Electricity Submetering on the Cheap: Stick-on Electricity Meters

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ABSTRACT

We demonstrate a low-cost, 21 x 12 mm prototype Stick-on Electricity Meter (SEM) to replace traditional in-circuit-breaker-panel current and voltage sensors for building submetering. A SEM sensor is installed on the external face of a circuit breaker to generate voltage and current signals. This allows for the computation of real and apparent power as well as capturing harmonics created by non-linear loads. The prototype sensor is built using commercially available components, resulting in a production cost of under $10 per SEM. With no high-voltage install work requiring an electrician, home owners or other individuals can install the system in a few minutes with no safety implications. This leads to an installed system cost that is much lower than traditional submetering technology.. Measurement results from lab characterization as well as a real-world residential dwelling installation are presented, verifying the operation of our proposed SEM sensor. The SEM sensor can resolve breaker power levels below 10W, and it can be used to provide data for non-intrusive load monitoring systems at full sample rate.

Introduction

Electricity usage in the USA is responsible for 40% of our primary energy expenditure and carbon emissions [1]. Research shows that electricity submetering combined with feedback to users, and maintenance follow-up can reduce a building's electricity use by 10% to 30% [2]. However, very few buildings are outfitted with the meters required to enable these savings because of the high cost of installation. Installing an in-panel electricity meter can cost a thousand dollars or more because an electrician must shut off building power (or perform hot work), open the electrical panel, install components, and install enclosures to cover the equipment and signal leads. We recently paid an electrician $800 per home to install TED meters on top of the $250 hardware cost. Some installations included return electrician visits due to meter issues. The payback period for such an install is long, and the cost and hassle is high for metering in research studies. In order to enable wider use of metering in research studies and to reduce building electricity usage, it is critical to develop electricity metering technologies that provide more granular energy information with dramatically reduced install costs.

Today's commercially available breaker panel submetering technologies require bulky current transformers (CTs) and voltage connections to be installed at every breaker. Replacing the in-panel hardware with Stick-on Electricity Meter (SEM) sensor devices on the outside of the circuit breakers provides a number of benefits. First, installation on the outside of the circuit breaker panel does not require an electrician and can be performed by untrained staff in only a few minutes. Second, since the system is contained between the panel face and panel door, no external wiring or conduit must be installed. These reasons, combined with lower hardware costs, pave the way for a non-contact SEM system that drastically reduces total submetering installation costs. Our SEM design is based on commercially available components and is practical for widespread adoption due to standard, low-cost PCB fabrication and assembly requirements. In this paper, we present the design of a SEM sensor PCB built using commercially available components. Our device shows very good measurement performance and can be built for a component cost below $10 in moderate quantities.

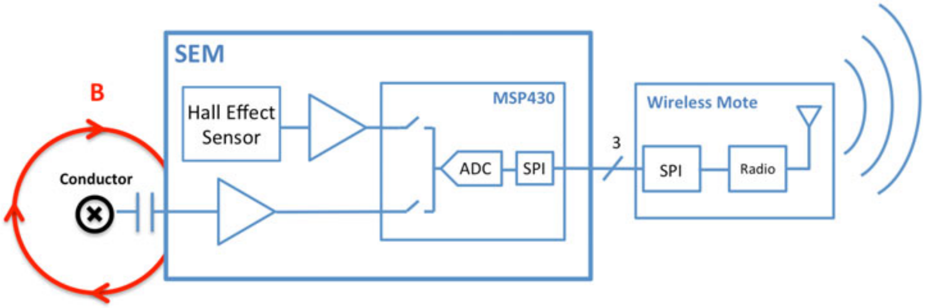

Figure 1. SEM system in-panel block diagram showing sensing techniques, SEM, and wireless interface board (mote).

System Overview

In this section, an overview of each SEM hardware subsystem and the flow of sensor data will be discussed. A block diagram of the in-panel system can be seen in Figure 1.

