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Effectiveness of a worker-worn electric-field sensor to detect power-line proximity and electrical-contact

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ABSTRACT

Problem: Construction workers suffer the most electrocutions among all industries. Currently, there are no electrical contact warning devices on the market to protect workers. This paper proposes a worker-worn electric-field sensor. As the worker is in proximity to, or in contact with, a live power-circuit, the sensor sets off an audible/visual warning alarm. The sensor also has the potential to wirelessly trip a wireless-capable circuit breaker, and to trigger a wireless transmitter to notify emergency response of an electrical contact. *Methods:* An experiment was conducted to measure electric-field variation on simulated human-wrists (10 defrosted hog-legs) in various proximities and in electrical-contact to a simulated power-circuit. The purpose of these tests was to determine the feasibility of developing a worker-worn electric-field detection sensor for use in protecting workers from contact with energized electrical conductors. *Results:* This study observed a significant electric-field-magnitude increase as a hog-leg approaches the live-circuit, and the distinct electric-field-magnitude jump as the leg contacts with the live-circuit. The observation indicates that this sensor can be an effective device to warn the workers of electrical hazards. Additionally, the sensor has the potential to wirelessly trip a wireless-capable circuit-breaker and trigger a wireless transmitter (such as a cell phone) to notify an emergency response. The prompt notification prevents the worker from further injury caused by postponed medical-care. *Impact on Industry:* Widespread use of this sensor could lower electrocution and electrically related injury rates in the construction industry.

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1. Introduction

The Census of Fatal Occupational Injuries (CFOI) data show that the electrical event was the sixth leading cause of occupational fatalities in the United States between 1992 and 2002 and contact with electric current was the fifth leading cause of occupational fatalities in the United States between 2005 and 2007. According to a study based on the National Traumatic Occupational Fatality (NTOF) database, construction industry workers suffered 40% of the total number of electrocutions for all occupations (with 160 annual electrocutions between 1980 and 1992) and had the highest death rate from electrocutions among all industries (McCann, Hunting, Murawski, Chowdhury, & Welch, 2003; Kisner & Casini, 1998). Although the annual average number of electrocutions declined to 143 between 1992 and 2003 (McCann, n.d.), the high number of electrocutions is still a safety concern in the construction industry. The Occupational Safety and Health Administration (OSHA) identifies on its "OSHA Construction eTOOL" website that the following five hazards are the most frequent cause of electrical injuries: (a) contact with powerlines, (b) lack of ground-fault protection, (c) path to ground missing or discontinuous, (d) equipment not used in manner prescribed, and (e) improper use of extension and flexible cords (OSHA, 2009a).

Among the electrical injury protection measures, the most effective method is the lockout/tagout procedure. Lockout/tagout is one of the OSHA regulations established to control hazardous energy; it covers the servicing and maintenance of machines and equipment in which the "unexpected" energization or start up of the machines or equipment, or release of stored energy, could cause injury to employees (OSHA, 2008). The lockout/tagout procedure effectively isolates the energized wires from the workers and protects workers from electrical injury.

In some special circumstances the workers need to work around a live wire. Before an employee works with the limited approach boundary of the energized electrical conductors or circuit parts, the employer should demonstrate that de-energizing introduces increased hazards, or the task to be performed is infeasible in a de-energized state (National Fire Protection Association [NFPA], 2009). The documented procedures should be followed and special equipment should be used to provide proven effective protection for employees (OSHA, 2008). In these working conditions a second line of protection is often necessary. Even for a worker who works in the lockout/tagout condition, a second line protection can protect the worker from electrical injury caused by

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unexpected nearby energized wires that are not locked-out or tagged out, such as an overhead powerline.

In order to protect construction and other workers from contacting overhead powerlines, some system concepts were proposed to detect powerline proximity using electric field sensors (Arcolando, Diercks, Hopkins, & Lynch, 2001; Paques, Bourbonnière, Laliberté, & Nguyen, 1995). Some electrical safety manufacturers have developed a variety of personal protective equipment that is able to warn the workers as they are in proximity of an energized power circuit (Homce, Cawley, & Yenchek, 2008; HD Electric Company, 2004). All of these proximity warning devices have a built-in electric field sensor to measure the 50 ~ 60 Hz electric field emitted by a nearby energized powerline. The devices, which detect worker body proximity to an overhead powerline, are hung around a worker's body. The devices, which detect crane proximity to a powerline, attach electric-field sensor probe(s) to a crane boom. All devices measure the 60-Hz electric field intensity to determine the proximity from the sensor to an energized powerline. The measured electric field intensity is inversely related to the distance between the device and the powerline. If the measured electric field intensity exceeds the pre-defined threshold, the devices set off audible or visible alarms to warn the workers of their body or crane boom proximity to the powerline. The electric field intensity emitted by an energized powerline is directly related to the powerline voltage. Since the sensitivity threshold of these sensors are pre-adjusted to detect a powerline with the voltage of usually 2400 volts or higher, the devices are effective in detecting high-voltage overhead powerlines (HD Electric Company, 2004). At a low-voltage (less than 600 volts), the electric field emitted by a power circuit is much weaker than at high-voltage. For the devices mentioned above, both their amplification gain and the proximity threshold are usually calibrated at the high-voltage electric field. At low-voltage, the devices become less capable, or even not functional, for detecting the proximity of power circuits, and therefore are less effective or even cannot protect workers working near a low-voltage power circuit or equipment, or while holding low-voltage electrical tools (usually at less than 600 volts).

If any of the five construction electrical hazard events (OSHA, 2009a) occur, it will cause electrical-contact between a worker(s) and an energized power circuit, and will likely cause electrical injuries to the construction worker(s). Unfortunately, since the above electric field sensors do not attach to the human body, they cannot detect a worker's body contact with an energized power circuit, and therefore cannot trigger a wireless transmitter to: (a) wirelessly send a tripping command to a wireless-capable circuit breaker to immediately de-energize the powerline; and (b) wirelessly send an immediate electrical-contact notification to a rescue office as a worker is in contact with an energized power circuit. This notification is especially useful for a lone worker who is electrically injured on a construction site without any immediate attention.

To address the issue that the current electric field sensors cannot be calibrated for both the high and low-voltage proximity detection, a National Institute for Occupational Safety and Health (NIOSH) project proposed a new type of electric field sensor that is capable of detecting the proximity of a worker's body to both high-voltage and low-voltage power circuits. In addition, the sensor is able to detect a worker's electrical-contact with an energized powerline or with a piece of electrical equipment with leaking voltage. This sensor could be used to design a powerline proximity detector that sets off audible or visible alarms as a worker approaches a high-voltage or low-voltage power line, sets off an electrical-contact alarm to warn the other on-site workers of the event, and triggers a wireless transmitter to send out an immediate wireless notification as the worker electrically contacts an energized circuit (a powerline, a piece of faulty electrical equipment, or power cord). Additionally, the sensor has the potential to wirelessly trip a wireless-capable circuit-breaker.

2. Methods

2.1. Configuration of Electric Field Sensor

The major configuration difference between this proposed electric field sensor and other electric field sensors mentioned above is that this sensor is equipped with a body electric field probe that is attached to a worker's wrist. Other electric field sensors do not have a body electric field probe. This wrist probe is composed of a pair of elastic conductive fabric cuffs strapped to a worker's wrist. The probe monitors the electric field on the worker's body. As the worker approaches a power circuit the correspondent body electric field monotonically increases. If the worker electrically contacts the circuit, the body electric field will have a significant jump that will allow the signal processor in the sensor to easily recognize the electric field jump as an electrical-contact, set off the electrical-contact alarm, and set the electrical-contact trigger. This trigger could activate a wireless transmitter to transmit an electrical-contact notification to a rescue office in a future proximity detector design. It also has the potential to transmit a signal to trip a wireless breaker.

