

AN OPTOELECTRONIC SENSOR FOR MONITORING SMALL MOVEMENTS IN INSECTS

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ABSTRACT

Optical movement detectors are often used in laboratory studies of insect behavior. They offer advantages of time resolution and ease of analysis compared with video. However, design and construction have rarely been described in enough detail to allow the devices to be built easily by others. We describe a simple optoelectronic system for measuring rapid movements in one dimension, such as the protraction of an insect leg. The leg casts a bar-shaped shadow onto a photodiode chip that is masked to expose a triangular area. Movement of the leg changes the total area of the triangle that is shaded. A preamplifier converts the change in photoelectric current to a voltage signal. The preamplifier includes an optional circuit for removing 120 Hz ripple resulting from AC-powered light sources by subtracting the output of a second, reference photodiode. We have used the system to quantify leg movements in an acoustic startle response of a field cricket (*Teleogryllus oceanicus* LeGuillou). This system could be adapted for a wide range of other applications in laboratory and field research.

Key Words: leg motion, position detector, photodiode, optoelectronic photodetector, cricket acoustic startle response

RESUMEN

Detectores ópticos de movimiento han sido usados frecuentemente en estudios de comportamiento de insectos en el laboratorio, donde ofrecen ventajas de resolución de tiempo y facilidad de análisis comparado con video. Sin embargo, su diseño y construcción han sido raramente descritos en suficiente detalle para permitir que otros puedan construir estos aparatos fácilmente. Describimos un sistema optoelectrónico para medir movimientos rápidos en una dimensión como la protracción de una pata de insecto. La pata forma una sombra en forma de barra a un chip fotodiodo que esta cubierto para exponer una área triangular. El movimiento de la pata cambia el área total del triangulo que esta sombreado. Un preamplificador convierte el cambio en corriente fotoeléctrica a una señal de voltaje. El preamplificador incluye un circuito para nulificar ondulación de 120 Hz de fuentes de luz con electricidad AC al restar la producción de fotodiodo de referencia. Hemos usado el sistema para cuantificar movimientos de pata en una respuesta de susto acústica del saltamontes *Teleogryllus oceanicu* (LeGuilou). Elementos de este sistema pueden también ser adaptados para otras aplicaciones en estudios de laboratorio y de campo.

Optoelectronic position detectors may be used to quantify behavior in a wide variety of settings. Optoelectronic methods have two advantages over video: (1) Temporal resolution is not limited by video frame rate, and (2) The detector can measure a single parameter of movement or position that would require extensive labor or computer processing to extract from video records. Descriptions of optoelectronic devices in the biological literature generally emphasize the unique features of a particular detector without providing details of design and construction. Potential users may be discouraged from applying these methods if they lack the practical electronics background to adapt the circuits found in electronics cookbooks or technical literature from chip manufacturers. We de-

scribe a photodetector and amplifier designed for monitoring leg protraction in a tethered flying Polynesian field cricket (*Teleogryllus oceanicus* LeGuillou), and readily adaptable to other uses as described in Results and Discussion.

We are studying an ultrasound-induced escape response in crickets, a flight turn that is a defense against echolocating bats (Moiseff et al. 1978). A cricket is flown on a tether and given pulses of ultrasound from a loudspeaker mounted to its left or right. We monitor one component of the startle response, a lateral outward swing of the metathoracic leg contralateral to the source of ultrasound (May & Hoy 1990). This movement has ~30 ms latency and 45 to 65 ms time-to-peak, too rapid to quantify with conventional video. We designed an

optoelectronic detector to convert leg position to a continuous voltage signal that indicates position without the need of further processing. The design uses a triangular detection surface in such a way that movement of the leg's shadow produces a change in illumination, and incorporates a method for canceling the light ripple that is found in AC powered light sources. These features are demonstrated below (Results and Discussion).

This device has performed well in measurements of the cricket acoustic startle response (e.g., Engel & Hoy 1999). Movement of the metathoracic femur is faithfully represented as a voltage signal, and ripple due to AC line power is eliminated. The circuit is conservatively designed using parts that are readily available in electronics stockrooms or outlets such as Radio Shack (electronics vendors and photodiode suppliers are listed in Appendix A). The circuit and photodetector are described in sufficient detail to be built as they are, and they could also be adapted to a variety of other purposes. It is our hope that descriptions such as this will enable more widespread use of optoelectronic methods in entomology and in biological research in general.

