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Design Construction and Testing of a Flying Prey Simulator

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DESIGN, CONSTRUCTION, AND TESTING OF A FLYING PREY SIMULATOR

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ABSTRACT

The goal of this research project is to investigate the neuronal control of flying prey interception in dragonflies by designing, constructing, and programming an apparatus to simulate the complex motions of a flying insect. Our three-dimensional motion device is capable of mimicking a flying insect by moving a small bead accurately up to speeds of 1 $\frac{m}{s}$ in any direction. Dragonflies are efficient aerial predators that can intercept and capture small insects in flight. Our stimulus device will be used to determine the way in which dragonfly neurons encode information about object movement in three dimensions. Sinusoidal position tracking experiments using multiple input frequencies were conducted using the apparatus. The results indicate that the machine operates smoothly with little variability between trials. Preliminary dragonfly testing with the apparatus showed favorable results, indicating proof of concept.

INTRODUCTION

Dragonflies are highly efficient aerial predators that have the remarkable capability of capturing small insects in flight. This complex process generally occurs in less than 300 ms with interception flights having success rates as high as 97 % [1]. Visual information concerning the prey's position, orientation, and velocity are converted into navigation directions, mapping the dragonfly's flight path to intersect with the prey's flight path. Our research is aimed at understanding the neuronal control in this rapid and higly accurate, visually-guided behavior.

This distinctive prey-capture behavior requires both rapid visual processing and information transmission, resulting in the evolution of large neurons. The specific neurons that control this process consist of target-selective descending neurons (TSDNs). TSDNs provide the dragonfly's flight control system with steering instructions to direct the flying dragonfly toward its prey. Fortunately, these large neurons are accessible for electrophysiological studies.

Motivation

To date, studies of the dragonfly visual neurons have been mostly restricted to two dimensions, the X direction (left - right) and the Y direction (up - down), recording responses to images displayed on a flat projection screen [2]. However, the flying insect prey pursued by dragonflies move in three dimensions and little is known about how the visual neurons encode the third (depth dimension). It is hypothesized that the Z dimension (front - back) movement is vital to understanding the exact roles of these neurons in prey interception. To address this question, we built an apparatus to aid in the investigation of these visual neurons. This device will simulate an insect flying in three dimensions, with all movements computer controlled via Simulink and Real Time Windows Target, both of which are components of MATLAB 7.10 (The MathWorks, Inc, Natick, MA).

Eight bilateral pairs of TSDNs are implicated in steering the

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interception flight. These neurons descend from the brain of the dragonfly to the wing motor regions of the thorax, transmitting visual information about prey movement [3] [4] [5]. Their activity drives steering adjustments in wing angle. Our device will be used to determine the way in which the TSDNs encode information about object movement in three dimensions. This apparatus has the potential to reveal which target-selective neurons encode three-dimensional movement and how their activity is modulated by movement in the third (depth) dimension. This information is crucial for understanding how the dragonfly intercepts its flying prey.

In order to better understand real-world responses, looming objects need to be introduced that are moving at various velocities and directions, while the dragonfly is held stationary. The looming artificial prey objects are composed of glass beads of varying sizes (1 mm - 1 cm) sturdily mounted on a fine nylon monofilament. The monofilament is not visible to the foraging dragonflies as evidenced in previous studies in which they occasionally collided with the monofilament in flight [6].

In a preliminary study, testing was conducted by controlling the bead by hand. The problem with moving the bead manually is that it makes it more difficult to track the kinematic properties (position, velocity, acceleration) of the bead at any given time. It also prevents the researcher from easily correlating the bead movement with the neuronal activity.

Neurobiological studies with the apparatus will help us understand the coding of three dimensional visual information by individual neurons. We expect to gain further comprehension of the visual selectivity and responsiveness of the TSDNs to three-dimensional object position and velocity.

