Locomotion Control of a Bio-Robotic System via Electric Stimulation

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Abstract

This paper investigates the reaction of a living insect to electric stimulation. Artificial electrical stimulation is one of the tools of neuroethology to investigate the neural system. By creating artificial inputs to the system, specific reaction can be observed. The escape turn is a well-known reaction pattern of an insect in response to the appearance of a predator.

In the first part we analyze the locomotory reaction of an insect (Periplaneta Americana) to various electrical stimuli. These stimulus-reaction measurements are done on a light-weight styro-foam trackball which is connected to a computer. This allows to record the turning rate and the forward movement of the insect in response to antennal stimulation. Based on this data a simple mathematical model is established. As a simple example of an autonomous bio-robotic system and to verify the black-box model an electronic backpack which does line-tracking has been built. Using two photosensors as inputs the electronic backpack forces the insect to walk along a black line.

1 Introduction

Legged locomotion is still a difficult problem in robotics. The complexity of the sensory-motor integration of internal and external stimuli to generate stable and robust locomotion make legged locomotion a still difficult-to-solve problem. Insects have mastered this problem formidably. Insects have only 10^5-10^6 neurons, which is many orders of magnitudes less then the number of neurons in mammals (about 10^{10}-10^{12}). While there are still many neurons involved in visual processing, a single leg is controlled by a population of only about 70 motor neurons which all have been identified [1]. With the small number of motorneurons involved in insect locomotion, an understanding of the neural interaction and feedback seems not impossible. The insect locomotory system can then serve as an inspiration and a model for robotic locomotion control.

Using insects as parts of robotics systems has been proposed recently. Kuwana *et al.* [2] used the antennae of a silk moth (*bombyx mori*) as natural pheromone sensors on a small mobile robot. Using a recurrent neural network the robot was capable to recreate the naturally occurring zig-zag pattern of the real insect when following a pheromone plume in the air.

It is a well-known fact that excitable tissue such as muscles and nerves can be stimulated and controlled electrically. Plonsey *et al.* [3] analyze the effect of a point current source on an unmyelinated fiber. Electric stimulation via electrodes in the excitable tissue can be done by pulses from a micro-controller [4]. Arabi *et al.* [5] built a micro-stimulator based on an application-specific IC (ASIC), which receives energy and control commands over an RF link.

The locomotion of cockroaches is studied from the mechanical and neurophysiological aspect in [6] and [7]. Both authors have spent years of research on the locomotion behavior of the cockroach.

In the present paper we have built a computer interface with a trackball. The stimulation unit is centered around an 8-bit microprocessor. The electrodes were made from 100 µm-diameter platinum or stainless steel.

Further we have built a series of electronic backpacks which are placed on the back of a living insect. Following commands from a microcontroller the electrodes stimulate a whole nerve bundle. To achieve control over a single nerve fibre the use of micromachined electrodes together with flexible ribbon cables will be considered in the future [8].

2 Experimental setup

In order to create a mathematical black-box model of the cockroach behavior which links the electric stimulation

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signals to the behavioral output, the following system was built.

2.1 The trackball-computer interface

To measure the locomotory reaction to electric stimulation the cockroach is kept fix on a trackball (Fig. 1). A light-weight styro-foam ball (1.48 g) is placed on two optical rotary encoders (Sansei Electric OME-060-2) to record the ball's forward movement (pitch) and its rotation (yaw). The encoders give a resolution of 0.3 cm/incr. and 0.75 deg/incr. respectively. The encoder signals are decoded by an 8-bit µ-processor (PIC16LC71) which sends the results over a 9600 Baud serial line to a Macintosh computer. The encoders can work in *position mode* which returns the absolute position *s(t)* along the trajectory in cm and the absolute heading $\theta(t)$ in degs., or in *rate mode* which returns the turning rate $\dot{\theta}(t)$ in deg/sec and the forward speed *v(t)* in cm/sec. The host computer runs a LabVIEW program to chart the information received from the trackball and to save this data to a file. The µ-processor unit and the host computer are connected by a bidirectional line. The µ-processor sends trackball data to the host computer and the host computer in turn sends set-up and trigger commands back to the stimulation unit.