MATERIALS AND METHODS

This section describes the essential features of design and construction. Additional notes are provided in Appendix A, along with a list of parts and suppliers. For an introduction to electronic components, schematic diagrams, and assembly techniques see Mims (2000) or other basic texts.

Movement Detector

There are several approaches to optoelectronic movement detection. (1) Use of small arrays of discrete photodetectors to determine the position of a light or shadow (e.g., Kittmann 1991; Erber & Kloppenburg 1995; Roberts 1995). (2) Use of a linear position-detector photodiode chip (e.g., Helversen & Elsner 1977; Hedwig 1988; Kelly & Chapple 1988; Mayer et al. 1988; Hedwig & Becher 1998). (3) Use of a simple photodetector chip to measure a moving shadow (e.g., Meyer et al. 1987; Rüschi & Thurm 1989; Clark et al. 1990; Götz 1987; May 1990). The first two approaches are relatively complicated, and reports have not given sufficient details for circuits to be constructed readily. Our device is a refinement of the third approach.

If a shadow has a single moving edge, then a simple rectangular photodiode can act as a position sensor because the shaded area varies linearly with position, resulting in a linear change in the output of the photodiode (Meyer et al. 1987; Rüschi & Thurm 1989; Clark et al. 1990). However, when the shadowing object has both leading and trailing edges, as an insect appendage does, the shadow's

area does not change with position. In this case, a mask with a triangular or crescent-shaped opening can be interposed into the light path between the appendage and the photodetector (Götz 1987; May 1990; May & Hoy 1991). As the appendage's shadow moves to a wider part of the triangular opening, the shaded area of the photodetector increases. This makes a simple and effective position indicator, as we show below (Results and Discussion). In the cricket leg position detector described here, a triangular mask is affixed directly to the photodetector surface, as in May (1990), eliminating the need for optics between the mask and the photodetector, as in Götz (1987).

Our photodetector uses a 10×20 mm unpackaged silicon photodiode chip (EG&G Vactec, St. Louis, MO, VTS 3081). A predecessor of our design used a CdS photoconductor chip in a voltage-divider circuit (May 1990). We chose a silicon photodiode because of its superior frequency response and uniform surface geometry compared with CdS photoconductors (*Photodiodes*, Hamamatsu, Bridgewater, NJ, 1997). For structural support, the chip is fastened with double-sided foam tape to an IC (integrated circuit) mount (Fig. 1C) with the chip lead wires soldered to the pins. A second IC mount serves as a socket, with wires leading to the amplifier. In our setup this socket is attached to a swivel ball joint mounted on a rod. The small size of the detector assembly allows it to be placed around electrodes for simultaneous neural and behavioral recording from a flying cricket (J.E.E., unpublished data) and minimizes disturbance of the acoustic field.

The photodiode chip is masked with black graphics tape (Chartpak, Leeds MA) to leave a triangular area exposed (Fig. 1C). The tethered cricket is illuminated from above with a fiber-optic light guide, so that the metathoracic femur casts a bar-shaped shadow onto the photodetector, which is 1 to 2 cm below the leg. As the leg pivots laterally, its shadow moves to a wider part of the triangle. The area of the shadow on the triangle, and the resulting change in photocurrent from the photodetector, are proportional to the magnitude of lateral movement (see Results and Discussion).

Position Amplifier

A photodiode produces a current directly proportional to the amount of illumination (*Photodiodes*, Hamamatsu, Bridgewater NJ, 1997, p. 5). The amplifier (Fig. 1A) converts this current signal to a more conveniently analyzed voltage signal with the desired level of gain. The first operational amplifier (op amp), IC1, of the position amplifier converts current (i) to voltage (v). The current-to-voltage gain is determined by feedback resistance R , with the relationship $v = iR$. The value of R is best chosen by trial and error