The other distinct device configuration is that this sensor has a two stage signal output that amplifies both the low-voltage and high-voltage electric fields. The low-voltage electric field stage has a high-gain amplifier and the high-voltage electric field stage has a low-gain amplifier. As the worker approaches a low-voltage circuit, the sensor sets off a low-voltage proximity alarm. As the worker approaches a high-voltage powerline, the sensor sets off both low- and high-voltage proximity alarms.

2.2. Electric Field Sensor Probe

As mentioned, the electric field sensor probe is composed of a pair of elastic conductive fabric cuffs. The width of the cuffs is 2 cm, and the length of the cuffs is long enough to surround a worker's wrist. The cuffs are separated 10 cm apart and insulated from the wrist with a thin plastic film (about 2.54 micro-meter thick). According to Eq. 1 for cylindrical capacitance (AJ Designer, 2009),

$$C = \frac{2\pi\varepsilon_0\varepsilon L}{\ln\frac{b}{a}} \tag{1}$$

where C is cylindrical capacitance between the cuff and the wrist, $\varepsilon_0 = 8.85$ pF/m, $\varepsilon = 2$ (plastic dielectric constant), $L = 20$ mm (cuff width), $a = 60$ mm (wrist diameter) and $b = 60.00254$ mm (cuff diameter), the capacitance between the cuff and the human wrist is 53 nF. The electric field sensor probe is capacitively coupled with the human wrist.

2.3. Power Circuit Electric Field in Proximity and Electrical-contact Conditions

As the worker's wrist is near an energized power circuit without electrical-contact, the probe senses the electric field emitted by the power circuit, as shown in Eq. 2 (Griffiths, 1999),

$$E_r = \frac{\lambda}{2\pi\varepsilon_0 r} \tag{2}$$

where E_r is the vector electric field on the probe in the radial direction, λ is the charge density on the power circuit which is proportional to the voltage on the circuit, and r is the distance from the power circuit to the probe on the wrist (r is much shorter than the length of the power circuit). If more than one power circuit exists, the total electric field is the superposition of these individual vector fields.

2.4. Computer Modeling to Simulate Human Wrist in Electrical Proximity and Contact

The computer modeling to simulate the electric field distribution on a human wrist in electrical proximity and contact conditions was

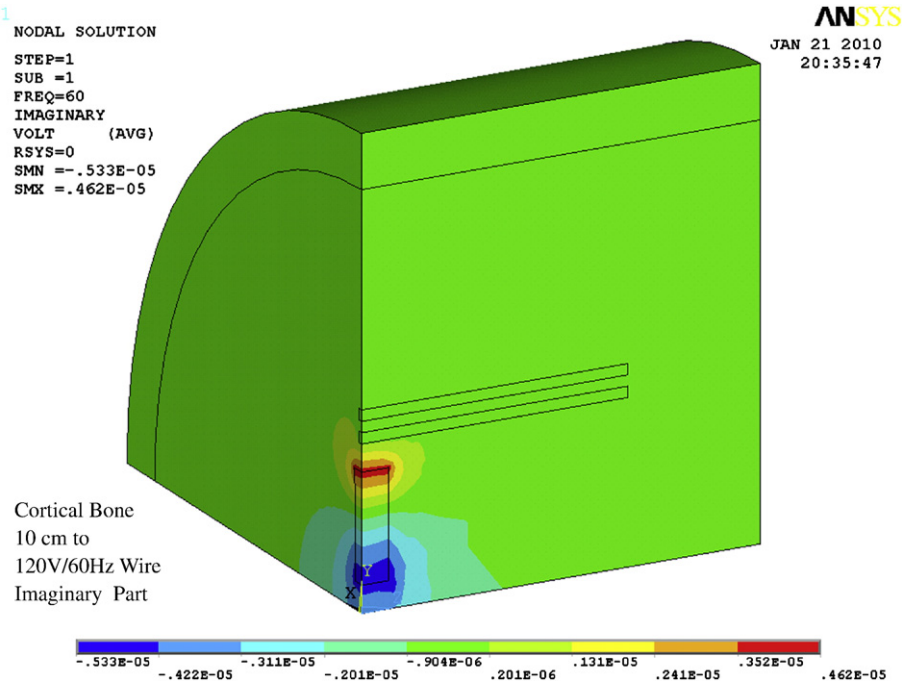


Fig. 1. The electromagnetic field modeling shows 9.95 micro-volts of voltage difference across the ends of a cortical bone as the bone is 10 cm apart from a 120 volt power circuit.

conducted in the NIOSH electronics lab using ANSYS Multiphysics finite element analysis software. The human wrist was simulated by a cortical bone, which is the main composition of a human wrist, with a conductivity of 0.02 Siemens/meter, a dielectric constant of 7,692.6, and a length of 40 cm. The simulated electric field modeling shows that the imaginary voltage across both ends of the cortical bone is 9.95 micro-volts, as the bone is 10 cm away from a power circuit energized with 120 volt/60 Hz power source (Fig. 1).

As the cortical bone electrically contacts the 120 volt power circuit (in the modeling, a 10 mega-ohm resistor was connected between the circuit and the bone to simulate the wrist skin resistance), the bone with a conductivity of 0.02 Siemens/meter becomes a part of the energized circuit. In this case the electric field modeling shows -3.4856 volts of imaginary voltage on the top of the bone and -3.4861 volts on the bottom (Fig. 2).

The voltage difference across the bone is 500 micro-volts, 50 times higher than when the bone is 10 cm away from the 120 volt circuit. This voltage discrepancy clearly differentiates the electric field on the cortical bone with electrical-contact from that with proximity.

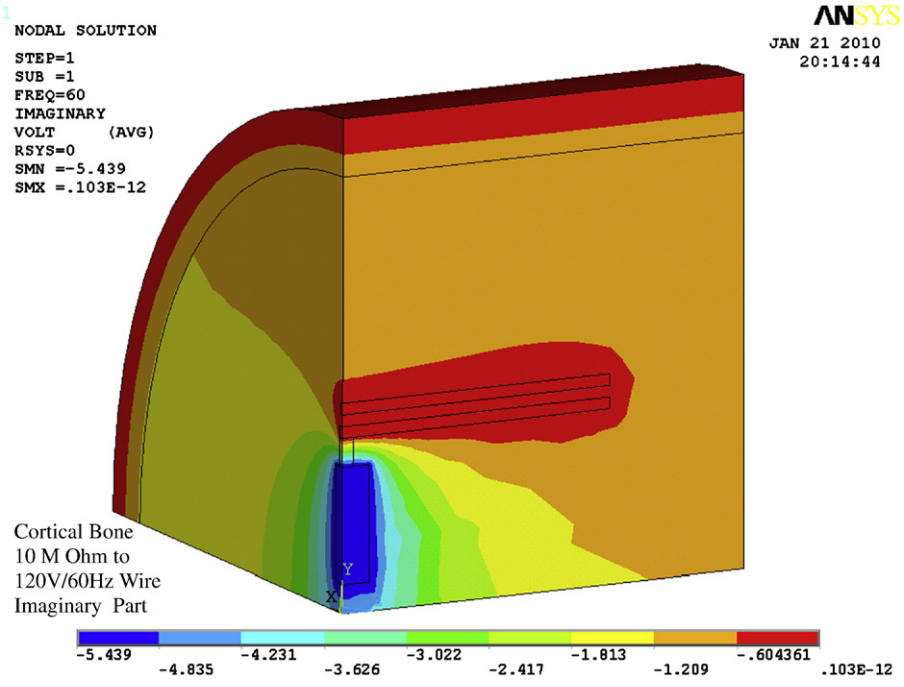


Fig. 2. The electromagnetic field modeling shows 500 micro-volts of voltage difference across the ends of a cortical bone as the bone electrically contacts the power circuit.

