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The Design, Construction, and Application of a 3D Flying Prey Simulator to Aid in the Investigation of Neuronal Control in Dragonflies

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Abstract

The goal of this interdisciplinary 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 glass bead accurately up to speeds of 1 m/s. Dragonflies are highly efficient aerial predators that have the remarkable capability of intercepting and capturing small insects in flight. This complex process generally occurs in less than 300 ms, with success rates as high as 97%[1]. Prey capture behavior requires both rapid visual processing and information transmission, resulting in the evolution of large neurons in the control pathway. Eight pairs of large neurons, called Target-Selective Descending Neurons (TSDNs), are implicated in steering the 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. Our stimulus device will be used to determine the way in which the TSDN's encode information about object movement in three dimensions. To date, visual neuron studies 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. However, Dr. Olberg of the Biology Department at Union College hypothesized that the z-dimension (front - back) movement is vital to understanding the exact roles of these neurons in prey interception. An understanding of visually guided prey interception by dragonflies, could lead to the development of effective guidance mechanisms for military or civilian use. The device consists of 80/20 extruded aluminum parts, timing belts and pulleys, ball bearings, metal axles, and DC brushed motors with encoders. The device is computer controlled by Simulink and Real Time Windows Target, which are components of MATLAB.

Keywords: Neuronal Control in Dragonflies, Prey Interception, Control Theory

1. 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.

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) and rotation-selective descending neurons (RSDNs). TSDNs provide the dragonfly's flight control system with steering instructions to direct it toward its prey. RSDNs provide rotational flight stability by incorporating multisensory inputs concerning the dragonfly's surroundings. Fortunately, these large neurons are accessible for electrophysiological studies.

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[5]. 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). Dr. Olberg hypothesized that the z-dimension (front – back) movement is vital to understanding the exact roles of these neurons in prey interception, because three dimensional prey motions, are more realistic to the dragonfly. To address this question, we are building an apparatus to be used to investigate the visual neurons. This device will simulate an insect flying in three dimensions, with all movements computer controlled via MATLAB.

Eight pairs of large neurons, called Target-Selective Descending Neurons (TSDNs), are implicated in steering the 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[1]. Our stimulus device will be used to determine the way in which the TSDN's encode information about object movement in three dimensions. In conjunction with Dr. Olberg's research, this apparatus has the potential to reveal the target-selective neurons that encode three-dimensional movement, allowing the dragonfly to intercept 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 will be composed of glass beads of varying sizes sturdily mounted on a fine wire. In a preliminary study, testing was conducted by controlling the bead by hand. The problem with simply moving the bead manually is that it makes it more difficult to track the kinematic properties (position, velocity, and acceleration) of the bead at any given time. When moving beads by hand, one is also inclined to repeat similar patterns of motion, decreasing the accuracy and reliability of the results.

2. Methods

The project task involved designing and fabricating a machine to simulate the complex motions that insects exhibit in the natural environment. The design requirements included a maximum speed of 1 m/s in all dimensions and a motor rise time of 10 ms. With much of the initial structural design completed during the summer, the goal for the fall term was to obtain open loop control in all dimensions. This included calculating the required power for each motor, calculating the necessary gear ratios to obtain the correct linear speed, purchasing the proper materials such as ball bearings, timing belts and pulleys, designing motor mounts and brackets, and implementing these components into the device.

3. Results

After completing the power calculations and selecting appropriate motors and pulleys, the SolidWorks design includes the motors and respective drive trains for each dimension (Fig. 1).

