestrial cyborg beetles (Fig. 4C, Spearman's correlation test, ρ > 0.38, P < 0.001, df > 482). E.g., an increase from 10-16 Hz to 25-32 Hz raised the average turning speed from ~26 deg/s to ~49 deg/s in the right antenna stimulation (Fig. 4C). Herein, the highest frequency of 40 Hz was selected based on existing studies [13, 20, 27]. Further increasing this parameter might continue speeding up the beetle's reaction. However, as sensory systems tend to have a short stimulation frequency bandwidth for linear and natural responses [30], too high frequencies could lead to obnoxious behaviors, like falling [20], worsening the beetle's locomotion control.

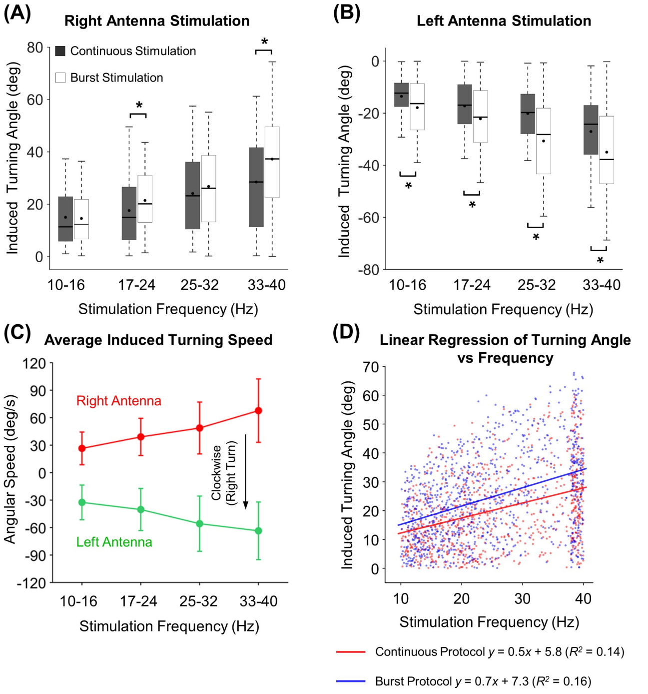

Fig. 4. The enhanced locomotory response under Burst Stimulation. (A) – (B). In general, despite using the same stimulation intensity, the turning angle induced by this modulated protocol is more significant than that of the Continuous Stimulation (given the same stimulation frequency, *: P < 0.01, t-test, 53 ≤ stimuli ≤ 182 per frequency group). The boxplots are drawn with a whisker of 1.5. The black circles denote the mean values. (C) The Burst Stimulation allows the induced angular speed (and thus turning angle) to be graded by the stimulation frequency. Higher frequencies tend to provoke faster angular speeds. Data are shown as mean ± standard deviation, 80 ≤ stimuli ≤ 170 per frequency group. (D) Linear regressions of the induced turning angle to the stimulation frequency in the two protocols (859 ≤ data points ≤ 941 for each line). With a positive slope and higher intercept, the equation of the Burst Protocol shows its graded ability and advantages over the Continuous Stimulation.

The Burst Stimulation's beneficial effect might be explained via the profile of its elicited angular speed (Fig. 3). Like the Continuous Stimulation, the angular speed reached its first peak after the ~100 ms, i.e., after the first burst and dropped afterward. This peak also increased in tandem with the stimulation frequency. E.g., it averagely increased by ~51% from ~47 deg/s to ~71 deg/s when the frequency was raised from 10-16 Hz to 33-40 Hz (at the right antenna stimulation, Fig. 3). Unlike the Continuous Stimulation, following its recession after the first burst, the angular speed tended to recover in successive bursts. In the right antenna stimulation at 17-24 Hz, for example, the maximum angular speed within these three bursts could recover to its initial peaking amplitude of ~55 deg/s after reducing to ~42 deg/s (at 50 ms after the first peak) (Fig. 3). This trend agreed with the initial idea that this burst-shaped signal would increase the peak numbers, thus enhancing the beetle's response.