At high-voltage, the electric field modeling shows that the imaginary voltage across the ends of the cortical bone is 746 micro-volts, as the tissue is 10 cm away from a power circuit energized with 9,000 volt/60 Hz power source (Fig. 3).

The data obtained from the ANSYS electric field modeling show that it is feasible to design an electric field sensor that monitors the wrist electric field to detect both the wrist proximity and electrical-contact with a low-voltage (120 volts) power circuit, and to detect wrist proximity to a high-voltage (9,000 volts) powerline. A high-gain amplifier that can pick up electric field signal in the micro-volt range is needed in the electric field sensor design.

2.5. Experimental Electric Field Sensor Circuits

The experimental electronic circuitry of the electric field sensor is composed of a variable high-gain preamplifier, a 60-Hz narrow band-pass filter, a fixed-gain post amplifier, an analog-to-digital signal converter, a microcontroller, a 915 MHz RF digital signal transmitter, a 915 MHz RF digital signal receiver, and a desktop PC with a digital data acquisition board, as shown in Fig. 4.

In order to avoid any signal interference caused by an improper grounding connection, the input and output of the sensor circuit are isolated from any real ground and have no direct connection with the PC. The measured electric field signals are sent to the PC via 915 MHz RF transmission. The initial electric field signals picked up by the wrist sensor probe are weak and with ambient interfering electrical signal spectra. These initial electric field signals are pre-amplified by the pre-amplifier. The amplified signals are sent to the 60-Hz band-pass filter with a bandwidth of only 3 Hz to filter out the interfering frequency spectra. The filtered signals are sent to the post-amplifier, which amplifies the signals to 1-5 volt range in order to be digitized by the analog-to-digital converter. The converted digital electric field signals are "biphase" encoded by the microcontroller to become a "0"/"1" balanced signal stream, which is suitable for RF transmission. The biphase electric field digital stream is sent to the 915 MHz Frequency Modulation (FM) transmitter in the sensor to be frequency-modulated and wirelessly transmitted to a nearby 915 FM wireless digital signal receiver that is connected to a desktop PC via a digital data acquisition board. The wireless receiver demodulates the FM signal stream and sends the stream to the PC via the digital data acquisition board. The LabVIEW program in the PC decodes the biphase electric field signals and translates the signals back into the voltage values.

Fig. 5 shows a photo of the Electric Field Sensor (right) and the 915 MHz FM Receiver (left).

The Electric Field Sensor has the sensor circuitry and the 915 MHz FM transmitter in its box. On its panel, there is one buzzer (in black color) for generating the audible alarm, two gain switches (in dark-red color) to adjust the amplifier gains for high-voltage proximity, low-voltage proximity, and low-voltage electrical-contact measurements, three LED indicators to indicate the sensor working status, two circuit reset switches (white color), one power switch (lower-right), and two sensor probe cables (red cable is "active" and black cable is "ground"). In the experiments, the two sensor probe cables were connected with two conductive cuffs attached on the simulated human wrists.

2.6. Using Hog Legs to Simulate Human Wrists

Since the experiments were conducted with live 120 volt and 9,000 volt simulated power circuits, it was extremely dangerous to let human subjects approach the live power circuit. Some biological tissue substitutes must be used to substitute human subjects in the experiments. The hog front legs' anatomical structure is very similar to that of a human wrist, with most of the tissue mass as cortical bones, and some minor amount of muscle, fat, and skin. It is expected that the conductivity and permittivity of a hog front leg are similar to those of a human wrist.

In the experiments, 10 defrosted hog front legs were used to simulate human wrists. Each of the hog legs was packaged in a thin film (about 2.54 micro-meter thick) plastic bag in order to insulate the hog legs from the conductive cuffs, as shown in Fig. 6.

Two elastic conductive fabric cuffs were tightened around the leg. The first cuff was placed 7-8 cm from the tip of the leg hoof, and the second was placed 10 cm apart from the first cuff in proximity/electrical-contact experiments. In orientation experiments, the second cuff was placed 5 cm apart from the first cuff.

2.7. Experimental Setups

The proximity and electrical-contact experiments were conducted on two Plexiglas boards, as shown in Fig. 7.

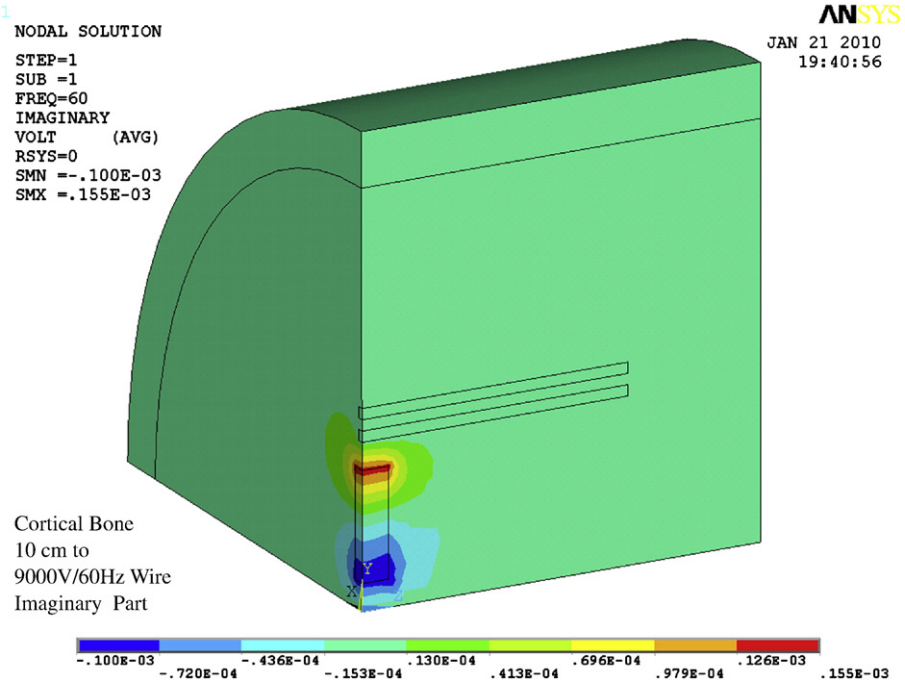


Fig. 3. The electromagnetic field modeling shows 255 micro-volts of voltage difference across the ends of a cortical bone as the bone is 10 cm apart from a 9,000 volt power circuit.