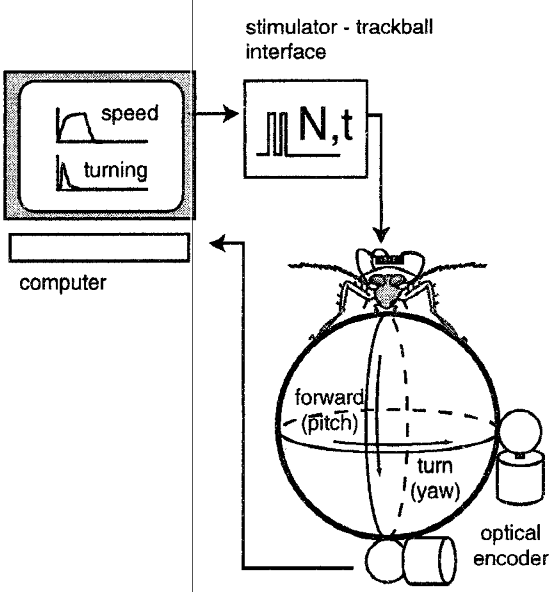

Figure 1: The trackball-computer interface.

2.2 Stimulus generator

On of the goals is to produce a portable stimulation unit, an electronic backpack, centered around an 8-bit µ-controller. To keep things simple the digital output is used directly to drive the electrodes. The µ-controller needs a supply voltage from 3 to 6 V. Depending on the type of peripheral sensors 1 or 2 Lithium cells were used to operate the circuit. The current flowing between the two electrodes is 10~100 µA corresponding to a tissue impedance of several tens of kOhms.

The stimulation signal is a train of rectangular pulses with a repetition rate *N* between 1 and 100. The pulses have a duty cycle of 50% and the pulse width *t* varies between 0.1 ms and 10 ms. The duration of the pulse train is:

$$\Delta T = N \cdot 2t \tag{1}$$

The energy used for a single stimulus with typical values is:

$$E = viNt = (3)(30\times10^{-6})(30)(1\times10^{-3}) = 0.27\times10^{-5}\text{J} \tag{2}$$

The CMOS µ-controller runs at any clock speed from DC up to 4 MHz. At low clock speeds the current consumption is around 1 µA and goes up to about 1 mA in the MHz range. When using low clock speed and the sleep command to shut down the processor several months of operation should be possible.

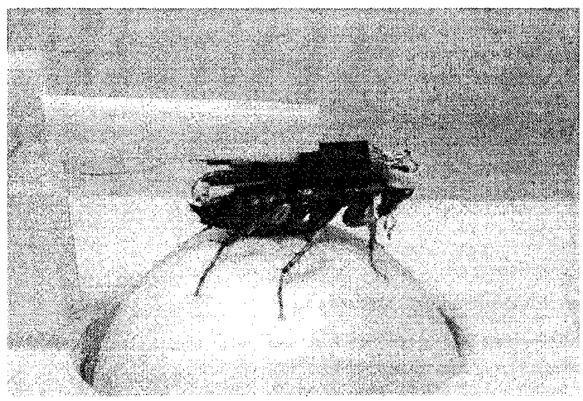

Figure 2: The cockroach on the trackball.