The difference between the two protocols was also shown via their linear regression models of the beetle's

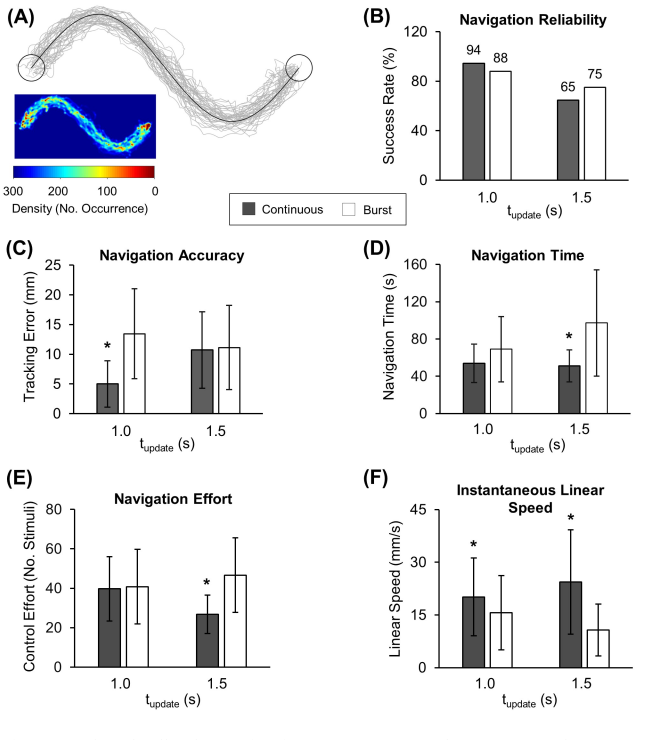

Fig. 5. The feedback navigation system's performance under Burst Stimulation. (A) The system successfully directs the beetle to follow the pre-determined sine curve. All successful navigations (gray colors) occupy ~81% of all carried-out trials and reassemble the shape of the assigned route. (B) – (F) The navigation differences between the two protocols. In general, these differences agree with the enhanced turning response provided by the Burst Stimulation (*: P < 0.05, t-test). Data are shown as mean ± standard deviation.

induced response to the stimulation frequency (Fig. 4D). While both models had a positive slope, indicating a graded relationship between the two factors, that of the Burst Stimulation possessed a larger intercept of 7.3 vs. 5.8 of the conventional protocol, suggesting more significant outputs. Herein, these results implied the efficiency of Burst Stimulation over Continuous Stimulation. This efficiency improvement was attained, although the two protocols generally employed the same stimulation amplitude, pulse width, and an active stimulation period of 400 ms.

C. Burst Stimulation in Autonomous Navigation

The feedback control-based navigation of the cyborg beetle demonstrated its engineering aspects, such as a tunable operation, in tandem with its biological features (Fig. 2B) [18, 40]. For instance, with the Continuous Stimulation, the reliability and accuracy of the navigation could be adjusted by tuning K_p and t_{update}. Navigations with a high success rate of 94% and a low tracking error of ~5 mm could be attained by keeping the beetle under frequent control (fast t_{update} of 1.0 s) and tuning K_p to a medium value of 0.50 (Figs. 5B-5C) [27]. Lager K_p would cause overshoots, and smaller K_p would be insufficient to correct the beetle's orientation. Under infrequent control (i.e., slow t_{update}, e.g., for power saving purposes), large K_p would counter the beetle's control-free motion and retain a high success rate [27].

