GrabAmps: Grab a Wire to Sense the Current Flow

Don Samitha Elvitigala[1]
samitha@ahlab.org

Roshan Peiris[2]
roshan@kmd.keio.ac.jp

Erik Wilhelm[1]
erikwilhelm@sutd.edu.sg

Shaohui Foong[1]
shao@sutd.edu.sg

Suranga Nanayakkara[1]
suranga@sutd.edu.sg

[1]Singapore University of Technology and Design, [2]KMD, Keio University

ABSTRACT

In this paper, we present GrabAmps, an intuitive interface that allows users to simply grab a bundled cable and get feedback on the AC (Alternating Current) current flow through it. Single phase and three phase AC was estimated with a regression model developed using principles of applied electromagnetism. This regression model is embedded into a standalone glove with a display attached at the rear so that the users can intuitively read the current consumption information. The users may configure the glove to detect AC single phase or AC three phase current using the same sensor setup on the glove. End users such as electrical engineers and electricians who frequently wear gloves during their work can benefit from GrabAmp to identify a wire that is live, or even grab and move along a wire to trace any potential failures. We believe GrabAmps can potentially speed up maintenance processes and monitor equipment more efficiently without downtime, which is increasingly important for data centres and other critical infrastructure.

CCS Concepts

Human-centered computing~Ubiquitous and mobile computing systems and tools • Hardware~Sensors and actuators

Keywords

Intuitive Interfaces; Non-invasive Current Sensing; Augmented Glove

1. INTRODUCTION

An intuitive interface that provides an estimation of the electrical current flow is desirable in many instances, such as providing residential energy consumers with real-time electricity price feedback [3][19] and monitoring/troubleshooting an industrial machine without machine downtime. However, most of the current sensors are not intuitive for two reasons. Firstly, they require tedious invasive or semi-invasive installation, which requires users to either isolate a single wire or access crowded sockets and circuit breakers [15] [16]. Secondly, the feedback is presented through an indirect means where users have to login to a web portal or mobile application [19]. Non-invasive current sensing of an AC cable is a challenging problem, since most of the magnetic field generated by current flowing through negative and positive wires is cancelled. In addition, irregularities (such as kinks or twisting of individual wires) within bundled-wire makes the sensing process even more difficult. Multi-core cable current clamp sensors already exist and are available as commercial products[1], but they are bulky and cannot be used in a ubiquitous manner.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work are owned by others than ACM must be honored. Abstracting with credits be permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request Permissions from permissions@acm.org

AH'17, March 16–18, 2017, Mountain View, CA, USA.

© 2017 ACM. ISBN 978-1-4503-4835-5/17/03$15.00

DOI: http://dx.doi.org/10.1145/3041164.3041199

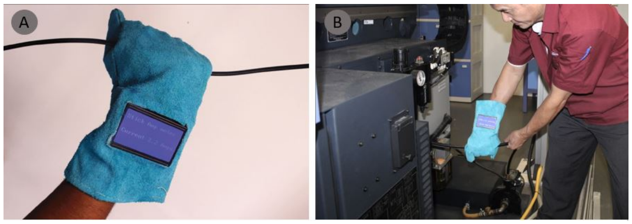

Figure 1: GrabAmps Sensing current non-invasively of (A)Domestic AC cable (B) Three Phase cable

To overcome the limitations on existing invasive and non-invasive sensors, we present GrabAmps, a glove which contains a non-invasive sensor that estimates the current through a bundled-cable and provide immediate feedback. The main sensing principle of GrabAmps is based on the Biot-Savart law that describes the magnetic field generated by a current carrying wire. We obtain a large collection of measurements by systematically changing the sensor orientations and current loads for different diameters of AC cables. These measurements were used to fit a linear regression model to estimate the current. With adjustments to the coefficients in this regression model, GrabAmps can be adapted to sense both single phase and three phase current measurements.

The non-invasive sensing characteristic of GrabAmps allows users to simply grab a bundled AC cable to estimate the current flow. The GrabAmps provides appropriate feedback using a screen attached at the rear of the glove that displays the measured current when grabbing onto a cable.