3 Experimental results

3.1 The distance as a function of parameter N and time

In the following series of experiments the forward distance in response to a stimulus was measured for 4 different settings of parameter N (3, 10, 30, and 100) and a constant parameter t=1ms. To minimize the influence of fatigue and sensitivity change over time, these four different stimuli are alternated. The stimulus strength is increased every 15 seconds from 3 to 100. This is repeated 10 times. The results are shown in Fig. 3, where the distance walked is plotted for four different settings of stimulus strength *N*. In general the order of the output (distance) coincides with the order of stimuli strength (number of pulses) but there are some overlaps. If we calculate the

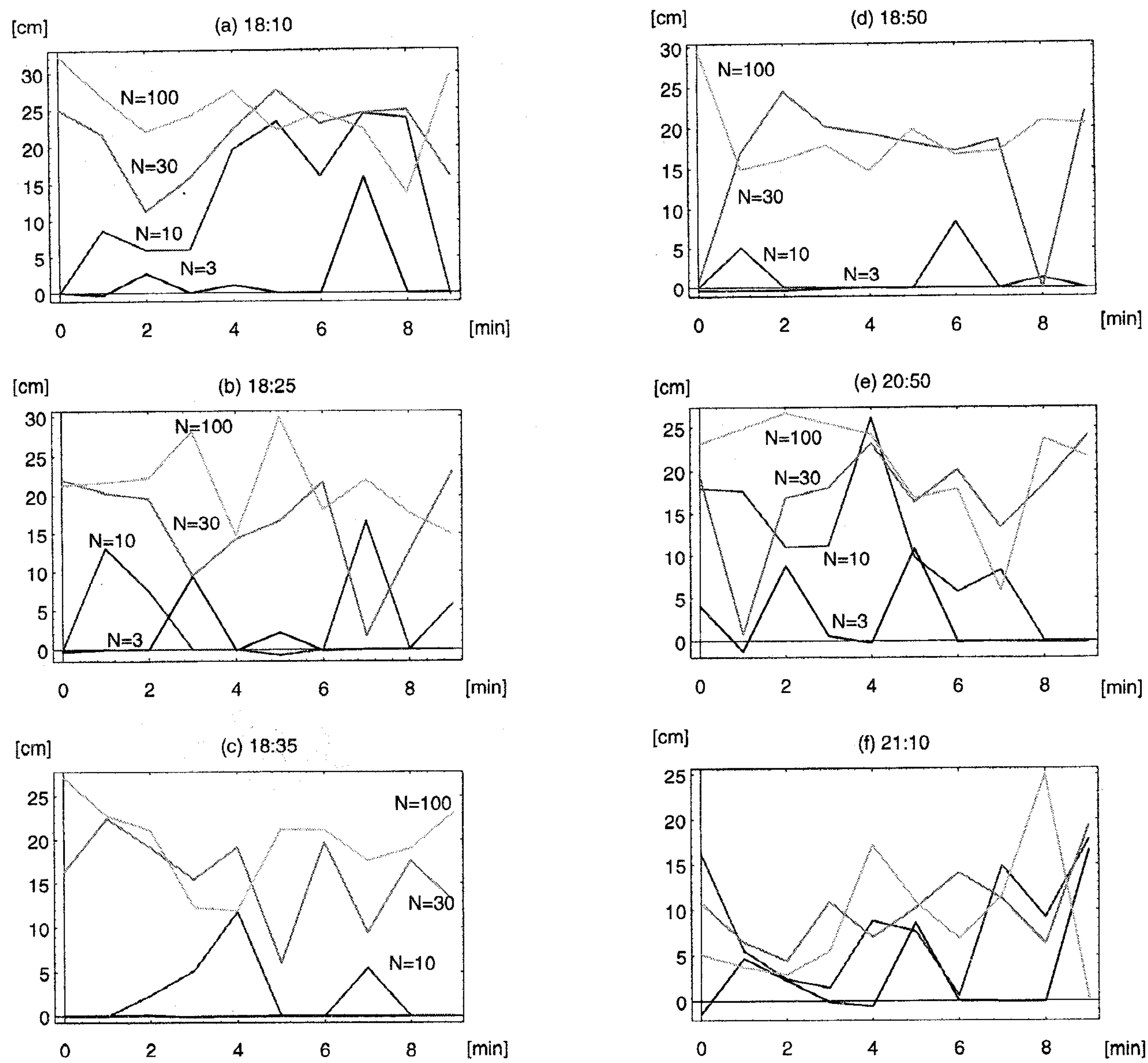

Figure 3: Distance walked for different stimulation parameter *N*.