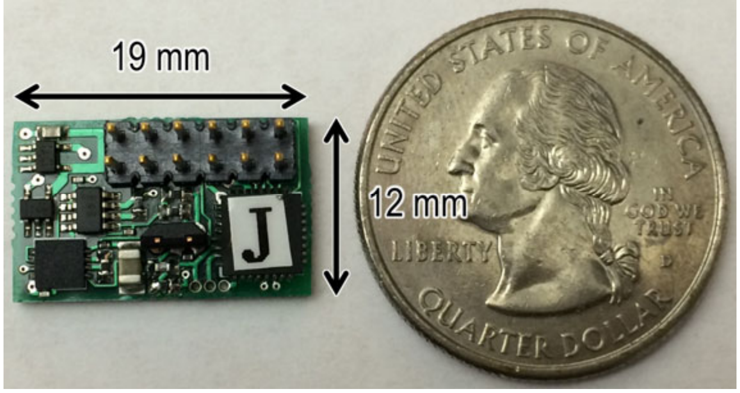

Figure 2. 19 x 12 mm (0.8 x 0.5 in) assembled Stick-on Electricity Meter with size reference.

SEM Board

Each SEM sensor board is equipped with electric and magnetic field sensors, an analog front end for signal conditioning, and a Texas Instruments MSP430 microcontroller that digitizes the signals and performs processing and communication. Details of the sensing and analog circuits will be discussed in a following section on Sensing Implementation. The entire SEM board consumes less than 0.1W and is powered using a standard AC to DC adapter. A close-up image of the 19 x 12 mm assembled SEM PCB board can be seen in Figure 2. The SEM's microcontroller is used for two purposes in our system: sampling the analog voltage and current sense signals, and transmitting samples to the wireless interface via a wired bus. To preserve information in the harmonics of the sensed current signals, a 960 Hz sampling rate is used in the 10-bit microcontroller ADC. This sampling rate is adjustable up to 3.8kHz to capture through the 31st harmonic. The current implementation passes the raw voltage and current samples back to the wireless interface board, and these raw samples are then sent wirelessly to a wireless gateway which calculates real power values. The processor on the SEM is capable of providing local processing of the raw samples as well, and will be a feature included in the next software revision. The total cost of the components on the SEM is $5, the board is $1, and the assembly is $3 when 1000 units are produced. Packaging the SEM will add an additional $1 to the cost leading to a total cost of $10 per unit. Retail prices of $30 would be reasonable given this very low hardware cost, and this is roughly the same as the cost of a split core current transformer. Total system retail cost for two SEMs and a gateway device would be about $125.

Wireless Interface Board

In this system, the wireless interface board [4] functions as a data relay station for SEM devices installed on the breaker panel. The wireless interface board pulls data off of up to eight SEM devices installed on the breaker panel, packages the data for transmission, and sends them over a wireless link to a gateway device. The wireless link uses an IEEE 802.15.4 radio and the OpenWSN [5] network stack. OpenWSN is an open source implementation of 6LoWPAN that utilizes a robust interference mitigation technique to maximize radio connectivity and reliability.

Wireless Gateway

A small computer such as the Raspberry Pi or BeagleBone equipped with an 802.15.4 USB dongle serves as the wireless gateway device. The gateway receives wireless data transmissions from the breaker panel wireless interface board and also performs subsequent DSP computations on the received samples. The signal processing algorithms are implemented in Python scripts, and this software unpacks the SEM's signals, calculates parameters of interest (e.g, real power, RMS voltage, RMS current), and posts the resulting data to a web-based data storage and display service [6]. Onboard data storage is present for logging up to as needed for up to one year of data at one minute time resolution.

Sensing Implementation

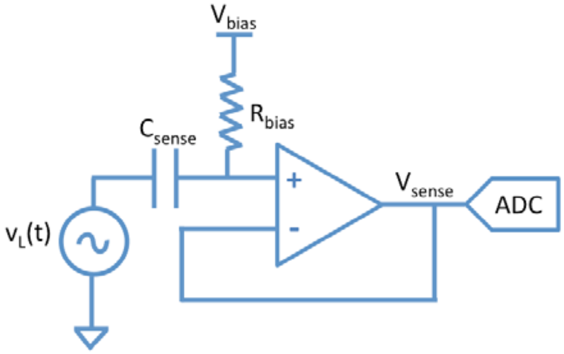

Figure 3. SEM board voltage sense circuit analog front end.