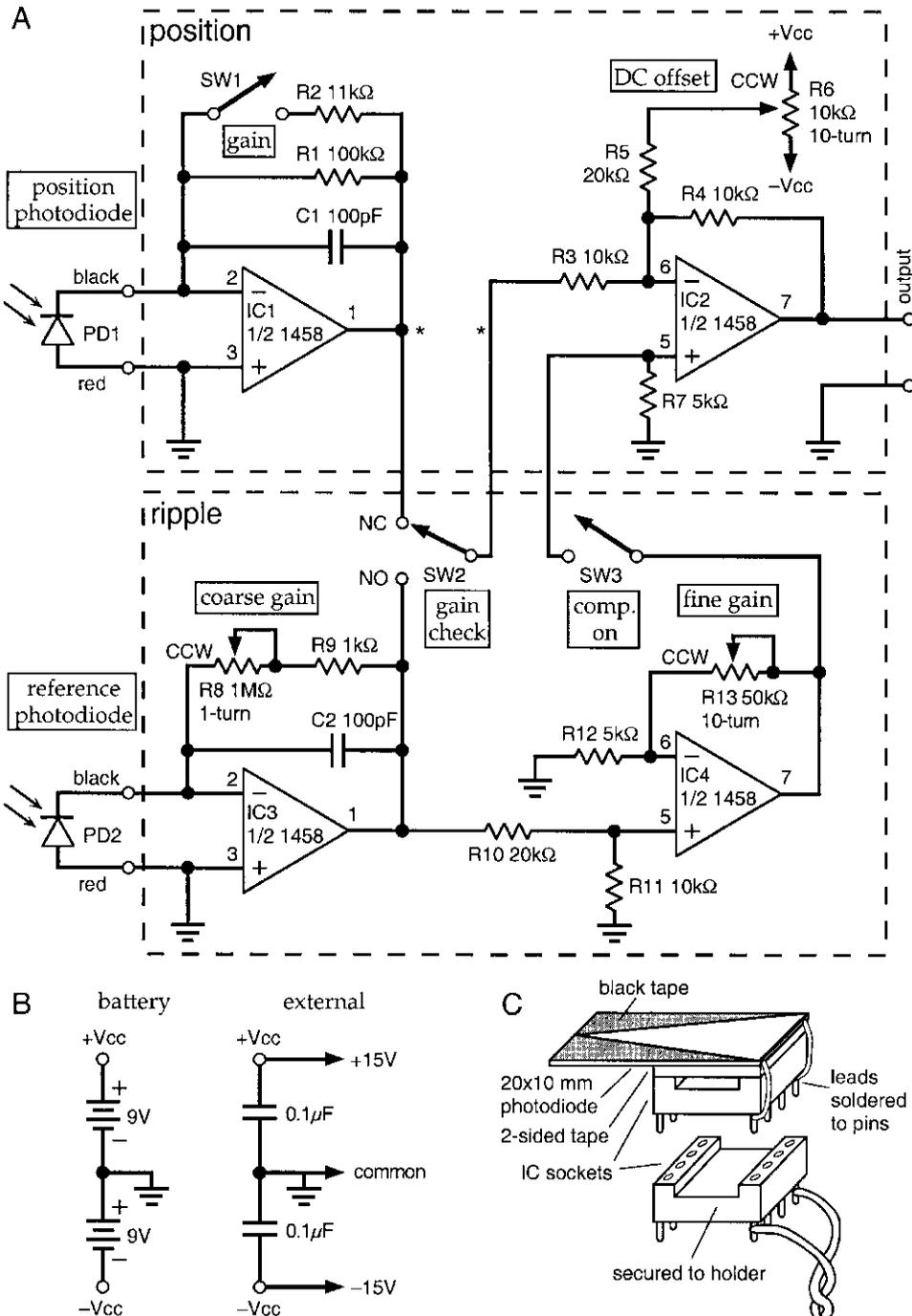


Fig. 1. Position detector design. A. Amplifier circuitry. The two components, the position amplifier and the ripple-compensation amplifier, are outlined in dashed boxes. If the position amplifier is built alone, the points indicated by asterisks are connected. Each IC is half of a 1458 dual op-amp package, with numbers indicating pin assignments. In R6, R8, and R13, CCW indicates the lead that has zero resistance when the potentiometer is turned fully counterclockwise. Abbreviations: C, capacitor; CCW, counterclockwise; IC, integrated circuit; NC, normally closed; NO, normally open; PD, photodiode; R, resistor; SW, switch; Vcc, power supply voltage. See Appendix A for a list of parts. B. Power can be provided by two 9 V batteries (left) or an external DC power supply not exceeding ±18 V (right). Open circles labeled +Vcc and -Vcc are nodes to be connected to the op-amp packages (pins 8 and 4, respectively) and to the terminals of R6. C. Photodetector. A photodiode is masked to expose a triangular area and mounted to an 8-pin integrated circuit (IC) socket for physical support. A second IC socket serves as a connector to the amplifier.

because the appropriate gain depends upon the strength of the light and the size and sensitivity of the photodiode. In our setup, R is 10 or 100 k Ω , set by $R1$ or by $R1$ and $R2$ in parallel ($R = R1 \times R2 / (R1 + R2)$). If lower light levels or a smaller photodiode are used, an R of several megaohms might be required. Switch $SW1$ allows switching between two gain settings during operation.