METHODS

The project involved designing, constructing, and testing a machine to simulate the complex motions that insects exhibit in the natural environment. The design requirements included a maximum speed of 1 $\frac{m}{s}$ in all dimensions and a motor rise time less than 10 ms in all directions. The size requirement was an interior volume of 46 cm^3 in which the bead can move.

The project goals were outlined as follows: (1) Devise and construct the structural framework of the apparatus, (2) achieve open loop control by implementing motors and encoders, (3) obtain closed loop control through Simulink and Real Time Windows Target, and (4) run neurobiological experiments with live dragonflies.

Basic Design Framework and Motor Selection

Based on the design requirements, the apparatus was created using t-slot extruded aluminum, timing belts and pulleys, ball bearings, metal axles, and DC brushed motors. The apparatus (shown in Fig. 1 during an experimental test run with a live dragonfly) works by moving a small glass bead simultaneously in three directions. The bead is mounted on a thin monofilament (not visible in Fig. 1) and moved in the lateral (left-right) direction by the X motor. The ends of the monofilament are connected to spindles attached to the two vertical posts (Fig. 1). Each of these spindles is moved in the vertical direction (up-down) by the Y motors. Two separate motors, marked Y1 and Y2 in Fig. 1, are used to move the bead in the Y direction, because the space in front of the dragonfly should be completely unobstructed. This prevented us from using just one motor and some sort of rigid coupling between the two vertical posts. Instead, we used two motors and employed control to ensure that their motions were synchronized. The Z motor moved the entire assembly (12.5 kg) in the Z (front-back) direction. It was mounted as low as possible to prevent visual obstruction.

Table 1. SUMMARY OF MOTOR SPECIFICATIONS.

Motor	X	Y	Z
Rated Voltage (V)	24	24	24
Peak Current (A)	1.99	23.8	40.4
No Load Speed ($\frac{rad}{s}$)	822	388	336
Stall Torque ($N-m$)	0.052	1.4	2.9
Power Output (W)	43	136	244
Gear Ratio	5	3	3

Since the load (bead + monofilament) in the X direction (left-right) is quite small, the X motor is the smallest among all motors used. The Y motors need to move the X motor and the spindle-monofilament assembly in the Y direction (up-down); hence they are bigger than the X motor. One of the Y motors, Y1, also carries a bigger load because it carries the X motor and the spindle assembly, while the Y2 motor carries just the spindle assembly. As mentioned previously, their vertical positions are synchronized using control. The Z motor needs to move the entire assembly, including the two vertical posts, in the Z direction (front-back); hence it is the largest motor used.

Power and gear ratio calculations were performed to select appropriate DC brushed motors and timing pulleys respectively. The motors also include encoders to allow for closed loop feedback control. Motor specifications in the three directions are summarized in Tab. 1. Note that the Y1 and Y2 motors are the same.

Motor drivers (Dimension Engineering SynRen 10, 25, and 2x25 A) were used in packetized serial mode to allow Real Time Windows Target to send signals to the motors. 500 counts per revolution (CPR) optical encoders were used to measure the bead position in each movement direction. Based on the gear ratios and timing pulleys for each dimension, the precisions in the X, Y, and Z directions were 1357, 586, and 599 $\frac{counts}{cm}$ respectively.