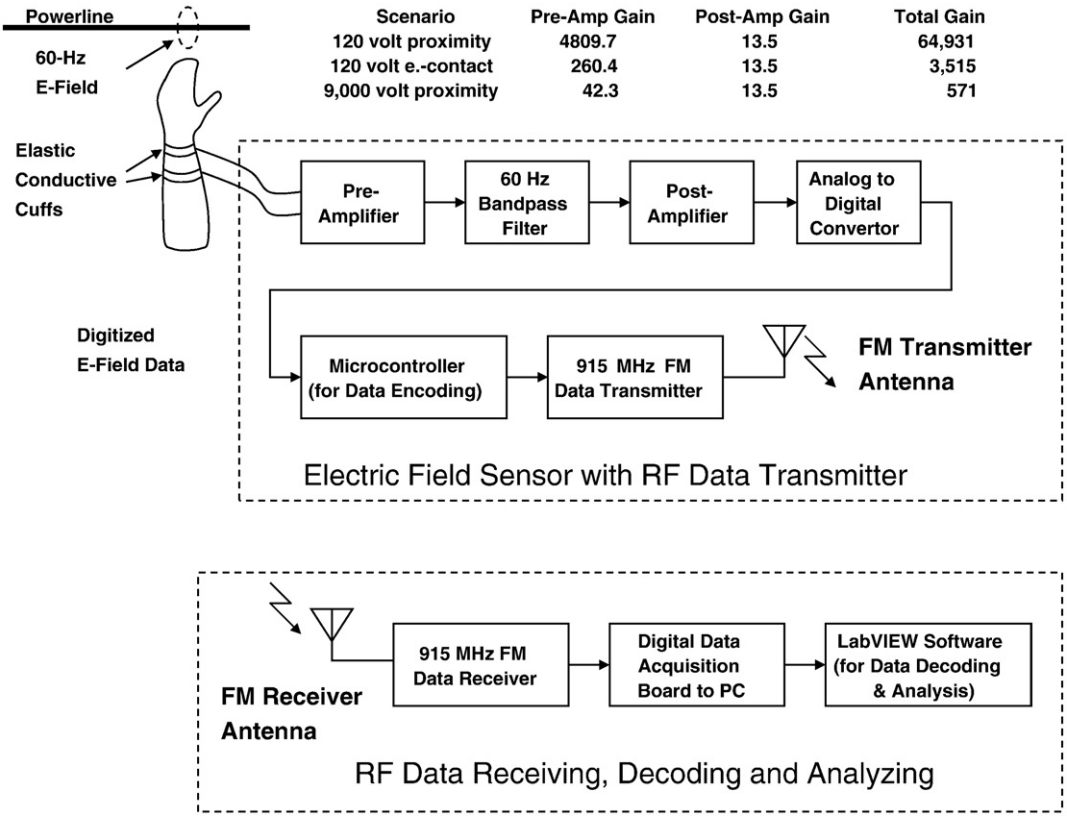


Fig. 4. Block diagrams of the electric field sensor circuitry.

A piece of Type NM-B (AWG 12-2 with Ground) electric cable with the length of 120 cm was fixed on one of the boards (Powerline Board) to simulate a low-voltage (120 volts) power circuit. In the high-voltage (9,000 volts) power line simulation, this AWG 12 cable was used to simulate the high-voltage "line" wire. A piece of insulated cable placed 40 cm behind and parallel to the "line" wire was used to simulate the high-voltage "neutral" wire. A 9,000 volt transformer converted 120 volt/60 Hz AC current to 9,000 volt/60 Hz AC current with the maximum current output of about 38 mA, and energized the "line" and "neutral" wires. Another piece of Plexiglas board (Hog-Leg Board) was placed perpendicular to the Powerline Board with 10 distance marks on the board: 100 cm, 80 cm, 60 cm, 40 cm, 20 cm, 10 cm, 5 cm, 2 cm, 1 cm, and 0 cm. At 0 cm, a piece of Plexiglas with the dimension of 120 m x 20 cm x 0.635 cm was selected to separate and insulate the simulated power circuits from the hog legs.

2.8. High-Voltage (9,000 Volts) Proximity Experimental Procedures

In the high-voltage proximity experiment, the simulated power circuit was energized by the 9,000 volt transformer. The conductive cuffs were separated 10 cm apart and tightened on a hog leg with the thin film plastic insulation. The cuff near the hoof was connected to the "ground" sensor input cable, and the other cuff was connected with the "active" sensor input cable. The voltage gain of the preamplifier was adjusted to be 42.3 and that of the post-amplifier was adjusted to be 13.5. The total voltage gain of the sensor was 571. Each of the 10 hog legs was positioned parallel to the simulated power circuit as seen in Fig. 6. First, the leg was positioned on the 100 cm

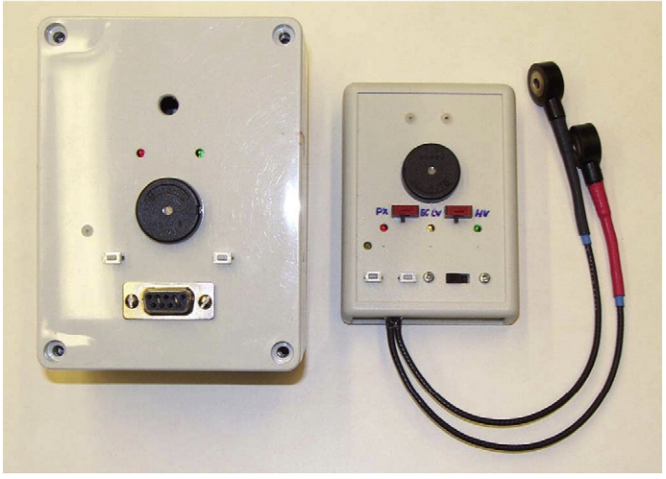


Fig. 5. The photo of the electric field sensor (right) and the 915 MHz FM receiver.

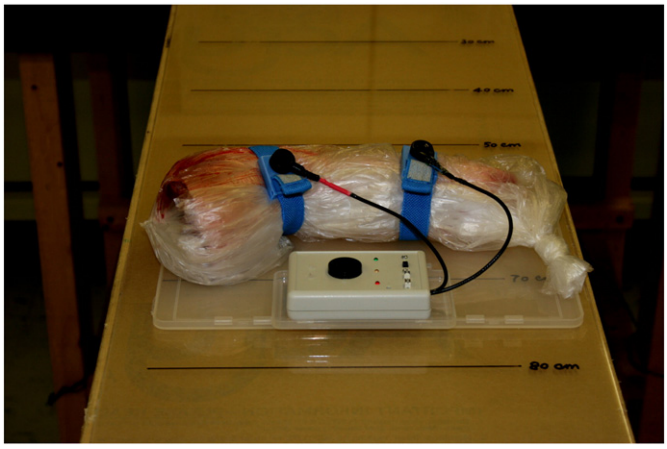


Fig. 6. The photo of a hog leg with two elastic conductive fabric cuffs.

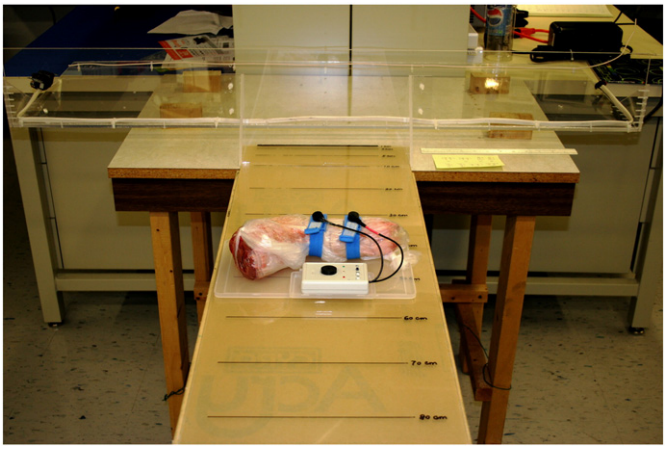


Fig. 7. The photo of the experimental setup on two pieces of Plexiglas.

distance mark on the Hog-Leg Board. The electric field on the cuffs was measured 10 times and wirelessly transmitted to the PC by the RF transmission. The LabVIEW program on the PC decoded the voltage values measured on the cuffs and calculated the mean and standard deviation values, and saved them on the PC hard disk. The leg was in turn moved to 80 cm, 60 cm, 40 cm, 20 cm, 10 cm, 5 cm, 2 cm, and 1 cm distance marks, and the above measurements were repeated on each of the distance marks. These measurements were repeated again on each of the 10 hog legs.