The second op amp ($IC2$) adds a DC offset to the signal, allowing the baseline of the output voltage to be adjusted to the middle of the input range of a recording device or oscilloscope. Potentiometer $R6$ controls the amount of DC offset, functioning as a voltage divider together with resistor $R5$. $IC2$ also inverts the voltage signal. In our setup the anode of the photodiode (red lead) is connected to the positive input of $IC1$ so that a leg swing away from the body (which increases shadow area) causes a negative photocurrent fluctuation leading to a negative voltage signal. $IC2$ inverts this so that the lateral leg swing of an escape response produces a positive output signal. If a negative-going signal were desired, the photodiode leads would be connected in the reverse orientation. Either orientation is permissible because the photodiode is not voltage-biased in this circuit.

Ripple Compensation

Light from AC-powered lamps can have a pronounced ripple at twice the line frequency (120 Hz in North America). In our setup a standard fiber optic light source (Dolan-Jenner, Woburn MA, Series 180) provides strong illumination with low heat and allows the lamp housing to be kept outside of the Faraday cage. However, the optic ripple is considerable (Fig. 2B).

This ripple can be cancelled electronically (Fig. 2B). A reference photodiode is placed near the movement detector but out of the path of the cricket's shadow. Both photodiodes pick up the light ripple, and the movement detector also senses a change in illumination as the leg moves. Ripple is eliminated by subtracting the reference signal from the movement signal. The reference photodiode need not be identical to the movement detector photodiode, nor need their levels of illumination be matched, because the gain of the reference signal can be adjusted over a large range. Appendix B shows a straightforward method for adjusting the gain so that the reference signal exactly cancels the ripple in the movement signal.

The first op amp ($IC3$) of the ripple compensation amplifier converts the reference photocurrent to a voltage signal (Fig. 1A). Coarse gain control is adjusted at this stage by potentiometer $R8$, and fine gain control is adjusted at the second op amp ($IC4$) by potentiometer $R13$. The reference signal is subtracted from the movement signal by feeding it into the positive input of the position

amplifier's second op amp ($IC2$). To build the position amplifier only, without ripple compensation, connect the points marked with asterisks in Fig. 1A and omit all components in the ripple section.

An alternative to electronic subtraction of light ripple is use of a DC-powered light source (Fig. 2B). We converted our Dolan-Jenner fiber optic light source to DC power by cutting the wires that connect the variable transformer to the lamp, diverting the transformer output to a DC converter in a separate housing, and feeding the DC power back to the lamp. The DC converter consists of a full-wave rectifier protected with a heat sink, with the output leads connected across 93,000 μF of capacitance in parallel to the lamp. Because the cost of capacitors increases with voltage rating, 15 V capacitors were used and the power supply transformer is kept in the lower end of its range. This provides ample light for our purposes.

Testing Linearity and Ripple Compensation

To show that the voltage signal is a linear function of shadow area, a metal rod (2 mm diameter) was mounted on a motor so that it swung across the photodetector 1.5 times per second (Fig. 2A). The far edge of the photodiode was 108 mm from the axle, giving the rod a speed of 1 m/s as it passed over the photodiode. The output of the amplifier was recorded without ripple compensation and with electronic compensation (Fig. 2B, left and center traces). Then, with electronic compensation inactivated, the DC converter was switched into the lamp power supply without otherwise altering the setup (Fig. 2B, right trace).

To demonstrate adjustment of ripple compensation (Fig. 3), the position photodetector was set up to monitor the left metathoracic femur of a tethered flying cricket. The reference photodetector was a fragment of a broken solar cell (~0.15 cm² lit area). Voltage outputs were digitally sampled at 5 kHz and 0.3 mV resolution. To show escape responses in both directions (Fig. 3E), a second photodetector and amplifier (also with ripple compensation) monitored the right metathoracic femur. Both photodetectors were in place throughout the series of records in Figure 3. Ultrasound pulses were 20 kHz carrier frequency, 10 ms duration. The cricket preparation and acoustic setup have been described elsewhere (May & Hoy 1991; Wyttenbach & Hoy 1997); as previously, hind wings were cut short so they would not interrupt the light path.