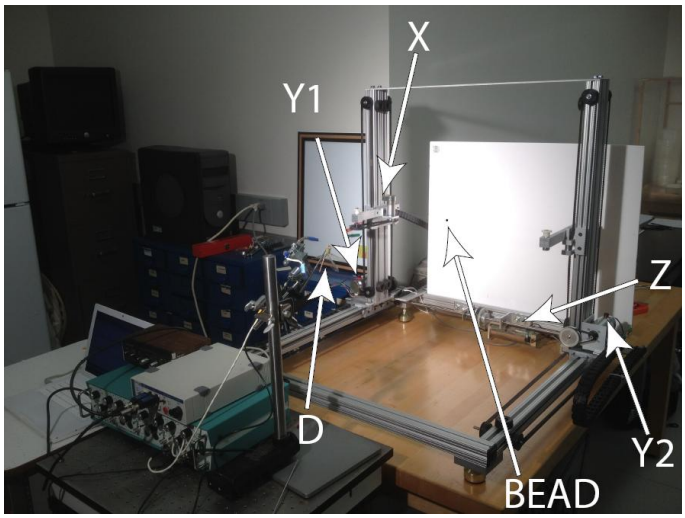

Figure 1. EXPERIMENTAL APPARATUS: D=DRAGONFLY, X=X MOTOR, Y1=Y1 MOTOR, Y2=Y2 MOTOR, AND Z=Z MOTOR. THE THREE MOVEMENT DIRECTIONS ARE ALSO INDICATED. X DENOTES LEFT TO RIGHT DIRECTION, Y UP AND DOWN DIRECTION, AND Z FRONT TO BACK DIRECTION.

Friction Cancellation

The precision of the motion control apparatus was slightly compromised due to friction. Our system involves repeated velocity reversals in all three dimensions, making it necessary to reduce the unwanted friction. Although our motors have the potential to generate linear speeds up to 1 $\frac{m}{s}$, the machine is typically used only at low velocities. Low velocity, bidirectional position tracking systems are particular vulnerable to friction errors [7].

In the controller algorithm for each motor, biases were experimentally determined to eliminate Coulomb friction at low velocities. For example, in the X dimension, when a signal between -8 to +8 was sent to the motor, the bead failed to move. In order to eliminate the Coulomb friction that prevented the motor from rotating, a bias of 8 was added to the signal. Figure 2 plots the signal versus steady state velocity for the X motor without friction cancellation to demonstrate how the bias was derived.

Closed Loop System

The closed loop feedback control system was modeled in Simulink using Real Time Windows Target. The general form of the model is shown in Fig. 3. A simple proportional controller was used in all directions. The proportional gains were 0.1, 0.1, 0.1 and 0.2 for the X, Y1, Y2, and Z directions respectively.

Dragonfly Test Setup

Experimental tests were performed with a live dragonfly to validate the purpose of the apparatus. A dragonfly (Anax junius) was mounted with wax to a rigid bar. A small incision in the thorax exposed the ventral nerve cord between the prothoracic and

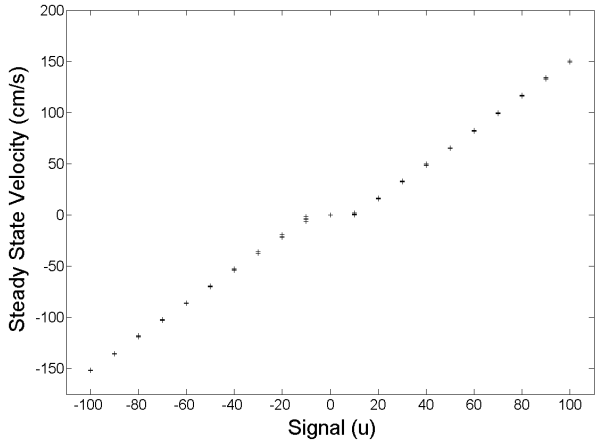

Figure 2. X MOTOR SIGNAL VS STEADY STATE VELOCITY BEFORE FRICTION CANCELLATION. NOTE: DEAD ZONE DENOTES FRICTION.