---

[1] http://www.mouser.com/ds/2/263/MMC850_DS_en_V02-15853.pdf

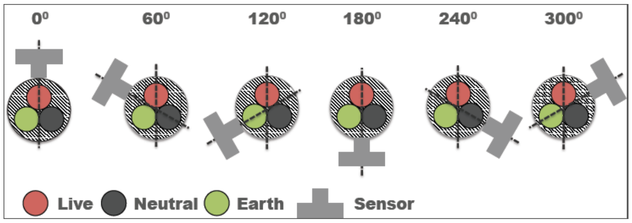

Figure 2: Sensor configurations on an AC wire for initial analysis

The main contributions of this paper includes the development of a regression model that can estimate the current flow for both single and three phase AC current; and development of a self-contained, non-invasive, compact wireless current sensor and demonstration of its design space through GrabAmps.

2. RELATED WORK

2.1 Invasive Current Sensing

MIT Plug [14] and [10] are some early works that introduced monitoring power consumption at the plug point level. In addition, Energine[2], Kill-A-Watt[3] and Efergy[4] have become popular as commercial plug modules. Generally, such products feature embedded displays that display the energy usage data on the device itself. Works such as Acme[10], Greenbox[5], EnergyHub[6] and Plogg[7] have gone a step further with introducing wireless sensor networks into these devices with information being available live on mobile and desktop computers. The transaction costs and time delays involved in these methods of influencing consumer behaviour have resulted in sub-optimal performance and limited effect of the significant investment in broad installation of these sensors in particular markets[8].

2.2 Semi-invasive current sensing

In [7], the authors discuss an approach to identify individual appliances in operation within an electric grid by monitoring the power meter. Other researchers have used similar methods to improve such processes [7] with higher frequency [12], [13], better features [3], [5] and better disaggregation algorithms [1], [8]. Furthermore, distributed smart meters too have attempted to monitor individual appliances from a central location [9]. These systems have featured a wireless sensor network for metering devices [10], [4]. Other approaches for energy monitoring include acoustic, light, temperature and vibration sensing in combination with power meters to classify working appliances and calculate each of its power [18]. However, most of this work attempt to differentiate energy consumption characteristics of individual appliances using measurements made from a central location. In these works, the current sensing was done in a central position, generally in a circuit breaker, using sensors or current transformers around the live wire. As such, these sensors need to be installed by a technician since it involves exposing an individual pole for attaching the sensor.

2.3 Non-invasive current sensing

Works of [11] and [17], have been looking at using EMF (electromagnetic field) detection technologies to monitor energy. These works attach EMF sensors to detect the change in the EMF generated by the current pulses when devices are switched on and off to identify individual appliances on the grid. The current sensing however is still done as previous methods at central locations. Commercial products such as Watts Up[9] require professional installation to provide an acceptable level of safety. Off-the shelf current clamps offer a non-invasive way to measure current[10]. However, these handheld device form factors are designed for ad-hoc use; not as a ubiquitous current sensor.

The above works suggest that there is a strong interest in different ways of monitoring individual appliances. However, these techniques are limited by processes such as requiring the users to instrument the environment with smart plugs or requiring support of a technician to setup smart power monitors at the circuit breaker level. With GrabAmps, we attempt to overcome these limitations by providing an intuitive wearable solution to monitor current flow in a non-invasive manner and provide immediate feedback.

3. OVERVIEW OF THE TECHNOLOGY

3.1 Development of regression model

In a typical cable, the wires that carry current to and from a device (eg. live, neutral and the earth) are combined together resulting in the magnetic field generated to be close to zero. This is due to the magnetic flux generated by the live wire being cancelled out by the inverse flux generated by the neutral wire that carries the returning current. However, since the individual wires are spatially separated within a bundled wired, there is a minute amount of flux that is generated in the magnitudes of micro Teslas as per the Biot-Savart law. A magnetic flux sensor that is within this range can sense this generated flux when placed closer to the wire.