RESULTS AND DISCUSSION

Linearity of Movement Detection

Photodiode chips have a uniform photosensitive surface (in contrast to photoconductors, which have a zigzag ribbon of photosensitive material).

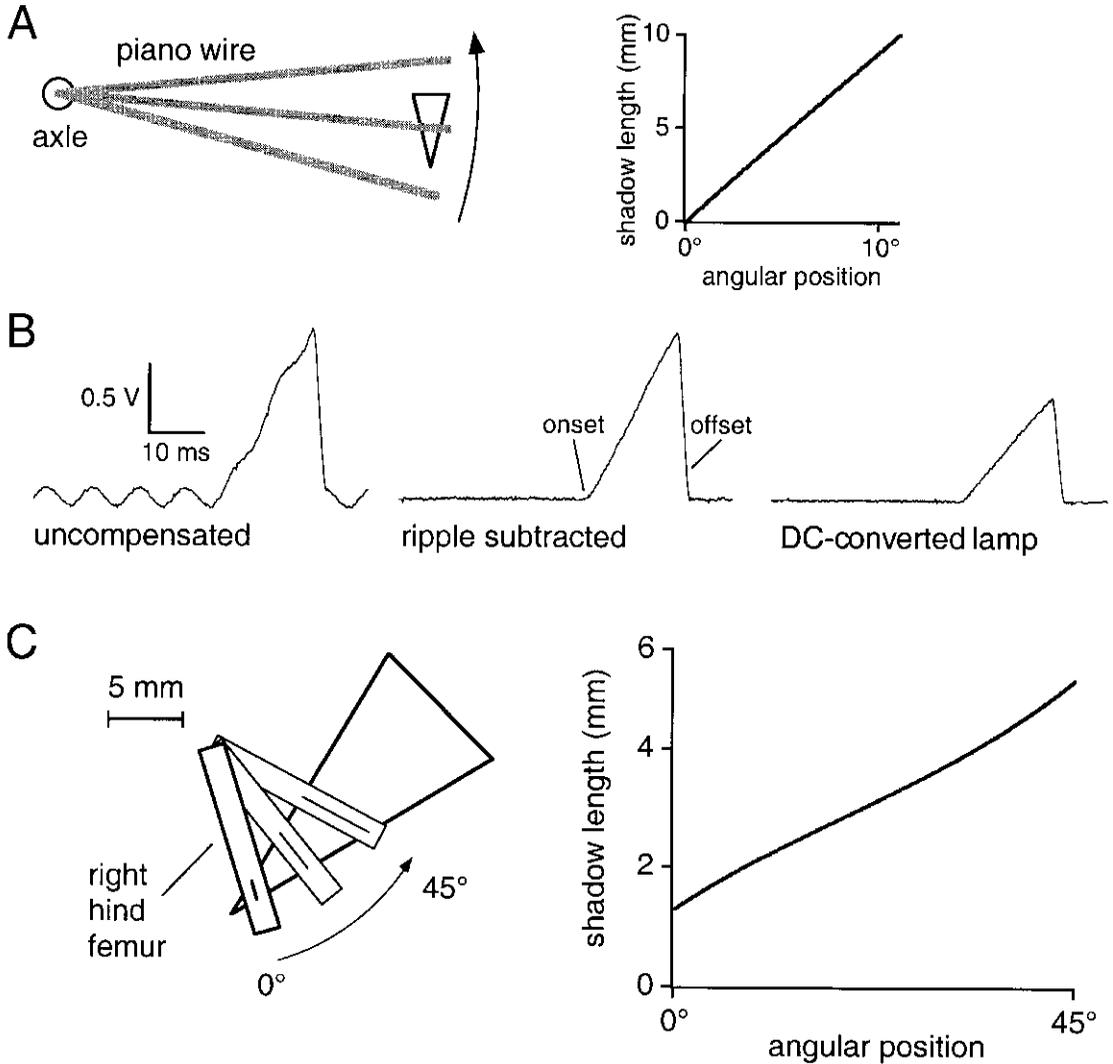


Fig. 2. System performance. A. Linearity testing. A 2mm thick rod passed across the photodiode at a speed of 1 m/s. The shadow's area is proportional to its length on the triangular photodetector. The graph shows the calculated length of the rod's shadow as a function of its angular position. B. Ripple compensation. Using the above setup, records were made without compensation for light ripple (left), with electronic compensation (center), and with the light source converted to DC operation (right). The two compensated traces are linear, as predicted in part A. Onset and offset are not instantaneous because of the 2 ms time required for the full width of the shadow to enter or leave the triangle. C. Calculations for a cricket leg. The metathoracic femur is essentially rectangular when viewed from above. As long as its shadow crosses the entire triangle, the area of the shadow on the triangle is proportional to its midline length. The calculated midline length is an approximately linear function of angular position over a range of at least 45°.

The photocurrent output of a photodiode should be a linear function of the area that is illuminated (or the area that is shaded). To test this, a rod about as thick as a cricket hindleg femur was moved across the triangular detector such that the area of the rod's shadow on the photodetector increased uniformly with time (Fig. 2A). The output signal increased uniformly as well (Fig. 2B), indicating that the output signal is a linear function of shaded area.

For the output signal to faithfully indicate leg deflection, however, the shaded area itself must be a linear function of the angular movement of the femur. This assumption holds rather well, provided that the photodetector is positioned so that the femur is perpendicular to the axis of the triangle when the femur is in the middle of its range of motion (Fig. 2C). This was demonstrated with a trigonometric model. The shadow of the femur on the photodetector can be represented as a