Similarly, the Burst Stimulation was also feasible for the feedback system (Fig. 5A). More than 81% of path-following trials were successfully completed under this signal (N = 5 beetles, n = 43/53 trials). Besides, their trajectories resembled the predetermined path (Fig. 5A, Movie 2), suggesting the signal could retain the system's accuracy. However, a closer look showed that the system performed differently under the Burst Stimulation despite using the same control parameters as the Continuous Stimulation ($K_p = 0.50$, $t_{update} = 1.0$ and 1.5 s, N = 5 beetles, $25 \leq n \leq 28$ trials for each pair). At $t_{update} =$ 1.0 s, this protocol caused an increase of ~8 mm in the average tracking error (t-test, $P < 0.001$, $df = 37$) (Fig. 5C). This accuracy decline agreed with the P controller's operation. As the induced turning angles became larger, keeping K_p unchanged would cause overshoots, thus worsening the navigation accuracy. As the feedback system was tunable [27], a decremental change in K_p might be beneficial. Under infrequent control ($t_{update} = 1.5$ s), there was no significant difference in the navigation accuracy between the two protocols ($P = 0.88$, $df = 30$, Fig. 5C). At this slow t_{update}, the beetle's control-free motion possibly dominated the effectiveness of a medium K_p [27]. However, as the turning angles became more significant to somewhat counter the control-free motion, the success rate at this condition slightly hiked up by 10% under the modulated signal (Fig. 5B). Herein, larger K_p might provide higher success rates [27].

The differences between the two protocols were also found in the navigation time and control effort. In specific, the feedback system required more time and a larger number of stimuli to successfully direct the beetle using the Burst Stimulation (Figs. 5D-5E). Perhaps, as the beetle's reaction became more profound, it was more difficult for the system to correct its orientation using the same K_p. Thus, the navigation effort was increased, especially when the control-free motion was significant at $t_{update} = 1.5$ s (Fig. 5E, t-test, $P = 0.02$, $df = 30$). The difficulty in the orientation correction would then suppress the thrust controller, which controlled the beetle's accelerated motion (Figs. 2B-2C), thus reducing its linear speed during the navigation (Fig. 5F, t-test, $P < 0.001$, $df > 4000$). At $t_{update} = 1.5$ s, this speed was averagely reduced twice under the new stimulation protocol (Fig. 5F). The navigation time was then expanded (Fig. 5D, t-test, $P < 0.01$, $df = 30$). Like tracking error, lowering K_p might benefit the control effort and navigation time under the Burst Stimulation. Besides, as the beetle's response to its elytra stimulation could be graded [20], the simple thrust controller could be replaced with other advanced controllers, e.g., a P controller, to allow a direct regulation of these two factors.

D. Limitations and Future Works

Despite the feasibility of the Burst Stimulation's implementation in the feedback control-based navigation, further studies should be conducted to examine its performance more comprehensively. Like Continuous Stimulation [27], different navigational trends and applications under this modulated signal might be revealed by adjusting K_p and t_{update}. Besides, using this signal to control other locomotion (e.g., the forward acceleration via elytra stimulation [20]) and other ambulatory insect species (e.g., Madagascar hissing cockroaches [14]) is also worth investigating. Further optimization of its parameters is also essential. For instance, the locomotory effect of varying the stimulation-free period should be studied [30]. Besides, optimizing the number of bursts might be needed. For example, while increasing in the 2nd and 3rd bursts, the angular speed showed a downtrend at the last one (Fig. 3). In addition, studies on the beetle's response degradation (due to habituation and/or tissue damage) under this protocol would be vital for practical uses. Generally, a sustainable response would require optimal stimulation parameters [11], biocompatible electrodes [41], and safe implantation processes [42]. Finally, onboard localization systems, like IMU [43], should be developed for onsite operations.

IV. CONCLUSION

This study proposes Burst Stimulation as a more efficient approach for the locomotion control of terrestrial cyborg insects than Continuous Stimulation. Under the same stimulation intensity, this new modulated signal enhanced the beetle's responses up to 50% in magnitudes while retaining their graded manner. Moreover, its use in a feedback control system demonstrated a success rate of around 81%. While further investigation is needed to fully evaluate its performance in the feedback control system, this modulated signal would potentially help further optimize the autonomous navigation of terrestrial cyborg insects.

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