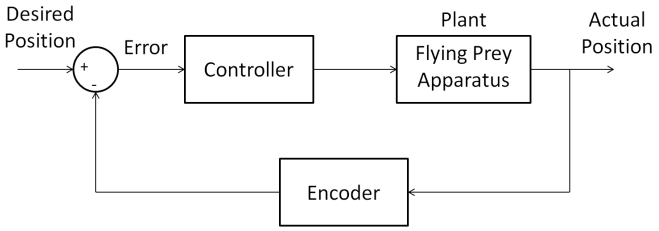

Figure 3. THE GENERALIZED CLOSED LOOP CONTROL SYSTEM.

mesothoracic ganglia. A small hook electrode, fashioned from bare 100 μm silver wire, was positioned under one of the paired connectives of the nerve cord. The recording site was insulated by the injection of petroleum jelly, and a ground electrode was inserted through a leg socket near the recording site. The dragonfly, with implanted electrodes was mounted ventral side up, so that movements of the 3 *mm* bead were centered on the acute region of the dorsal compound eye.

The dragonfly was held stationary while the TSDN signals were recorded. It was crucial for the dragonfly to be completely isolated from the vibrations caused by the mechanical components of the device to eliminate the responses of vibration sensitive neurons. For this reason, the experimental animal and recording hardware was mechanically isolated from the stimulus apparatus with an anti-vibration air table. However, dragonflies are not known to have any hearing organs or to show any responses to sounds, so the subtle mechanical noise of the apparatus did not affect the electrophysiological recordings.

The signal from the recording electrode was amplified (A-M systems Model 1700, bandpass 0.3-5 KHz) and passed to a data acquisition system (AD Instruments Powerlab running LabChart 6 software). Synchronization pulses were sent from MATLAB to the data acquisition system to synchronize the start of the electro-

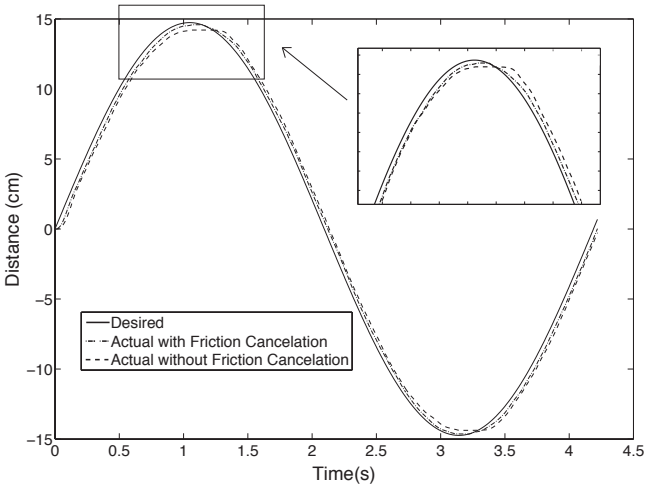

Figure 4. X MOTOR FREQUENCY TESTING AT 1.5 HZ.

physiological recordings with the start of the programmed bead trajectory. This allowed us to match specific neuron spikes with the kinematic properties of the bead at any given time. A sample is shown in fig. 6C.

RESULTS

Sinusoidal Tracking

Closed loop sine wave frequency response testing was performed separately for each motor in the system to determine the root mean square (RMS) errors with and without friction cancellation. Testing was conducted at low (1.5 Hz), medium (3 Hz), and high (6 Hz) frequencies.

Five trials were conducted for each motor for both with and without friction cancellation cases (note: friction cancellation has not been performed yet for the Z motor). For each trial, one cycle with an amplitude of approximately 8.5 cm was analyzed to determine the RMS error. Figure 4 illustrates the frequency response at 1.5 Hz for the X motor with and without friction cancellation. The results of the five trials for each motor were averaged and the standard deviations were calculated. Figure 5 summarizes the results of the experiments at each frequency. The repeatability of results with sinusoidal tracking was excellent. This led to extrememly small standard deviations. For this reason, the error bars, even though present, are not visible in Fig. 5 for most of the cases.

Dragonfly Testing

Figure 6 shows the correlation between the dragonfly neuron spikes and the X, Y, and Z positions when the bead followed a collision-like path. The bead trajectory formed the shape of a pyramid, with the pyramid's apex positioned at the head of the dragonfly (Fig. 6).