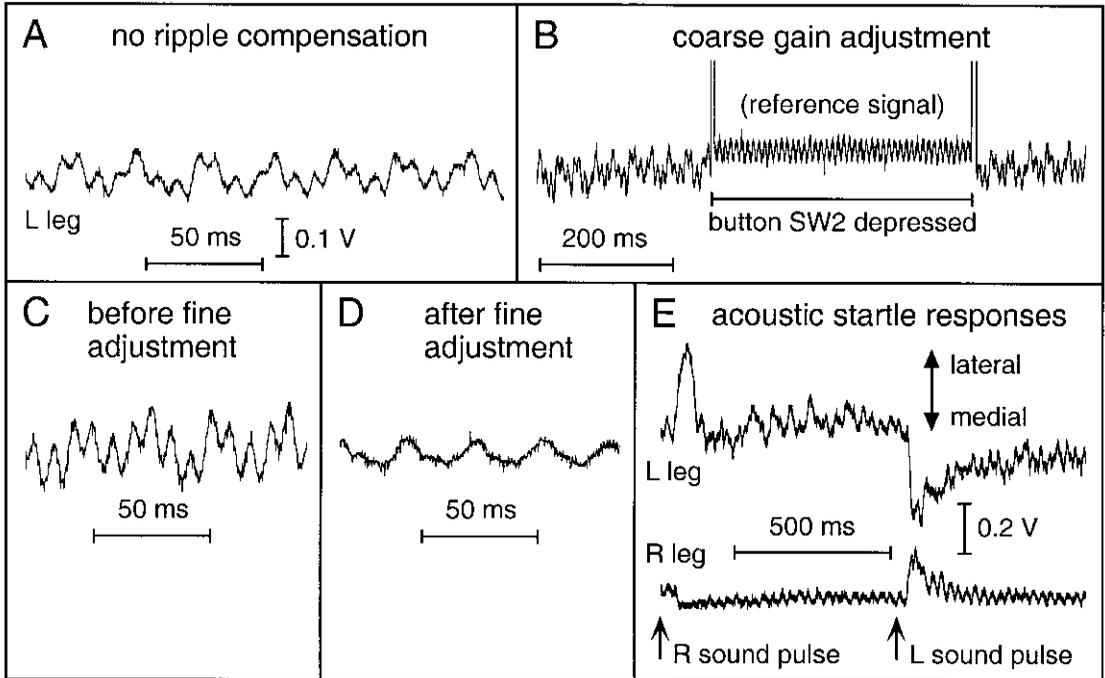


Fig. 3. Adjustment of ripple compensation. The position photodetector monitored the left metathoracic femur of a tethered flying cricket. Voltage scale of Panel A applies to all panels except E. A. Signal without ripple compensation (SW3 open). Fluctuations are a combination of light ripple (120 Hz) and leg vibration due to wing beats (~35 Hz). B. Coarse gain (R8) is adjusted to minimize the jump of the trace when the reference signal is switched into the movement amplifier path using pushbutton SW2. C. Ripple compensation is engaged (SW3 is closed) but fine gain has not been properly balanced to eliminate ripple. D. Fine gain (R13) has been adjusted to minimize ripple. Remaining fluctuations reflect real leg movements due to wing vibration. E. Escape responses in the same preparation. A second photodetector and amplifier monitored the right metathoracic femur. For both legs, a positive voltage signal indicates lateral deflection. Ultrasound pulses from the right and then the left side (arrows) evoked outward lateral movements of the contralateral hind legs. Differences in amplitudes of vibration and escape response between the two legs were real (not an artifact of using two different detectors and amplifiers).

bar of uniform thickness (Fig. 2C). As long as this bar crosses two sides of the triangle, the area of the shadow on the triangle will always be proportional to the length of the shadow at its midline. The trigonometric model shows that with optimal positioning of the photodetector, this midline length is an approximately linear function of angular movement over a range of 45° (Fig. 2C) (leg movement in the escape response rarely exceeds 20° , Miles et al. 1992).

In our experiments it is not necessary to determine the relationship between the degree of movement and the amplitude of the voltage signal. We are concerned with relative changes in the amplitude of the leg response in a habituation paradigm. The habituated responses are simply normalized to control responses within the same trial. However, the position-to-voltage scale for a trial could be determined by moving the cricket's femur to different angles using forceps, recording the resulting voltage output levels, and measuring the leg angles from videotape recordings made during the same manipulations.

Compensation for Light Ripple

When illumination is provided by an AC light source, the optic ripple adds substantial "noise" to the movement signal (Fig. 2B; Fig. 3A). We compared two methods for eliminating this ripple, subtracting it electronically or adding a DC converter to the light source. Both approaches worked well (Fig. 2B). Electronic subtraction is the most flexible method because any source of light can be used. The gain of the reference signal must be calibrated with each use, but this can be done by a simple procedure (Appendix B, Fig. 3). DC illumination is the more direct method. DC illuminators may not be commonly found in many laboratories, but an AC unit can be converted to DC operation as described above.