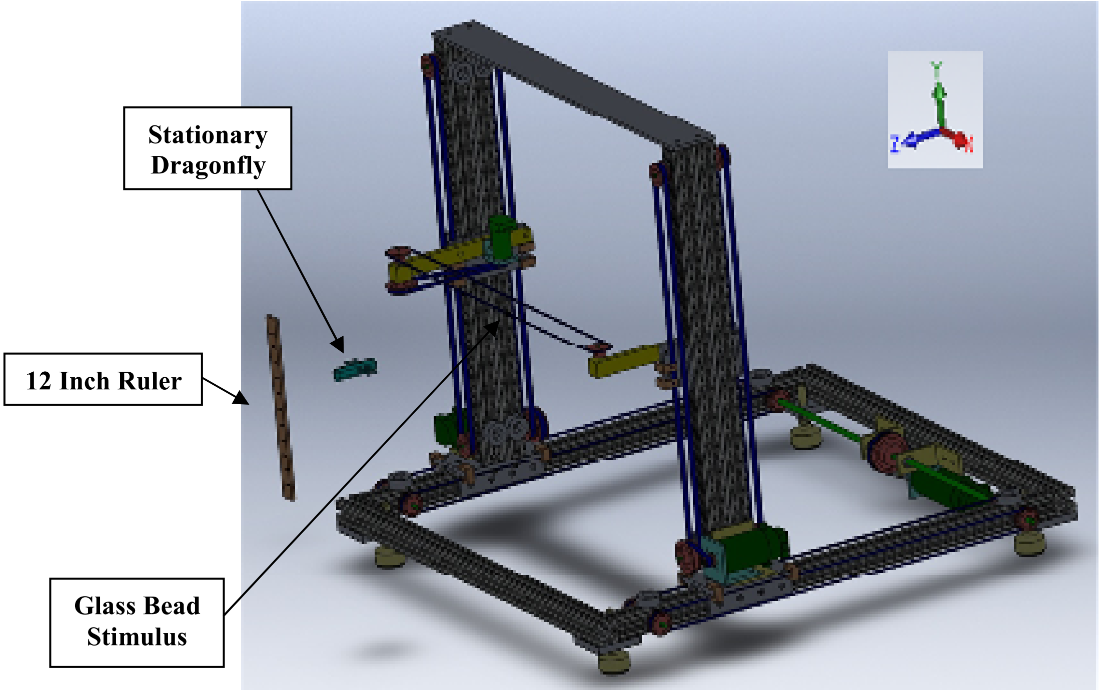

Figure 1. Complete SolidWorks model of the 3D flying prey simulator (12 inch ruler used as a scale)

Using 80/20 extruded aluminum, timing belts, timing pulleys, ball bearings, and custom parts fabricated by the machine shop, the present state of the 3D flying prey simulator is illustrated below (Fig. 2).

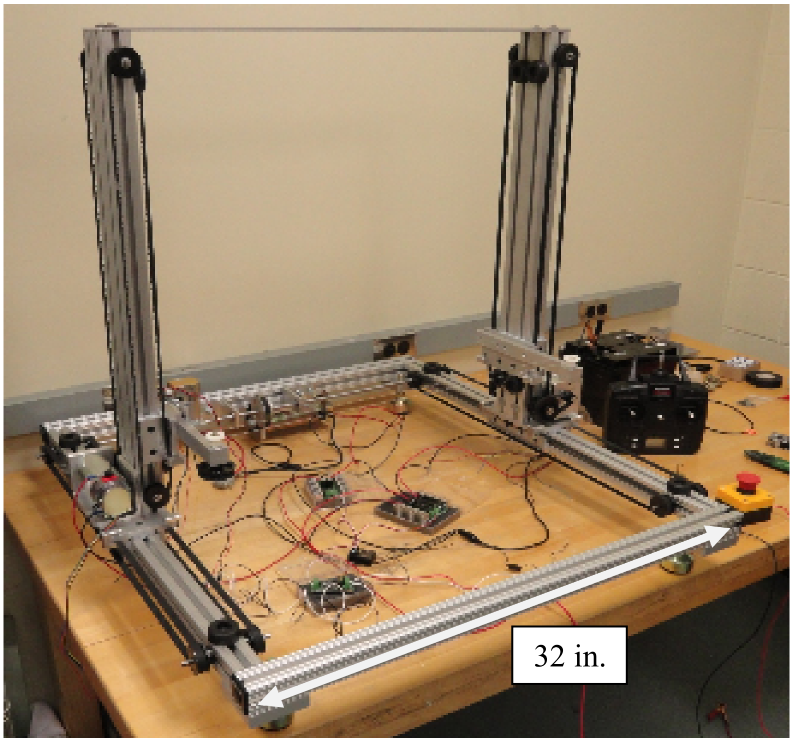

Figure 2. Construction accomplished during the fall term, with x, y, and z dimension open loop motion control complete (for scale, the length of the front 80/20 part is 32 inches)

3.1 matlab modeling

Each motor in the system was modeled using transfer function analysis in MATLAB to determine the output to a given input voltage. This analysis will be helpful for us when we implement closed loop feedback control, because we can anticipate the system response to any given input.

Using Fig. 3, transfer functions were derived for each motor. For this example, the z-dimension motor was analyzed.