average of these values as shown in Fig. 4, the strong variation is cancelled and we can see the underlying dependence of the output result on the input stimulus strength. There we can also see the fatigue effect of repeated series of stimuli (each series comprises 40 stimuli). If the cockroach has time to recover (2 hours between series 4 and 5), the sensitivity to stimuli increases again.

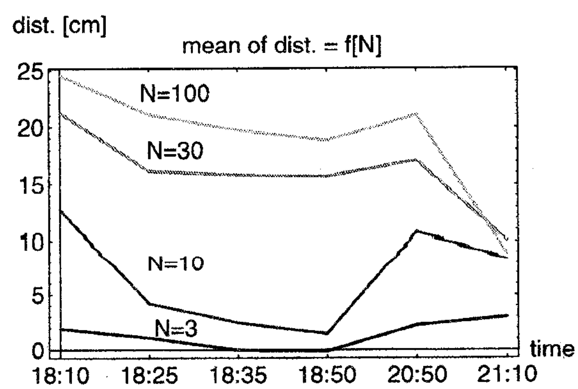

Figure 4: Average distance over time.

3.2 The turning angle as a function of electrode site and parameter N

Applying electric stimuli to the antennal stump results in an escape motion towards the contralateral direction. In a series of experiments the rotation angle was recorded for stimuli alternating between the left and the right antenna. These results are shown in Fig. 5. Every 30 seconds a stimulation train is applied to the cockroach under test. The stimuli are alternatingly applied to the left and the right antenna. The rotation angle for each stimulus is measured. From the plots we see there is quite good directional separation between stimuli to the left and to the right. Only a few times the lines overlap. The turning angle increases with N, however if the total pulse duration as given in eq. 1 exceeds 200 ms the directionality decreases. The reason is that for bursts longer than 200 ms the insect first turns to the opposite side but turns back shortly after. Therefore to control direction the antennal pulse train must be short.