Other Applications

This design includes a photodetector that converts angular position to a photoelectric signal, a photodiode amplifier with DC offset compensa-

tion, and a second amplifier incorporating continuous gain adjustment and subtraction of its output from the first amplifier. These three components could be adapted to a variety of uses. (1) The photodetector could monitor other appendages such as wings or antennae, and the shape of the mask could be altered as needed to track the movement of a particular appendage (Götz 1987). Photodiodes come in several sizes, from 1×3 to 20×20 mm, and can be connected in parallel if larger areas are needed (larger solar cells may also be used). (2) The position amplifier could be used with an unmasked photodiode in applications where the timing of movement is of more interest than its spatial characteristics. For example, in the laboratory an unmasked detector could indicate the wing beat frequency of a tethered insect or detect an animal's transit past a point in a cage. The latter application could be adapted in the field for counting visits to a colony or lure. (3) The ripple compensation amplifier could serve as the basis for other applications requiring differential processing, such as automatic compensation for variation in ambient light levels. Another potential application is dual-photodiode movement detection (Crawford & Fettiplace 1985; Iwazumi 1987), in which a shadow overlaps two adjacent photodiodes and moves onto one as it moves off of the other.

The advantages of fine temporal resolution and simplicity of analysis mentioned in the Introduction make optoelectronic movement detection attractive for a variety of applications. We hope that this description will provide a point of entry for workers without much electronics background, and a starting point for those with more experience who can modify the design to suit their particular applications.

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APPENDIX A: CONSTRUCTION AND DESIGN NOTES

Photodiode chips in sizes from 1×3 mm to 20×20 mm are available from Advanced Photonix (Camarillo, CA, 805-987-0146, www.advanced-photonix.com), Perkin Elmer (formerly EG&G Vactec; St. Louis, MO, 314-423-4900, www.perkinelmer.com) and Hamamatsu (Bridgewater, NJ, 908-231-0960, usa.hamamatsu.com). Solar cells of 20×40 mm are available from Edmund Scientific (Barrington, NJ, 800-728-6999, www.edsci.com) and Radio Shack (Fort Worth, TX, 800-843-7425, www.radioshack.com). Allied Electronics (Fort Worth, TX, 800-433-5700, www.alliedelec.com), Newark Electronics (Chicago, IL, 800-463-9275, www.newark.com), and Radio Shack are comprehensive vendors that carry all the remaining parts.