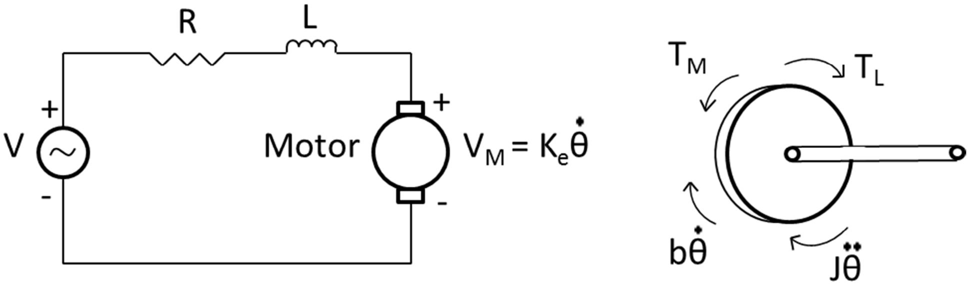

Figure 3. Electrical circuit of a motor (left) and the corresponding mechanical system with T_L representing the load torque (right)

Equation (1) was derived using a mesh current analysis for the electrical circuit in Fig. 3.

– (1)

Equation (2) was derived using Newton's second law for the mechanical system in Fig. 3.

(2)

For the case of the z-dimension motor, the free body diagram of the horizontal sliders is illustrated in Fig. 4, where M represents the mass of the system (total load on both of the horizontal sliders).

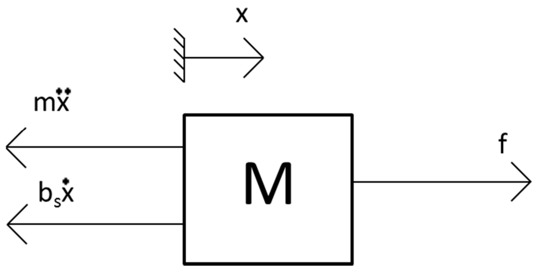

Figure 4. Free body diagram of the horizontal sliders used to determine the load torque on the motor

Using the free body diagram pictured in Fig. 4 and the mechanical system in Fig. 3, the following equations were derived.

(3)

$$T_L = rf \tag{4}$$

$$x = r\theta \tag{5}$$

Combining equations (3), (4), and (5), the load torque on the z-dimension motor was derived.

$$T_L = mr^2\ddot{\theta} + b_s r^2\dot{\theta} \tag{6}$$

Now inserting equation (6) back into equation (2).

$$b_M\dot{\theta} + J\ddot{\theta} + mr^2\ddot{\theta} + b_s r^2\dot{\theta} = T_M = K_t i \tag{7}$$

Taking the Laplace transform of equation (7) and rearranging terms.

$$\theta(s)s(b_M + Js + mr^2 s + b_s r^2) = K_t I(s) \tag{8}$$

Also taking the Laplace transform of equation (1) and rearranging terms.

$$I(s) = \frac{V - K_e s\theta(s)}{(Ls+R)} \tag{9}$$

Substituting equation (9) into equation (8).

$$\theta(s)s(b_M + Js + mr^2 s + b_s r^2) = K_t\left(\frac{V - K_e s\theta(s)}{(Ls+R)}\right) \tag{10}$$

Rearranging the terms in equation (10) to obtain the appropriate transfer function with the output (motor shaft position) over the input (voltage).

$$\frac{K_t}{s(b_M+Js+mr^2s+b_sr^2)(Ls+R)+K_tK_es} = \frac{\theta(s)}{V} = \frac{Output}{Input} \tag{11}$$

Grouping like terms, the final transfer function for the z-dimension motor becomes.

$$\frac{\theta(s)}{V} = \frac{K_t}{s^3(JL+mr^2L)+s^2(b_ML+JR+mr^2R+b_sr^2L)+s(b_sr^2R+K_tK_e+b_MR)} \tag{12}$$

Using the motor specifications for the z-dimension motor listed in Table 1, the transfer function was plotted in MATLAB to observe the open loop step response.

Table 1. z-dimension motor specifications used to plot the open loop step response in matlab

J = 4.7E-5 %Rotor Inertia (kg-m^2)
b = 1.7E-5 %Viscous Damping (N-s/m)
K_t = 7.06E-2 %Torque Constant (N-m/A)
K_e = 7.06E-2 %Back-EMF Constant (V/rad/s)
R = 0.59 %Motor Resistance (Ω)
L = 0.87E-3 %Motor Inductance (H)
b_s = 118.3 %Horizontal Slider Viscous Damping (N-s/m)
r = 0.01587 %Radius of Timing Pulley (m)
m = 10.58 %Mass on Horizontal Sliders (kg)

The open loop step response for the shaft position and linear distance of the z-dimension motor are illustrated below (Fig. 5).