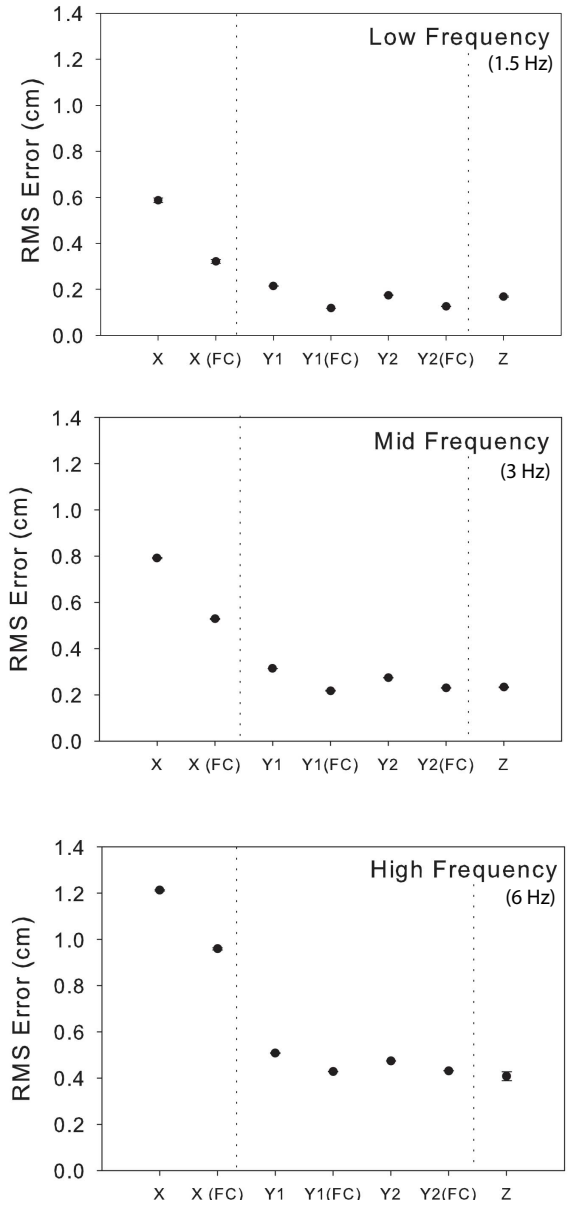

Figure 5. FREQUENCY TEST RESULTS FOR TRACKING IN X, Y1, Y2, AND Z DIRECTIONS. FC DENOTES FRICTION CANCELLATION.

DISCUSSION

Although this is an interdisciplinary project involving elements of both control theory and biology, this paper focuses more on the former. The device is fully functional and when more experiments are performed, the data will be published in appropriate venues. Also, details such as transfer function analysis in z and s domains, open and closed loop pole locations, stability analysis, and step responses are currently being worked out and will be made available in a forthcoming journal publication. Although a former stability proof is not yet available, we can report that the apparatus did not exhibit any unstable behavior in any of the experiments discussed in this paper and indeed has a remark-