2.9. Low-voltage (120 Volts) Proximity and Electrical-contact Experimental Procedures

In low-voltage proximity and electrical-contact experiments, the simulated power circuit was energized with a 120 volt power source. The conductive cuffs were positioned on the hog legs the same as those in the high-voltage proximity measurements. Again, the electric field on each of the 10 hog legs was measured 10 times on each of the 9 distance marks on the Hog-Leg Board. The voltage gain of the preamplifier was adjusted to be 4809.7 and that of the post-amplifier was fixed to be 13.5. The total voltage gain of the sensor was 64,931. After the measurements on the 1 cm distance mark, a bare wire, which was connected with the 120 volt "line" wire, contacted the hog leg skin, and the correspondent electric field on the leg was measured 10 times. Then, the live bare wire penetrated the hog leg skin with a depth of about 1 cm, and the correspondent electric field on the leg was measured 10 times. For the electrical-contact electric field measurements, the voltage gain of the preamplifier was adjusted to be 260.4 and that of the post-amplifier was fixed to be 13.5. The total voltage gain of the sensor was 3,515. The above measurements were repeated again on each of the 10 hog legs.

2.10. Hog Leg Orientation Effect Experimental Procedures (9,000 and 120 Volts)

Concerned that the orientation alteration of a human wrist might vary the electric field level on the wrist and affect the proximity detection accuracy, experiments were conducted to investigate the relationship between a simulated wrist (hog leg) orientation and the wrist electric field variation. In the experiment, the power circuit was energized with the 120 volt power source. The conductive cuffs were separated 5 cm apart, and tightened on the hog legs with the thin plastic film insulation. The electric fields on each of the 10 hog legs were measured as the leg was positioned on the 40 cm distance mark, and the leg orientation was in four directions: (a) the leg hoof was pointed to the power circuit, (b) the leg rotated 90 degrees clockwise, (c) the leg rotated 180 degrees clockwise, and (d) the leg rotated 270 degrees clockwise. In each leg orientation, the electric field was measured 10 times as the conductive cuff near the hoof was connected to the "active" sensor input cable, and the cuff away from the hoof was connected to the "ground" sensor input cable. The electric field measurement repeated 10 times again as the "active" and "ground" cables were swapped. The above measurements were repeated at both high and low-voltages, and repeated again on each of the 10 hog legs.

3. Results

3.1. Electric Field Signal Noise Filtering

Fig. 8 shows the effect of 60 Hz filtering in the sensor circuitry on electric field signal purity.

In Fig. 8, the oscilloscope traces on the left are the proximity electric field signals and the traces on the right are electrical-contact electric field signals. The yellow traces are amplified electric field signals from the output of the pre-amplifier before the 60-Hz bandpass filter. The purple traces are amplified electric signals from the output of the post-amplifier after the bandpass filter. The interfering noise spurs on yellow traces are mostly filtered out from the purple traces.

3.2. High-Voltage (8,896.3 Volts) Proximity Measurements

In the high-voltage proximity measurements, the power circuit voltage was measured as 8,896.3 volts. As the hog legs were moved from 100 cm to 1 cm to the energized power circuit, the mean voltage on the conductive cuffs monotonically increases from 91 micro-volts at 100 cm to 2,456 micro-volts at 1 cm, as shown in Fig. 9.

3.3. Low-Voltage (118.0 Volts) Proximity and Electrical-contact Measurements

In the low-voltage proximity and electrical-contact measurements, the power circuit voltage was measured as 118.0 volts. As the hog legs were moved from 100 cm to 1 cm to the energized power circuit, the mean voltage on the conductive cuffs monotonically increases from 1.3 micro-volts to 17.5 micro-volts. As the 120 volt "line" wire touched the hog leg skin, the voltage jumped to 473.7 micro-volts. As the "line" wire further penetrated to the leg skin, the voltage increased to 534.9 micro-volts. The total voltage curve is shown in Fig. 10.

3.4. Effects of Hog Leg Orientation at High-Voltage (8,896.3 Volts) and Low-voltage (118.0 Volts)

Table 1 shows the effect of the hog leg orientation on the voltage variation on the sensor probe cuffs. It shows the mean voltage values on the sensor cuffs with each of the 16 hog leg orientation/polarity/power-circuit-voltage combinations.

During the measurements, the hog legs were positioned on the 40 cm distance mark on the Hog Leg Board. The mean-voltage on the sensor cuffs is calculated in Eq.3:

$$MeanVoltage = \frac{\sum_{HL=1}^{10}\left[\frac{\sum_{M=1}^{10}(VoltageMeasuredOnCuffs)}{10Measurements}\right]}{10HogLegs} \quad (3)$$

Table 2 shows the voltage variation (in percentage) and the voltage deviation (in percentage) with each of the 16 orientation/polarity/power-circuit-voltage combinations.

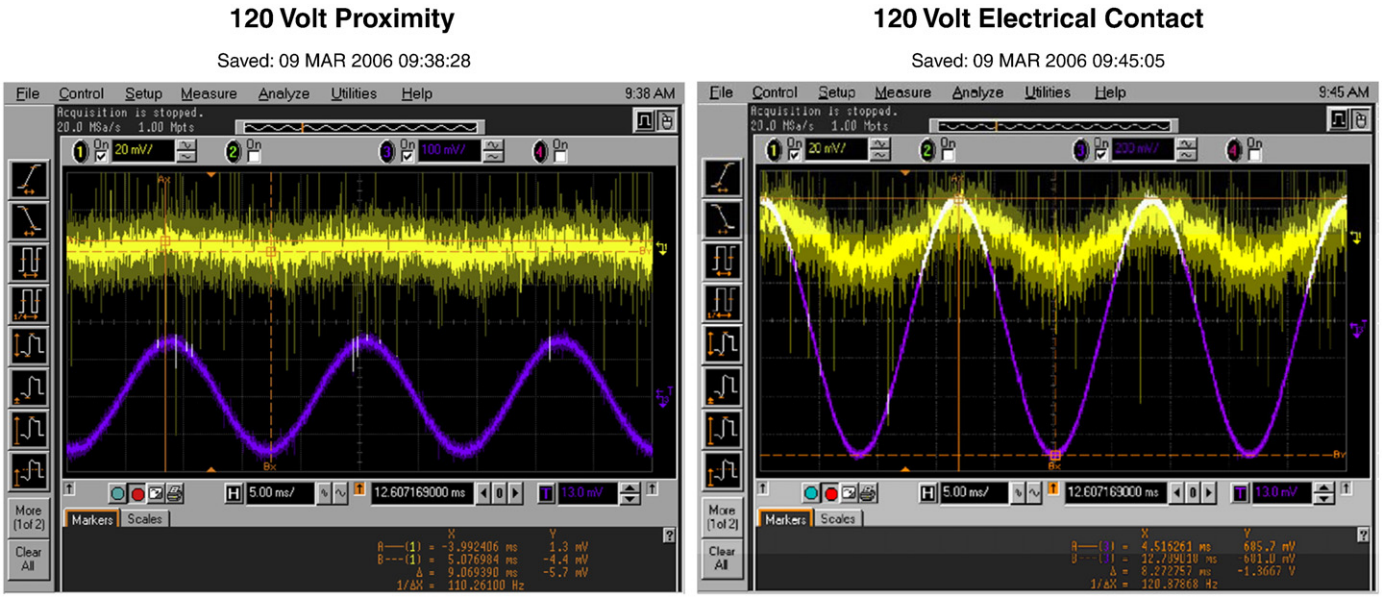


Fig. 8. The photo of noise filtering effects.