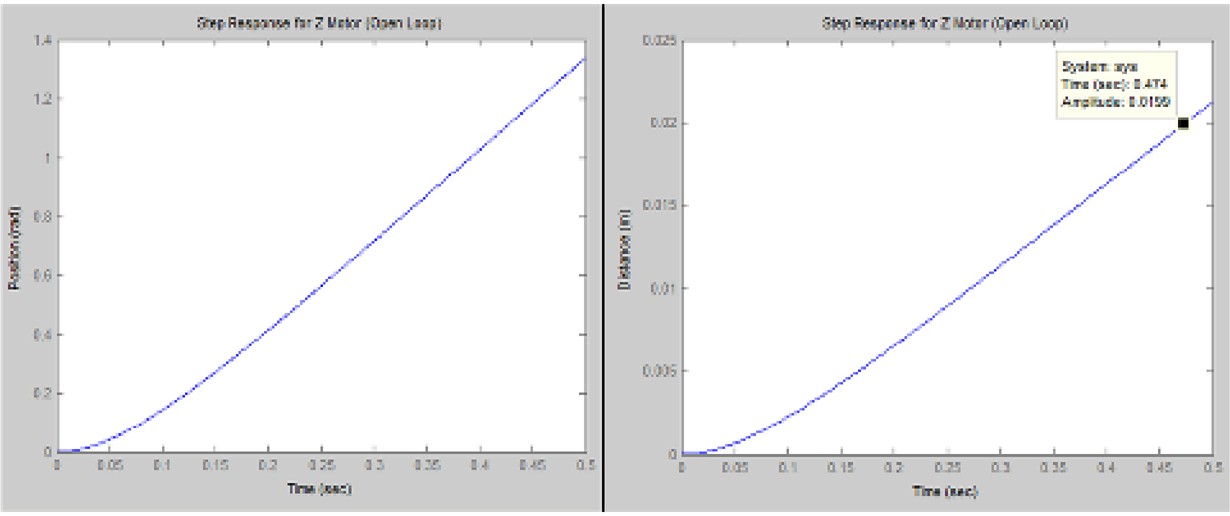

Figure 5. Matlab generated plots of the open loop z-dimension motor transfer function. Motor shaft position (left) and linear distance (right)

Analyzing the highlighted point on the linear distance plot (right side of Fig. 5), if the horizontal sliders move 0.0199 m in 0.474 sec when 1 volt is applied, then they will move 0.4776 m in 0.474 sec when 24 volts are applied. Using this information, the steady state velocity can be calculated as (0.4776 m / 0.474 sec) = 1.007 m/s, which was one of the main design requirements specified by Dr. Olberg.

The z-dimension motor transfer function was also modeled using a Simulink block diagram to compare the results obtained from the analytical solution (Fig. 6).