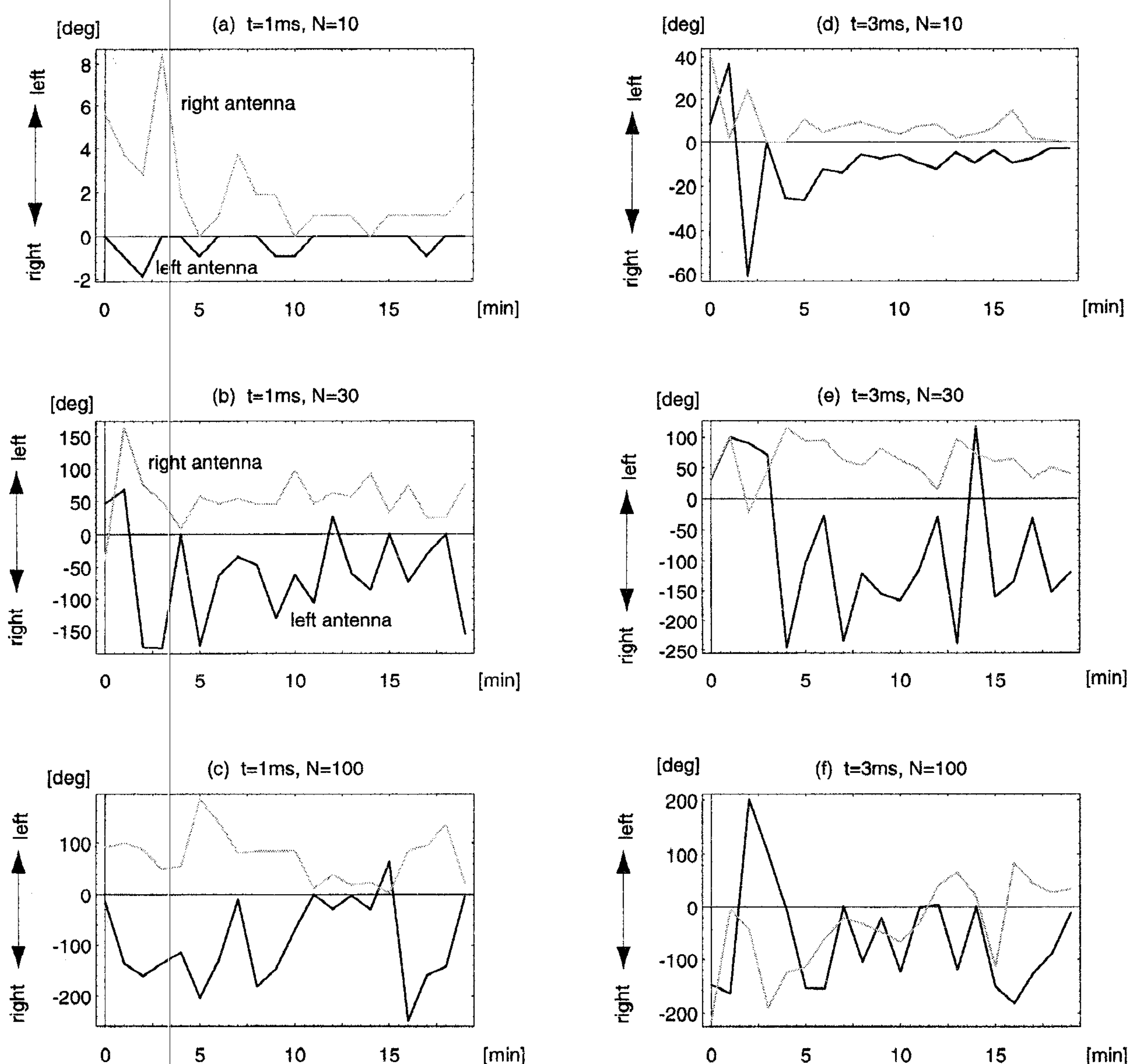

Figure 5: Rotation angle for stimuli alternating between left and right.

When plotting the mean turning angle as a function of N (see Fig. 5) we see a monotonously increasing relation between the parameter N and the rotation angle θ. However if the total stimulation pulse train length is too long then the reaction decreases. An optimum seems to be around 100~200 ms.

3.3 Statistical mean and standard deviation as a function of parameter N

There is quite a lot of stochastic variation in the output, but when averaging the output values one can detect an underlying regularity of the input-output relationship that follows Weber's law which states that perceived intensity

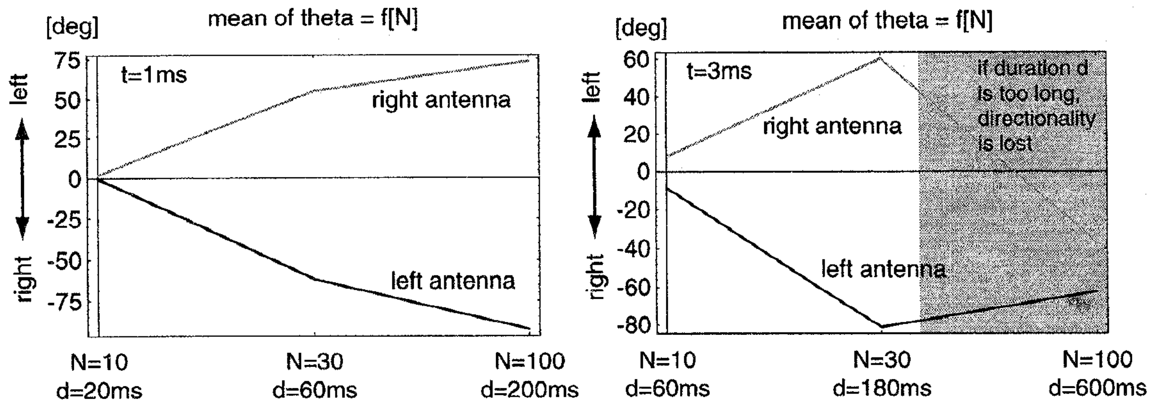

Figure 6: Mean of theta for 3 values of *N*.