To analyse this phenomenon, we placed the sensors in different radial positions from a wire arrangement as seen in Figure 1. Sensors were placed in five different orientations in a test-bed (single phase AC current source connected to a controllable resistive load) which was rotated 60° with respect to the placement of the live, neutral and earth wires as seen in Figure 2. The maximum flux readings were averaged over $N>1000$ samples for each angular position and for each of the 5 positions on the wire. At each position, maximum flux readings along the x, y, and z axes of each sensor were lumped together using vector summation. This makes the measurements insensitive to the orientation of the magnetometer.

---

[2] https://energenie4u.co.uk/

[3] http://www.p3international.com/products/p4400.html

[4] http://www.efergy.eu/

[5] http://getgreenbox.com/

[6] http://www.energyhub.com/

[7] http://www.plogg.co.uk/

[8] http://spectrum.ieee.org/energywise/energy/the-smarter-grid/the-smart-grid-needs-an-app-store

[9] https://www.wattsupmeters.com/secure/index.php

[10] http://en-us.fluke.com/products/clamp-meters/

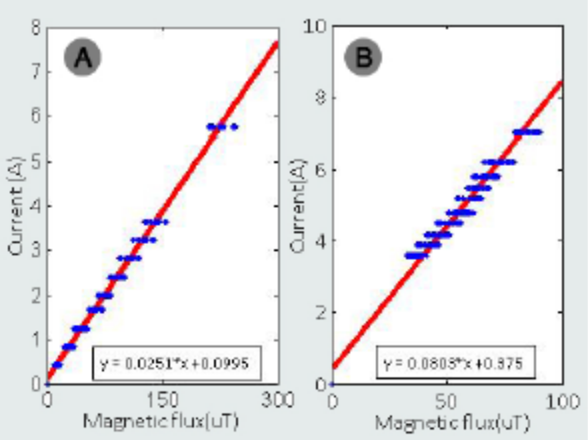

Figure 3: Linear regression model fit. (A) single phase current (B) three phase current

3.2 Linear regression model

AC single phase current: Our analysis showed that the maximum difference between the sensor readings occurred when two sensors are 180° apart. The trend shown by the flux measurements summed between the sensors in these relative orientations found to be decidedly linear with increasing current. A linear regression model Equation 1 was fit to the data where, ‘I’ represents measured current, ‘X’ represents sensor readings and ‘Θ_0’, ‘Θ_1’ are the coefficients.

$$I = \Theta_0 + \Theta_1 X \qquad (1)$$

The ground truth (reference current) was measured using a CT sensor attached to an isolating a single wire. From the measured data, the following were calculated:

$$\Theta_0 = 0:0995 \text{ and } \Theta_1 = 0:0251$$

$$I = 0:0995 + 0:0251X \qquad (2)$$

Since the magnetic sensors are arranged in a 180 degree separation, it ensures that at least one of the sensors is closest to the current carrying conductor than the other. This may also explain why a single regression model works for the same type of bundled cable (8mm three core AC cable) irrespective of wire arrangement (live, neutral and the earth) inside the cable.

AC three phase current: Similar process was used to develop a linear regression model for AC three phase current. The resulting model parameters are as follows:

$$\Theta_0 = 0:0803 \text{ and } \Theta_1 = 0:0375$$

3.3 Results

The Figure 3 shows the results of the linear regression models for both single phase and three phase AC. The results indicate that placing the sensors 180° apart at any positions senses the current through the wire with a maximum error of 0.2A. For the scope of this paper, this level of accuracy is acceptable to investigate potential usage scenarios and interactions.