Voltage Sensing

The analog circuits used for our capacitive voltage sensing scheme can be seen in Figure 3. The sense capacitance is essentially a parallel-plate capacitor formed between the bottom metal plane of the SEM board and the conductor in the circuit breaker. For large capacitive coupling, careful SEM board layout consideration was practiced to keep the bottom layer densely filled with metal. The output voltage of this sensor is:

$$V_{sense} = R_{bias} \cdot C_{sense} \cdot dV_L/dt$$

where dV_L/dt is the time-derivative of the breaker's line voltage

In order to calculate real power, the amplitude and phase of a monitored breaker's voltage signal must be determined. Our experiments show that measuring changes in line voltage can be done accurately, but the absolute magnitude cannot be easily determined without additional information. The line voltage amplitude can be measured once at any outlet using a multimeter or other device (e.g., a Kill-A-Watt) to determine the line voltage. With the line voltage amplitude known, this parameter is loaded into the SEM, and the SEM scales its measured voltage by the correction factor. **Figure 4** shows a histogram of the voltage sensor magnitude error over a 12 hour period where the voltage varied ±2%. A Power Standards Lab PQube was used to measure the ground truth voltage in Figure 4. Line voltage tends to change little over time (±5% or less), and the sensors used here are able to measure voltage to within 0.5% reliably.

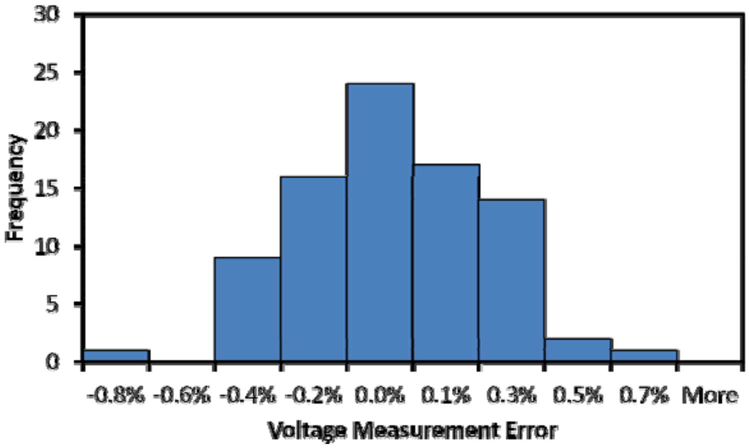

Figure 4. Histogram of measured voltage measurement error.

Phase measurement accuracy, however, is very critical for accurate power measurement particularly when there are large phase differences between the voltage and the current. Figure 5 shows how relatively small phase errors can contribute large measurement errors at low displacement power factors, but phase offset has very little impact at high power factors. This occurs because the slope of the cosine function is flat at 0° but gets increasingly steeper until 90°. This high slope means that small changes in the argument to cosine results in large changes in power value.

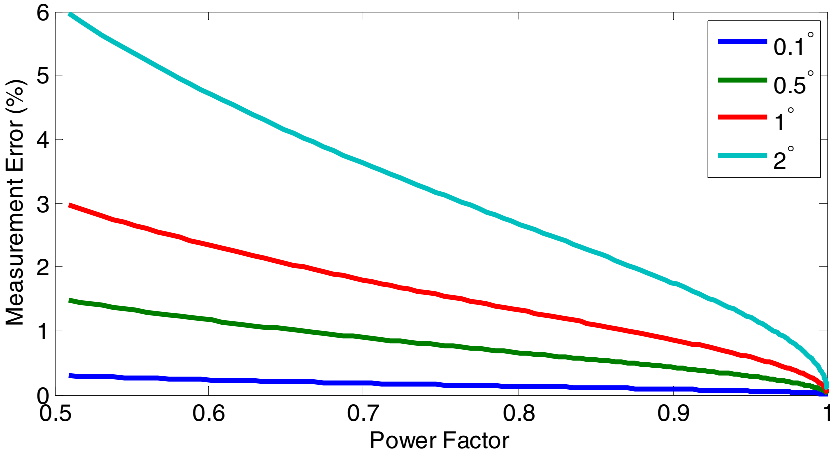

Figure 5. Power measurement error due to phase measurement offset between the voltage and current signals for 4 values of phase offset.

Therefore the correct phase of the breaker line voltage must be extracted to ensure accurate power calculation. Due to our capacitive sensing scheme, the phase of the voltage signal sensed is shifted 90° due to the derivative involved in the sensing mechanism .We must shift this signal by +90° before calculating $p(t) = v_L(t) \cdot i(t)$. We do this using a software phase-locked loop created in Python. A synthesized voltage signal with the correct phase and amplitude is used in subsequent real power calculations.