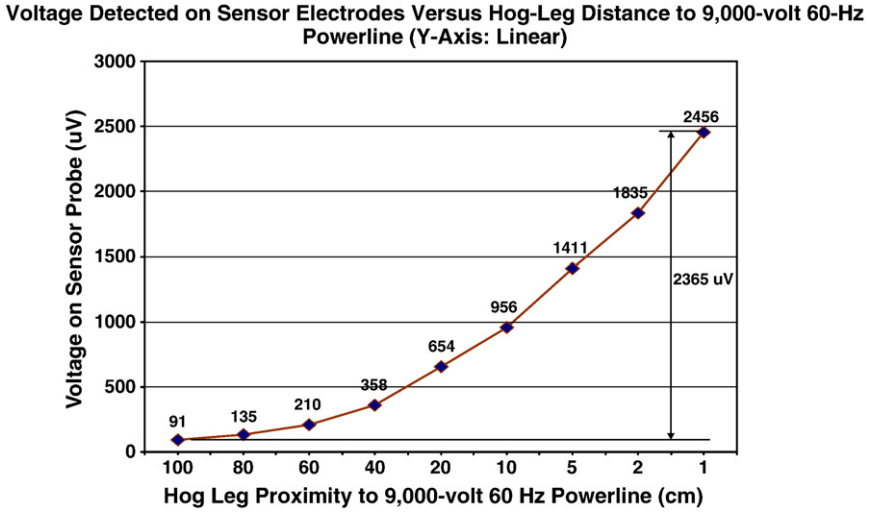


Fig. 9. The voltage on hog legs versus proximity distance at 8,896 volts.

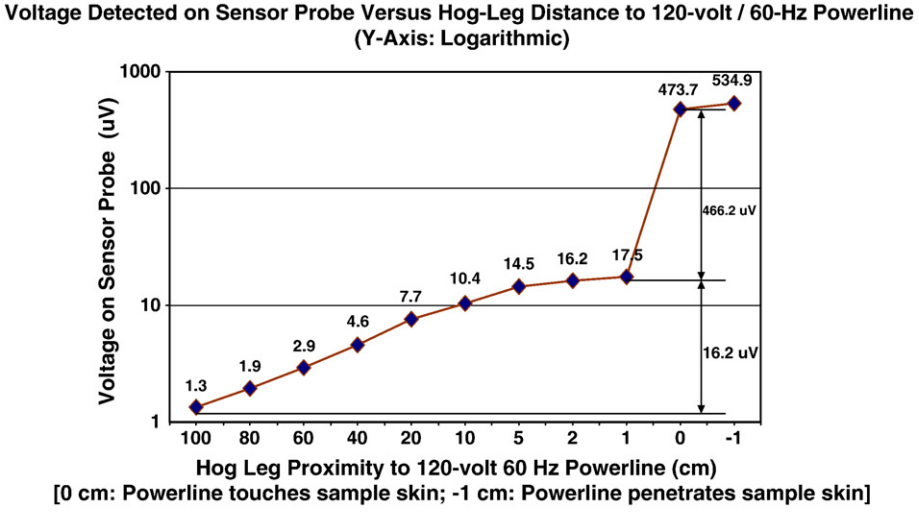


Fig. 10. The voltage on hog legs versus proximity distance and electrical-contact at 118 volts.

Table 1
The mean voltages on the prove cuffs as the hog legs changed their orientations.

Mean Voltage on the Sensor Cuffs (microvolt) ; Hog Leg (n = 10) Position: 40 cm; Measurements/Hog Leg: 10					
Hoof Orientations (Degrees)		0 (Hoof Points Front)	90 (Hoof Points Right)	180 (Hoof Points back)	270 (Hoof Points left)
120 Volts	Active to Hoof	2.922	2.895	3.643	3.792
	GND to Hoof	2.884	4.114	6.009	5.489
9,000 Volts	Active to Hoof	205.17	193.87	222.40	269.79
	GND to Hoof	185.64	275.57	419.01	402.08

The voltage variation is defined in Eq.4:

$$VoltageVariation = \frac{MeanVoltage - \frac{\sum_{Orientation}^{4}(MeanVoltage)}{4Orientations}}{\frac{\sum_{Orientation}^{4}(MeanVoltage)}{4Orientations}} \times 100\% \quad (4)$$

The voltage deviation is defined in Eq. 5:

$$VoltageDeviation = \frac{\sqrt{\frac{\sum_{Orientation}^{4}(MeanVoltage - \frac{\sum_{Orientation}^{4}(MeanVoltage)}{4Orientations})^2}{4Orientations}}}{\frac{\sum_{Orientation}^{4}(MeanVoltage)}{4Orientations}} \times 100\% \quad (5)$$

4. Discussion

4.1. Similarity of Hog Legs to Human Wrists in Dielectric Properties

The measured mean voltage values (10.4 micro-volts in 120-volt/10-cm proximity, 473.7 micro-volts in 120-volt electrical-contact, and 956 micro-volts in 9,000-volt/10-cm proximity) are similar to the ANSYS-software simulated voltage values, 9.95, 500, and 746 micro-volts in the respective conditions. All of the three pairs of measure and simulated data are in the same digit voltage ranges. It is verified from the data comparison that the measured voltage data on hog front legs are similar to the simulated data using human cortical bone dielectric properties in electrical proximity and contact conditions. Considering the largely diversified dielectric properties of the biological tissues and the availability of the limited biological tissues on the market, using hog front legs to simulate human wrists is a scientifically reasonable and economically feasible selection.

4.2. Feasibility to Detect Worker's Proximity to an Energized Power Circuit by Using a Pair of Capacitive Cuffs

The experimental results show that with the amplifier gain of 64,931 and the noise filter bandwidth of 3 Hz, an electric field sensor with a pair of capacitive cuffs attached to the human wrist is able to detect the proximity of the wrist as far as 1 meter from a 120 volt power circuit.

Comparing the proximity wrist-voltage curves at 118 volts with that at 8,896 volts, it can be seen that at a distance to the power circuit farther than 10 cm, the wrist-voltage is coarsely proportional to the power circuit voltage. This first property could be used to estimate the proximity wrist-voltage curves at other power voltages. Comparing the wrist-voltage curves at the distances to the power circuit farther than 10 cm, it can also be seen that the level of wrist-voltage is coarsely proportional to 1/r, where r is the distance from the wrist to the power circuit. This second property could be used to estimate the wrist-voltage at an extended distance farther then 1 meter. These two properties agree with the electric-field distribution equation with line charges (Eq. 2).

OSHA General Requirements - 1926.403 (K) requires a minimum clear distance between a worker and a live part at different power voltages (OSHA, 2009b). The two properties of the leg-voltage can be used to estimate the leg-voltage at these minimum clear distances. Table 3 lists five power voltage ranges, the required clear distances, the estimated leg-voltages, and whether the NIOSH electric-field sensor can sense the electric field at these minimum clear distances. Since the NIOSH sensor can sense the electric-field signals as weak as 1.3 microvolts, and all the estimated leg-voltages at the required minimum clear distances are greater than this voltage, this means that the NIOSH sensor is capable of detecting the proximity of a hog leg to the determined power voltages at the OSHA required corresponding minimum clear distances.