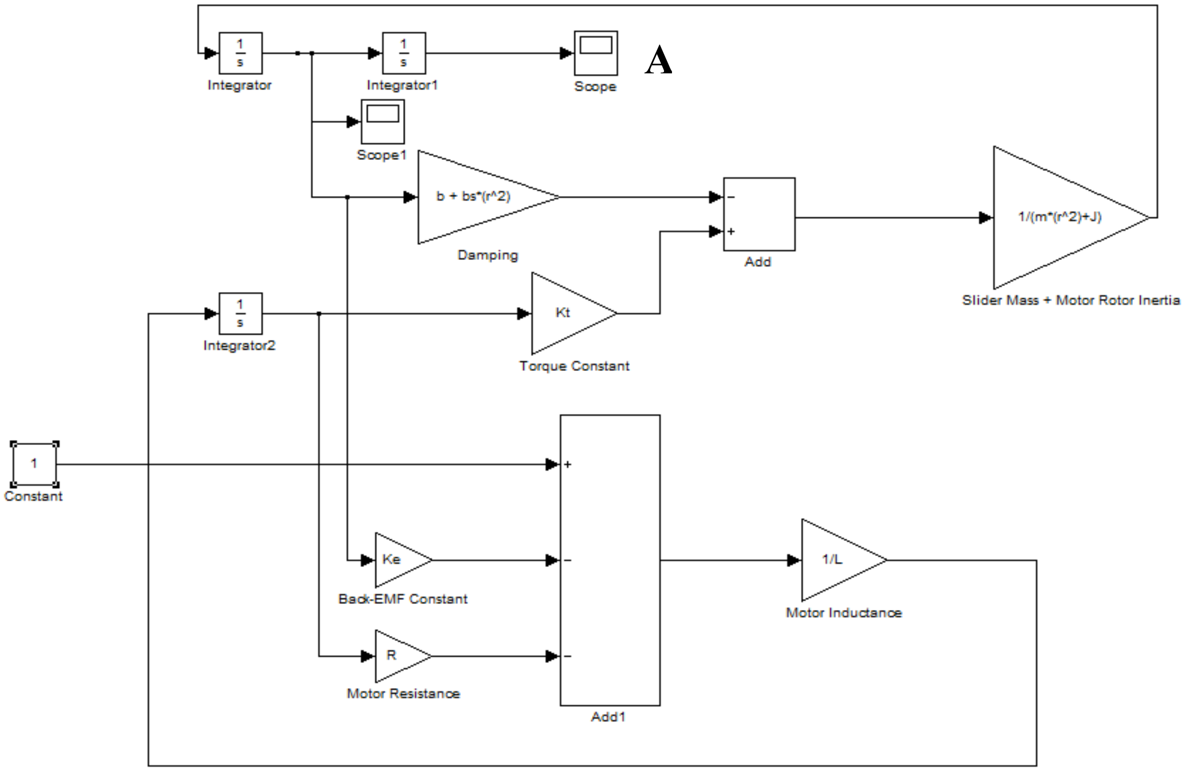

Figure 6. Simulink block diagram for the z-dimension motor transfer function

The plot produced from the scope labeled A in the Simulink block diagram is shown below.

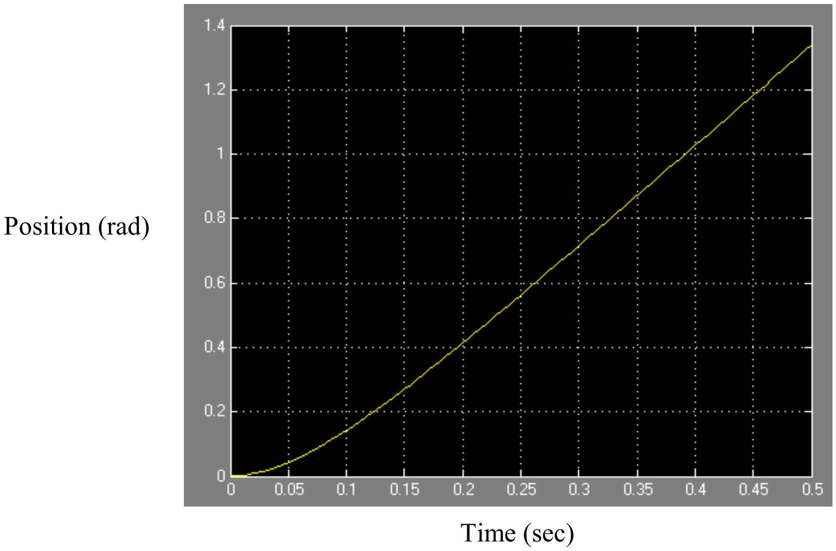

Figure 7. Motor shaft position (rad) versus time (sec); plot produced from the simulink block diagram transfer function for the z-dimension motor

The plot on the left side of Fig. 5 and the plot in Fig. 7 are exactly the same by comparing quantitative values point-by-point. Hence, confirming the result of the analytically derived transfer function.

4. Discussion

The stimulus apparatus will help further our understanding of the information transmitted by eight bilateral paired neurons, the Target-Selective Descending Neurons (TSDNs) in the dragonfly. These neurons are implicated in guiding the interception of flying insects by the foraging dragonfly. 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.

Once the device is fully functioning with closed loop feedback position control, we intend to perform sinusoidal frequency response tests to confirm the repeatability of the bead trajectory. Having the bead repeat a certain path is crucial for the project, because if the dragonfly elicited a certain response to a particular path, then we will have the ability to repeat that same path to see if we get similar results. Then we will program various bead trajectories, such as a raster-like motion where the bead covers the whole interior of the device and a collision-like path, where the bead trajectory forms a pyramid with the apex at the dragonfly's head. These paths will be used exclusively for test runs to prove that our device will actually elicit real neurophysiological responses in the dragonfly. More bead trajectory programs will be created for future research.

During experimental testing, the dragonfly will be held stationary while the TSDN signals are recorded either individually, with intracellular microelectrodes or in concert, with extracellular electrodes. Especially for the intracellular recordings, in which a microscopic (200 nm) electrode is inserted into individual neurons, it is crucial that the dragonfly be completely isolated from the vibrations caused by the mechanical components of the device. These could easily displace the electrode from the 15 – 40 micrometer axons. For this reason, the experimental animal and recording hardware will be 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 will not affect the electrophysiological recordings.

The expected results from the neurobiological studies with the apparatus will help us understand the interplay of the two major groups of descending inter-neurons that mediate the sensory control of flight; RSDNs and TSDNs. We expect to gain further comprehension of the visual selectivity and responsiveness of the TSDNs to three-dimensional object position and velocity[2]. 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.

5. References

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