4. GRABAMPS

Before developing GrabAmps, we encapsulate the above sensing technique as a compact device which can clamp onto a bundled wire. The overall setup of the initial GrabAmps clamp prototype is shown in Figure 4. In this version, we use the Freescale MAG3110 as the magnetic field sensors and an Arduino Pro Mini as the main processor to implement the regression model. An RGB LED and a OLED display has been used to provide simple immediate feedback on various states related to current monitoring

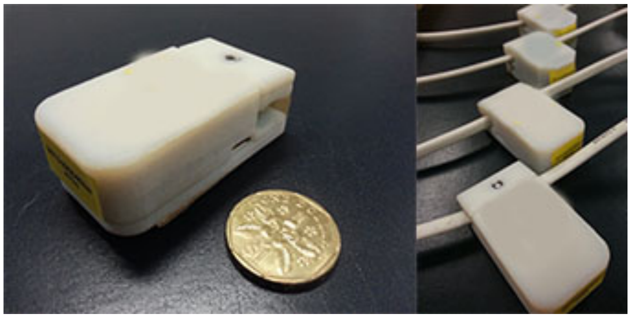

Figure 4: GrabAmps initial prototype

The non-invasive currents sensing capability of the first prototype motivated us to explore the design space of this novel sensing methodology. Many industrial settings, such as a wafer fabrication plant, demand instantaneous current monitoring without having to shut-down important processes. To address such situations, we developed GrabAmps by integrating the sensors to the palm and tip of the middle finger (Figure 5 (A), (B)). When the user grabs onto a wire, the sensors would form the required relative orientation of the sensors. With the display attached at the rear of the glove, the users can intuitively read the current consumption information. In addition, users may configure the glove to detect AC single phase or AC three phase current levels using the same sensor setup on the glove. GrabAmps can potentially speed up the maintenance processes and monitor equipment more efficiently without downtime (Figure 1 (B)). Generally, electrical engineers and electricians who frequently wear gloves during their work, can benefit from GrabAmps. For example, they can identify a wire that is live, or even grab and move along a wire to trace any potential failures, etc.

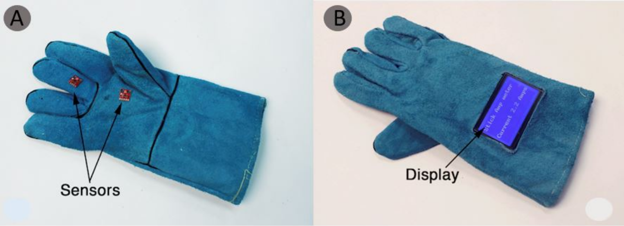

Figure 5(A) GrabAmps Sensors attached to the palm and the fingertip. (B) Display on the rear

In addition, GrabAmps can be useful in domestic (Figure 5 (A)) where users don’t have enough technical knowledge or expertise to use traditional current sensing equipment. In scenarios user can simply wear GrabAmps and can identify current carrying wires and measure current by simply grabbing and moving along a wire.

Also, this design is beneficial for the EM (electromagnetic) hobbyists who design and implement applications and systems with AC power supplies. For example, GrabAmps can be used to sense the EM signal of an AC power supply to observe and optimise other sources of EM. In addition, this can be used as an oscilloscope in digital applications to observe signal traces, digital communication signals, etc.

5. LIMITATIONS AND FUTURE WORK

There are few limitations of the existing system. As mentioned in the sensor specifications, the current version of the regression model works only with 8mm wires. In future we aim to develop regression models for various thicknesses and load the correct model automatically with thickness estimation (from two magnetic sensor data). In addition, the sensors, upon activation, requires a few seconds to warm-up for calibration. Moreover, the regression model's error could be up to 0.2A which could be significant for high precision current monitoring applications. This error is partly because of the sensing limitations of the sensor. In future versions, we wish to address these limitations and enhance the robustness of GrabAmps.

6. ACKNOWLEDGMENTS

This research was funded by MIT- SUTD International Design Center and JST-ACCEL "Emboided Media" project.

7. REFERENCES

[1] Bowman, M., Debray, S. K., and Peterson, L. L. 1993. Reasoning about naming systems. *ACM Trans. Program. Lang. Syst.* 15, 5 (Nov. 1993), 795-825. DOI= http://doi.acm.org/10.1145/161468.16147.