is proportional to the logarithm of physical intensity. Fig. 7 shows the time evolution of the reaction to a repeated series of stimuli of alternating strength. The parameter N takes again the values 3, 10, 30, and 100.

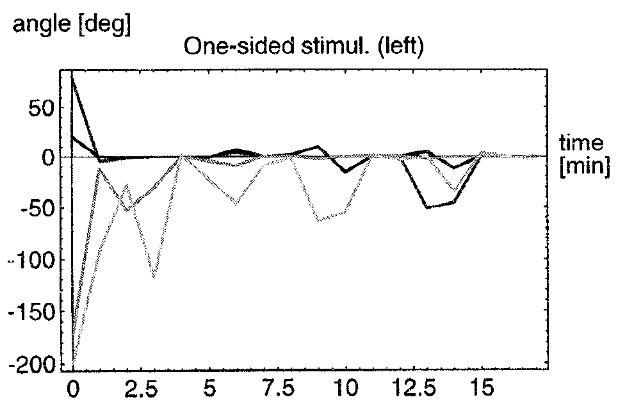

Figure 7: Turning reaction to a one-sided stimulus.

This plot shows that the reaction (turning angle) decreases in the form of a negative exponential. This is due to fatigue and desensitization caused by repeated stimuli. Plotting the average values on a log-lin graph shows that above a certain threshold (N=10) the points lie on a straight line.

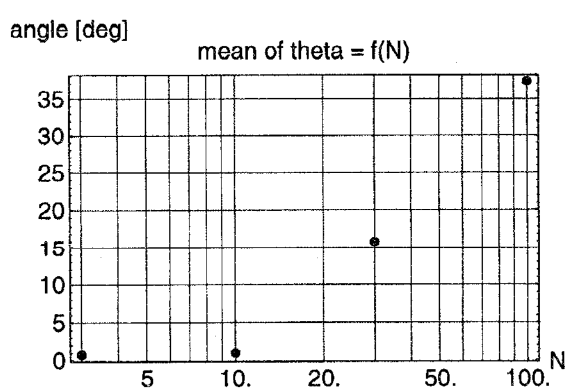

Figure 8: Mean of theta plotted for N=3, 10, 30, 100.

$$\overline{\theta(N)} = k \cdot \log N \tag{3}$$

The same holds for the standard deviation of the turning angle. Again these points lie on a straight line (see Fig. 9).

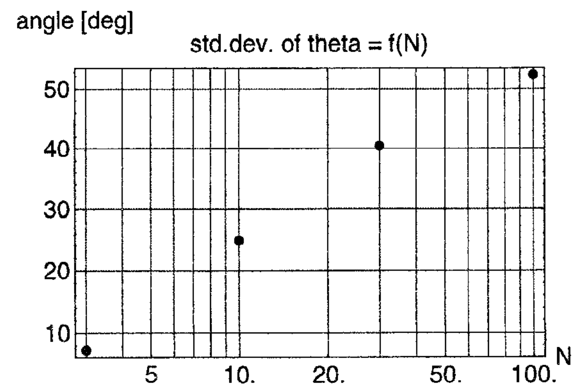

Figure 9: Standard deviation of turning angle.