In addition to the two photodiodes, the circuit shown in Fig. 1 A requires the following parts: fixed $1/4$ or $1/8$ Watt resistors of 100 k Ω (R1), 11 k Ω (R2), 10 k Ω (R3, R4, R11), 20 k Ω (R5, R10), 5 k Ω (R7, R12), and 1 k Ω (R9); variable resistors of 10 k Ω (R6), 1 M Ω (R8), and 50 k Ω (R13); 100 pF capacitors (C1-2), type 1458 dual op-amp packages (IC1-4); SPST switches (SW1, SW3); SPDT momentary pushbutton switch (SW2); DPST switch (power on/off, not shown in Fig. 1). Note that R6 and R13 should be 10-turn potentiometers for greater precision in setting DC offset and ripple gain. Other parts needed to house the circuit include a case, circuit board, connection jacks (banana or BNC), and so on.

We used bipolar 1458 dual op amps (Radio Shack 276-038) because they are resilient and readily available. For biological applications requiring exceptional high-frequency or low-noise performance, this design could be refined by selecting high-performance op amps, by optimizing the feedback capacitance (C1), or by voltage-biasing the photodiode. Guidelines can be found in technical literature from photodiode manufacturers (e.g., *Photodiodes*, Hamamatsu, Bridgewater, NJ, 1997).

Resistors R1 and R2 should be at least 1 k Ω to prevent exceeding the op amp current rating, yet small enough to avoid saturating the op amp at high light intensities. The ideal values of R1 and R2 for a particular setup are best determined by trial and error. This process is made easier if R1 and R2 are plugged into an IC socket instead of being soldered directly to the circuit board. The range of gains available during normal use could be extended over several orders of magnitude by making SW1 a rotary switch and installing additional resistors. Capacitor C1 is included to prevent ringing. However, it should be noted that the feedback circuit is a low pass filter with a cutoff

frequency of $f = [2\pi R1 C1]^{-1}$; therefore C1 should be small enough to avoid filtering out biological signals of interest.

The maximum useful gain of the first op amp of the position amplifier is limited because the DC baseline resulting from overall illumination is amplified along with the signal due to movement. If movements of the leg shadow are small relative to the lighted area of the photodiode, the final output signal after DC compensation will also be small. This can be countered to some extent by reducing the unused lighted area of the photodetector as much as possible. At the second op amp, the baseline signal is subtracted using DC offset compensation. Therefore, an additional amplifier stage could be placed after the second op amp if more gain were needed. We have not found this to be necessary.

In the DC offset compensation circuit, R5 should not be much greater than R4 because the ratio R4/R5 is a gain factor that limits the available range of offset. At the same time, R5 must be greater than R6 to give R6 sufficient linearity as a variable voltage divider. A "voltage-follower" amplifier could be added as a buffer between R6 and R5 if desired. This would make the R6 voltage divider linear without regard to R5, and would also allow a larger R6 to be used (to reduce the current drain on batteries, for instance).

APPENDIX B: ADJUSTING RIPPLE COMPENSATION

For electronic subtraction to be effective, ripple in the reference and position signals must have the same amplitude. This is achieved by adjusting the gain of the ripple compensation amplifier through the following simple procedure:

1. *Adjust position detector amplifier.* Set oscilloscope to DC mode and confirm that ripple compensation is not engaged (SW3 is open). Set the position amplifier gain (SW1) and adjust DC offset (R6) to center the signal (Fig. 3 A).
2. *Adjust coarse gain of reference signal.* Use the momentary pushbutton (SW2) to switch the reference signal into the movement amplifier path (Fig. 3 B). Adjust R8 to minimize the jump in the oscilloscope trace as SW2 is pressed and released.
3. *Adjust fine gain to minimize ripple.* Switch the oscilloscope to AC mode and engage ripple compensation by closing switch SW3 (Fig. 3 C). Adjust R13 to minimize the size of the ripple (Fig. 3 D). In this example (Fig. 3 D), light-source ripple has been effectively eliminated. The remaining "noise" is biological in origin (leg vibration due to wing beats).
4. *Readjust DC offset.* Return the oscilloscope to DC mode and adjust DC offset (R6) to center the trace.