4.3. Feasibility to Detect Worker's Electrical-Contact to an Energized Power Circuit by Using a Pair of Capacitive Cuffs

It can be seen from the measured wrist-voltage versus distance curve at 118 volts that there is a voltage jump from 17.5 to 473.7 micro-volts as the hog leg skin contacts the “line” wire. An electrical-contact threshold can be easily determined within this great voltage gap, and the microcontroller in the sensor can easily recognize the electrical-contact. At 8,896 volts, by using the first property of the leg-voltage, the estimated electrical-contact wrist-voltage should jump from 2.45 to 66.48 millivolts. The electrical-contact threshold can be easily selected between this voltage gap, and the microcontroller can easily recognize the electrical-contact at 9,000 volts.

4.4. Differential Threshold for Detecting 120 Volt Electrical-contact

Fig. 11 shows both the wrist-voltages versus distance curves at both 8,896 volts and 118 volts.

Table 2
The voltage variation and voltage deviation caused by hog leg orientation changes.

Electric Field Variation from the Mean Electric Field (= Variation from Mean/Mean *100%)						Deviation (= Std Dev/Mean*100%)
Hoof Orientations (Degrees)		0	90	180	270	
120 Volts	Active to Hoof	-11.8	-12.6	9.8	14.5	12.3
	GND to Hoof	-37.6	-11	30	18.7	26.4
9,000 Volts	Active to Hoof	-7.9	-13	-0.2	21.1	13
	GND to Hoof	-42.1	-14	30.7	25.4	29.8

Table 3
The OSHA required minimum clear distance with 5 voltage ranges and the correspondent estimated hog leg electric field magnitudes.

OSHA General Requirements - 1926.403 (K) : Minimum Clear Distances				
Voltage Range (V)	Required Minimum Clear Distance		Estimated Hog Leg Voltage (uV)	NIOSH Device Capable to sense the Signal?
0-150	3 feet	~ 1 m	1.625	Yes
151-600	4 feet	~1.3 m	7.077	Yes
601-2500	5 feet	~1.6 m	22.131	Yes
2501-9000	6 feet	~1.9 m	48.455	Yes
9001-25000	9 feet	~2.8 m	91.33	Yes

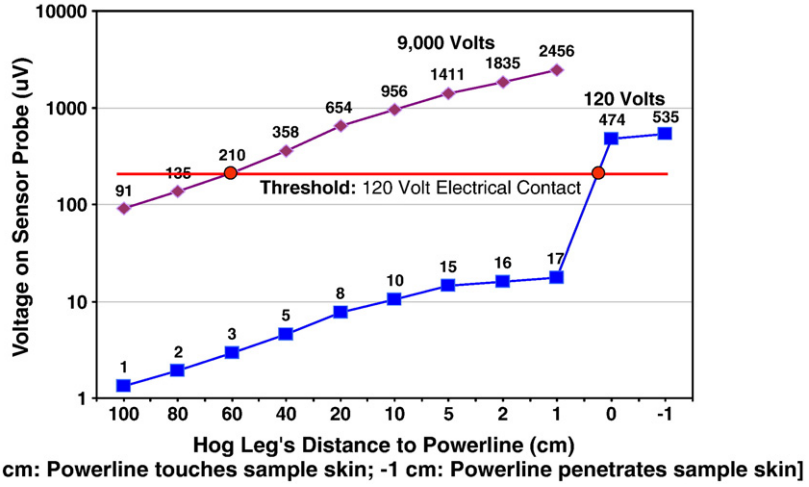


Fig. 11. The voltage on hog legs versus proximity distance and electrical-contact at both 8,896 volts and 118 volts.

It can be seen that the wrist-voltage of the electrical-contact at 120 volt is already in the 9,000 volt proximity wrist-voltage range. Suppose a threshold is drawn between 17.5 and 473.7 micro-volts. If the sensor detects that the wrist-voltage is above this threshold, the microcontroller would be confused whether the threshold-passing is caused by wrist-proximity to a 9,000 volt powerline or caused by a 120 volt electrical-contact. To resolve this problem, a differential threshold is proposed to distinguish the 120 volt electrical-contact from the 9,000 volt proximity. The differential threshold lets the microcontroller recognize the voltage jump by comparing the latest threshold-passing with the last moment wrist-voltage. If the last moment wrist-voltage is still in the 120 volt proximity range, the latest threshold-passing should be caused by 120 volt electrical-contact. If the last moment wrist-voltage is already beyond the 120 volt proximity range, the latest threshold-passing should be caused by 9,000 volt proximity.

4.5. Proposed Sensor Circuitry Design for Dual Voltage Proximity/ Electrical-contact Detection

Fig. 12 shows the block diagrams of the proposed circuitry design for proximity and electrical-contact detections in both 9,000 volt and 120 volt ranges.

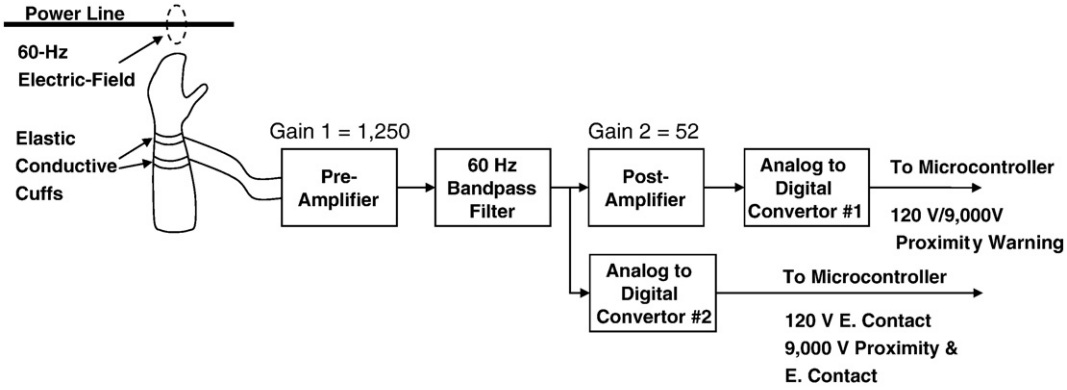
The circuitry has two analog-to-digital (A/D) converter outputs. The voltage gain of the 1st A/D output is 1,250 and that of the 2nd A/D output is 65,000. The 120 volt proximity threshold of 1.3 micro-volts at the distance of 1 meter can be amplified to 84.5 millivolts at the 2nd A/D output. The 9,000 volt proximity threshold of 45 micro-volts at the distance of 2 meters can be amplified at the 2nd A/D output to 2.925 volts. The 120 volt electrical-contact differential-threshold of 300 micro-volts can be amplified to 375 millivolts at the 1st A/D output. The 9,000 volt electrical-contact threshold of 4 millivolts can be amplified at the 1st A/D output to 5 volts. This electric field sensor circuitry is able to detect both the proximity and electrical-contact at dual voltages. The drawback is that if a 9,000 volt proximity event occurs, the strong electric field sensed by the sensor cuffs will overwhelm the 120 volt proximity and electrical-contact signals and temporarily disable the 120 volt proximity and electrical-contact detections until the sensor is out of the 9,000 volt proximity. When a worker using this sensor gets a high-voltage proximity alarm, the worker should take the high-voltage proximity as the first priority, and also be vigilant with the proximity or contact at other voltages lower than 9,000 volts. If the worker still wants to work at a lower voltage, the worker can turn off the alarm.