[2] Fröhlich, B. and Plate, J. 2000. The cubic mouse: a new device for three-dimensional input. In *Proceedings of* CHI 2000, 526-531. DOI= http://doi.acm.org/10.1145/332040.332491.

[3] Englert, F., Schmitt, T., Kossler, S., Reinhardt, A., and Steinmetz, R. How to auto-configure your smart home?: High-resolution power measurements to the rescue. In *Proceedings of* e-Energy 2013, 215–224

[4] Ganu, T., Seetharam, D. P., Arya, V., Kunnath, R., Hazra, J., Husain, S. A., De Silva, L. C., and Kalyanaraman, S. nplug: A smart plug for alleviating peak loads. In *Proceedings of the 3rd International Conference on Future Energy Systems: Where Energy, Computing and Communication Meet*, e-Energy 2012, 30:1–30:10.

[5] Gupta, S., Reynolds, M. S., and Patel, S. N. Electrisense: Single-point sensing using emi for electrical event detection and classification in the home. In *Proceedings of* Ubicomp 2010, 139–148.

[6] Gustafsson, A., and Gyllensw¨ard, M. The power-aware cord: Energy awareness through ambient information display. In *Proceedings of* CHI 2005, 1423–1426.

[7] Hart, G. . Nonintrusive appliance load monitoring. *Proceedings of the IEEE 80,* 12 (Dec 1992), 1870 1891.

[8] Jiang, ., Luo, S., and Li, J. An approach of household power appliance monitoring based on machine learning. In *Proceedings of (ICICTA),* 2012, 577–580.

[9] Jiang, X., Dawson-Haggerty, S., Dutta, P., and Culler, D. Design and implementation of a high-fidelity ac metering network. In *Proceedings of* IPSN 2009, 253–264.

[10] Jiang, X., Van Ly, M., Taneja, J., Dutta, P., and Culler, D. Experiences with a high-fidelity wireless building energy auditing network. In *Proceedings of* SenSys 2009, 113–126.

[11] Kim, Y., Schmid, T., Charbiwala, Z. M., and Srivastava, M. B. Viridiscope: Design and implementation of a fine grained power monitoring system for homes. In *Proceedings of* Ubicomp 2009, 245–254.

[12] Laughman, C., Lee, K., Cox, R., Shaw, S., Leeb, S., Norford, L., and Armstrong, P. Power signature analysis. *Power and Energy Magazine, IEEE 1,* 2 (Mar 2003), 56–63.

[13] Lee, K., Leeb, S., Norford, L., Armstrong, P., Holloway, J., and Shaw, S. Estimation of variable-speed drive power consumption from harmonic content. *Energy Conversion, IEEE Transactions on 20*, 3 (Sept 2005), 566–574.

[14] Lifton, J., Feldmeier, M., Ono, Y., Lewis, C., and Paradiso, J. A platform for ubiquitous sensor deployment in occupational and domestic environments. In *Proceedings of* IPSN 2007*,* 119–127.

[15] Patel, S. N., Gupta, S., and Reynolds, M. S. The design and evaluation of an end-user-deployable, whole house, contactless power consumption sensor. In *Proceedings of* CHI 2010, 2471–2480.

[16] Patel, S.N., Robertson, T., Kientz, J. A., Reynolds, M. S., and Abowd, G. D. At the flick of a switch: Detecting and classifying unique electrical events on the residential power line. In *Proceedings of* UbiComp 2007, 271–288

[17] Rajagopal, N., Giri, S., Berges, M., and Rowe, A. A magnetic field-based appliance metering system. In *Cyber-Physical Systems (ICCPS), 2013 ACM/IEEE International Conference on* (April 2013), 229 238

[18] Uddin, M., and Nadeem, T. Machinesense: Detecting and monitoring active machines using smart phone. *SIGMOBILE Mob. Comput. Commun. Rev. 16,* 4 (Feb. 2013), 16–17.

[19] Weiss, M., and Guinard, D. Increasing energy awareness through web-enabled power outlets. In *Proceedings,* MUM 2010, 20:1–20:10.