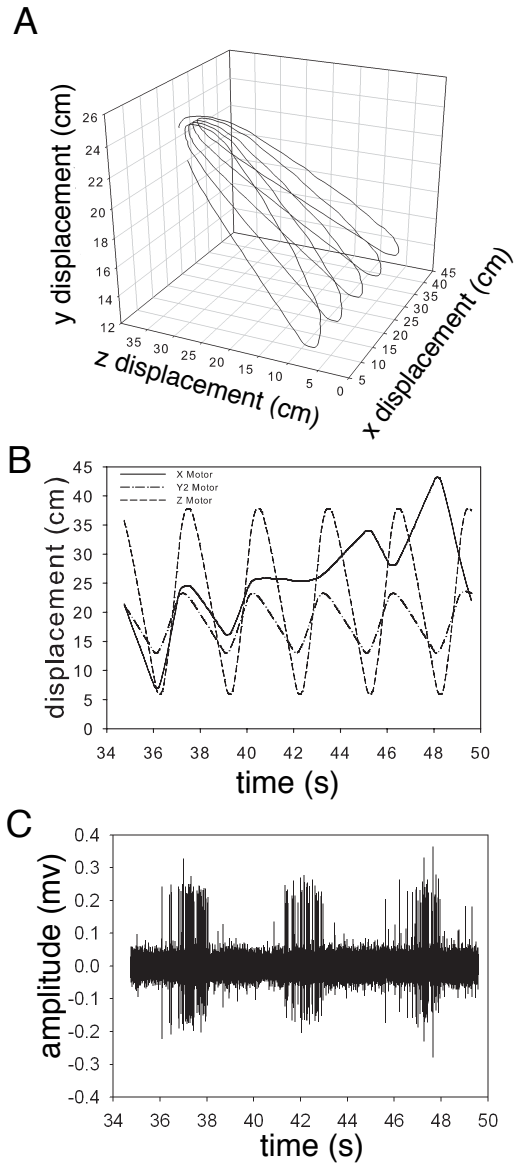

Figure 6. A: 3D BEAD TRAJECTORY, B: DISPLACEMENT VS TIME IN ALL DIRECTIONS, AND C: DRAGONFLY NEURON RESPONSE.

able level of repeatability. The maximum standard deviation was just 0.019 cm for an 8.5 cm amplitude position command.

In all cases of sinusoidal tracking, as with any servo control system, performance decreased with increasing frequency (Fig. 5. Also, for all cases reported, friction cancellation decreased the RMS error, as expected. The error bars in Fig. 5 were quite small, demonstrating good repeatability.

The stimulus apparatus will help further our understanding of the information transmitted by the TSDNs in the dragonfly. These neurons are implicated in guiding the interception of flying insects by the foraging dragonfly [8]. They are known to transmit information about prey location and angular velocity (direction and speed), but very little is known at present about the way in which information concerning the third dimension, prey distance, is integrated into their responses or even about how such information is obtained.

Unraveling the neural basis of visually guided prey interception by dragonflies could reveal how a small group of neurons can drive a fast, complex, and highly reliable behavior such as the interception of flying insects. The results of this study could potentially lead to the development of effective guidance mechanisms for military or civilian use.

ACKNOWLEDGMENTS

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REFERENCES

[1] Baird, J., and ML, M., 1997. "Foraging behavior of pachydiplax longipennis". *Journal of Insect Behavior,* **10**, pp. 655–678.

[2] Frye, M., and Olberg, R., 1995. "Visual receptive field properties of feature detecting neurons in the dragonfly". *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology,* **177**(5), pp. 569–576.

[3] Tanouye, M., and Wyman, R., 1980. "Motor outputs of giant nerve fiber in drosophila". *Journal of Nuerophysiology,* **44**, pp. 405–421.

[4] Blondeau, J., 1981. "Electrically evoked course control in the fly calliphora erythrocephala". *Journal of Experimental Biology,* **92**, pp. 143–153.

[5] Pearson, K., and Robertson, R., 1981. "Interneurons coactivating hindleg flexor and extensor motoneurons in the locust". *Journal of Comparative Physiology,* **144**, pp. 391–400.

[6] Olberg, R., Seaman, R., Coats, M., and Henry, A., 2007. "Eye movements and target fixation during dragonfly prey-interception flights". *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology,* **193**(7), pp. 685–693.

[7] Ramasubramanian, A., and Ray, L. "Comparison of ekbf-based and classical friction compensation". *Journal of Dynamic Systems, Measurement, and Control,* **129**, pp. 236–242.

[8] Olberg, R., 1986. "Identified target-selective visual interneurons descending from the dragonfly brain". *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology,* **159**(6), pp. 827–840.