4 Mathematical Model

From the experimental results in the previous section we propose the following "black-box" model of the input-output relationship composed of 3 stages:

1. *Logarithmic scaling* of input stimuli strength according to Weber's law. There is a minimum threshold level below which the insect does not react. There is also a maximum stimulation intensity above which the output doesn't change.

$$f(N) = k \cdot \log N \tag{4}$$

2. Internal *state and history.* This stage represents the fatigue and desensitization due to the accumulated previous stimuli. It is expressed as:

$$f_{\text{hist.}} = e^{-\left(\frac{a(i)}{a_{1/2}}\right)}, \qquad a(i) = \sum_{j=0}^{i} \log N \tag{5}$$

where $a(i)$ is the accumulated effect of the previous stimuli, and $a_{1/2}$ is the accumulated stimuli that makes the output drop to 1/e. As time passes, there is partial recovery.

3. *Stochastic change* to the output. The output is multiplied by a random variable with a Gaussian distribution:

$$Normal(\mu = 1, \quad \sigma = 1) \tag{6}$$

The three stages of the black-box model are shown in a block diagram as multiplicative factors in Fig. 10. The terms in stage 2 and 3 are normalized to 1.

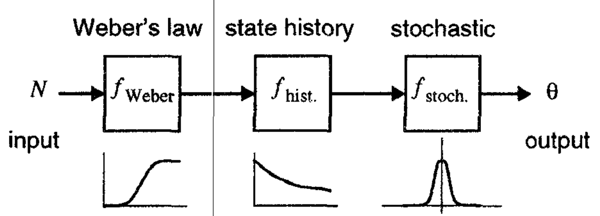

Figure 10: 3-stage model of input-output relation.

5 Autonomous electronic backpack

As a simple demonstration of a fully autonomous system, a line-tracing electronic backpack was built (Fig. 11). The controlling circuit is built on a 50μm-thin poly-imide PCB with SMD components. The whole circuit including a 3 V lithium cell weighs 1.9 grams, which is about two times the body weight of the cockroach. The circuit obtains information from its environment by two photosensors and uses an on-board algorithm to control the living insect via electric stimulation to walk along a black line. The algorithm is simple: the insect is placed on the black line with a photo-sensor on each side. If the insects walks off the line a sensor will detect the black line and give a stimulus to the opposite site. This makes the cockroach turn back onto the line. For short distances the insect can be kept on the track, however due to the large standard deviation the insect cannot be kept on the track for a very long time.

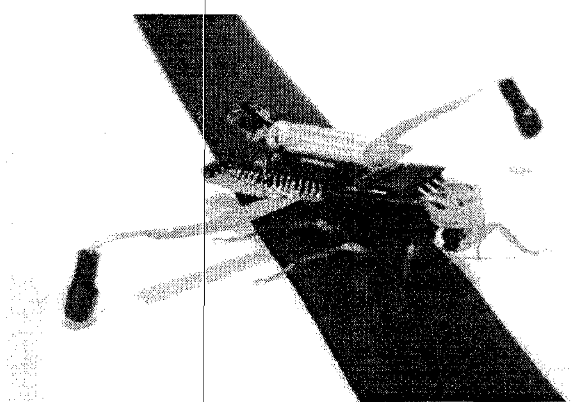

Figure 11: An electronic backpack in action.

6 Conclusions

The experiments with the cockroach show that the response to electrical stimulation on the antenna has directionality, but the variance is rather large. Limited directional locomotion control could be achieved with an electronic backpack by stimulating the afferent nerve fibres of the antennae.

In one experiment a cockroach carried an electronic backpack with stainless steel electrodes implanted in its abdomen for 5 months. Experiments with one-way infrared wireless communication were done as well. However due to the higher operating voltage necessary (5 V) the circuit became quite heavy and restrained the free movement of the insect.

The possibility of onboard signal generation opens interesting ways in entomological field research. The authors believe that by scaling down further the microelectrodes and miniaturizing the electronic circuitry the concept of an electronic backpack will be a tool contributing to a better understanding of the nervous system and the development of new models in insect neuroethology.

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