4.6. Effect of Sensor Input Cable Polarity on the Wrist-Voltage Variation

Table 2 shows the effect of sensor-input-cable polarity on the wrist-voltage variation. At both 120 volts and 9,000 volts, the wrist-voltage variation caused by wrist-orientation is two times less as the sensor input “active” cable is connected to the conductive cuff near the hog hoof, and the “ground” cable is connected to the cuff away from the hoof than that with the cable-cuff connect with opposite cable polarity.

4.7. Usage of Electric Field Sensor

The lockout/tagout procedure is always a front line protection, and this electric field sensor is only an additional second line protection. In situations where the electricians or workers are aware that the circuit is energized, the protection equipment includes adequate clothing and well-insulated tools. This electric field sensor can be an additional protection. Contact with overhead power lines was the most frequent occurring event (47.2%) in the construction industry (Janicak, 2008). This electric field sensor could be an effective protection to prevent a worker from contacting overhead powerline. For example, if a worker with a sensor mounted on the wrist holds a metal ladder and unintentionally approaches an



Scenario	Pre-Amplifier Gain	Post-Amplifier Gain	Total Gain
120 volt proximity	1,250	52	65,000
120 volt E. contact	1,250	---	1,250
9,000 volt proximity	1,250	52	65,000
9,000 volt proximity/E. Contact	1,250	---	1,250

Fig. 12. Proposed electric field sensor circuitry block diagrams.

overhead powerline, the sensor could detect the electric field from the powerline to the metal ladder and warn the worker of electrical proximity. Another typical event is the loss of proper grounding while a worker is operating a piece of electrical equipment. In this case, the sensor mounted on the worker's wrist could effectively detect the electric field spreading from the energized equipment surface to the worker's wrist and warn the worker of electrical contact (the worker might not immediately realize the electrical contact in the moment of ground loss if the worker's shoes are well insulated from the ground).

4.8. Future Research

As any part of a worker's body is in proximity to a live power circuit, the distance between that part of the body and the wrist, where the electric field sensor is mounted, will become a variable to affect the electric field intensity on the sensor. The farther the part of the body to the wrist, the weaker the measured wrist-voltage would be. This phenomenon will affect the accuracy of proximity detection. Future research should be conducted to characterize this distance effect and explore feasible resolutions.

This device may be integrated into a wireless-capable high voltage switching system to prevent workers from an arc flash caused injury/death. In this case, the device's proximity threshold can be adjusted to a distance between a human and the high voltage powerline where an arc flash is near to occur. As the electric field that the sensor detects exceeds the threshold, the sensor wirelessly transmits a tripping command to the wireless high voltage switching system to de-energize the powerline. Future research may be conducted to design a wireless high-voltage switching system using an electric field proximity sensor.

High voltage DC transmission is increasingly common with renewable energy sources and long distance transmission lines (e.g., from remote wind farms), and lower voltage DC systems are increasingly common to avoid losses in efficiency where DC is generated (e.g., solar or fuel cells), transformed to AC for transmission, and then returned to DC for use. Theoretically, according to the equation of electric field distribution caused by line charges (Eq. 2), an electric field sensor is able to detect the electric fields emitted by either AC or DC charges on a nearby power circuit. In terms of a human-wrist-mounted electric field sensor, the difference in sensing the electric field emitted between AC powerlines and DC powerlines is that the human wrist tissue with its high dielectric constant (the dielectric constant of cortical bone is 7692.6) loses its energy storage function in the DC condition and becomes pure conductive. The effect of the loss of energy storage on a human-wrist-mounted electric field sensor should be explored in further computer simulations and hog-leg experiments.

Future research should be conducted to explore the human response to the electrical proximity or contact warning.

5. Conclusions

Since the construction industry has the highest number of occupational electrocutions, developing a second line personal protection system (in addition to the front line lockout/tagout procedure) for protecting construction workers has the potential to reduce injuries from contact with electrical energy. This proposed electric field sensor could effectively warn the workers of their proximity/electrical-contact to a live power circuit at both the high-voltage and low-voltage powerline or faulty electric equipment. If the worker electrically contacts a live powerline or equipment, the device has the potential to wirelessly trip a wireless-capable circuit-breaker and to activate a cell phone to transmit electrical-contact notifications to a rescue office. Timely medical care could save a worker's life after the worker is electrically injured. Widespread use of this sensor could lower electrocution and electrically related injury rates in the construction industry.

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Disclaimer

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References

Arcolando, N., Diercks, M, Hopkins, J., & Lynch, J. (2001). *Power line proximity alarm. Project Number JKM-2A00, 2001*. Worcester, MA: Worcester Polytechnic Institute http://ece.wpi.edu/analog/mqps/jkm-2a00.pdf.

Designer, A. J. (2009). *Cylindrical capacitor design equations formulas calculator*. Author. http://www.ajdesigner.com/phpcapacitor/cylindrical_capacitor_equation.php.

HD Electric Company. (2004). *V-Watch personal voltage detector (Bulleton No. VW-300a, 2004)*. Park City, IL: Author. http://www.hdelectriccompany.com/assets/files/vwatch.pdf.

Griffiths, D. J. (1999). *Introduction to Electrodynamics, 62-63*. Upper Saddle River, NJ: Prentice Hall.

Homce, G. T., Cawley, J. C, & Yenchek, M. R. (2008). *A performance evaluation of two overhead power line proximity warning devices* (Information Circular 9510. *DHHS (NIOSH) Publication No. 2009–110, 2008)*. Atlanta, GA: National Institute for Occupational Safety and Health.

Janicak, C. A. (2008). Occupational fatalities due to electrocutions in the construction industry. *Journal of Safety Research*, *39*, 617−621.

Kisner, S. M., & Casini, V. (1998). Epidemiology of electrocution fatalities. In National Institute for Occupational Safety and Health (Ed.), *Worker deaths by electrocution: A summary of surveillance findings and investigative case reports DHHS (NIOSH) Publication 98-131* (pp. 9−19). Washington, DC: U.S. Government Printing Office.

McCann, M., Hunting, K. L., Murawski, J., Chowdhury, R., & Welch, L. (2003). Causes of electrical deaths and injuries among construction workers. *American Journal of Industrial Medicine*, *43*, 398−406.

NFPA. (2009). *NFPA 70E, Chapter 1, Article 130: Work involving electrical hazards*. Quincy. MA: Author.

OSHA. (2008). OSHA 29 CFR 1910 General Industrial Regulations. – 1910.147. *The control of hazardous energy (lockout/tagout)* (pp. 230−233). Washington, DC: Author.

OSHA. (2009). *OSHA Construction eTool: Electrical Incidents*. Washington, DC: Author. http://www.osha.gov/SLTC/etools/construction/electrical_incidents/mainpage.html.

OSHA. (2009). *Regulations (Standards - 29 CFR) General requirements. - 1926.403 (K), Safety and Health Regulations for Construction, Electrical*. Washington, DC: Author. http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10704.

Paques, J. J., Bourbonnière, R., Laliberté, L., & Nguyen, D. H. (1995). Study of the power line detection principle as a means of preventing contact accidents between concreting booms and power lines. *Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST), Études et recherches / Rapport R-114, Montréal* http://www.irsst.qc.ca/en/_projet_53.html.

McCann, M. (n.d.). *Why are so many construction workers being electrocuted?* Silver Spring, MD: CPWR - The Center for Construction Research and Training. http://www.elcosh.org/record/document/557/d000539.pdf.

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