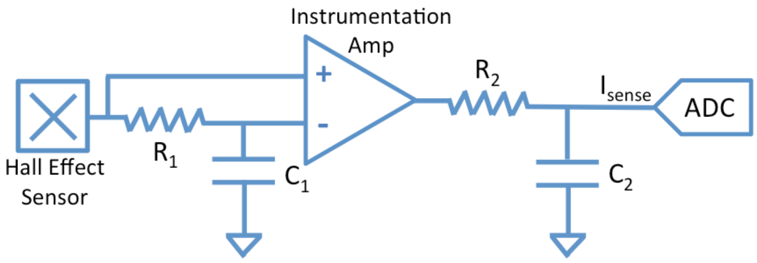

Figure 6. SEM board current sense circuit analog front end.

Current Sensing

At the heart of our current sensing scheme is a Hall Effect sensor that detects the magnetic field generated by currents flowing through a circuit breaker. The Hall Effect is a physical phenomenon where magnetic field induces a voltage difference to occur on two electrodes perpendicular to the direction of the magnetic field and to a current used to excite the sensor. We used commercially available Hall Effect devices, and a diagram of the current sensing analog circuitry is shown in **Figure 6**. The Hall Effect sensor outputs a very small signal that is proportional and in-phase to instantaneous current. We use a high gain amplifier to increase the magnitude of the signal before analog to digital conversion. We also noise limit the signal before it is digitized using a filter. This simple interface circuit enables a low-cost yet accurate measurement of the current.

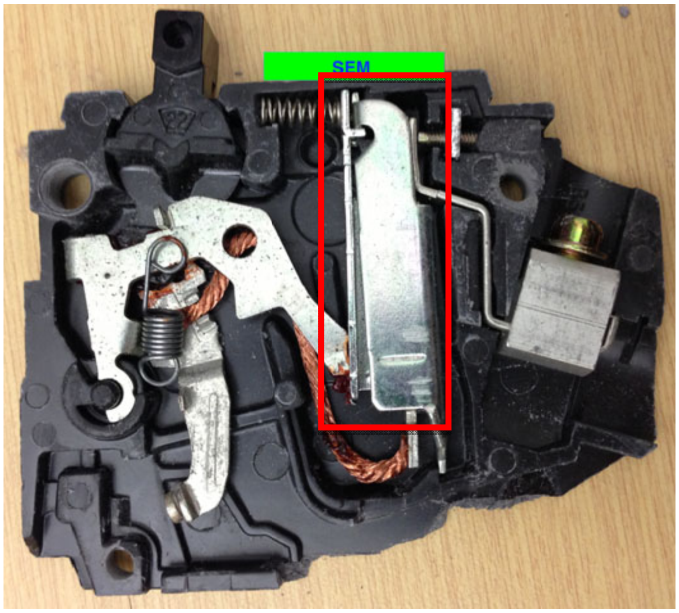

Figure 7. Bimetallic strip circuit breaker innards with SEM annotated and active elements that cause breaker to trip located in the box.

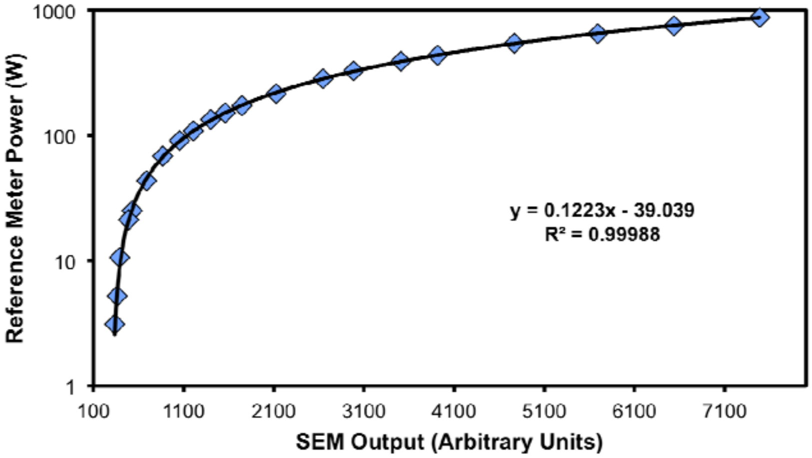

Figure 8. SEM output vs. reference plug-through power meter, showing great correlation to sub-10W load powers.

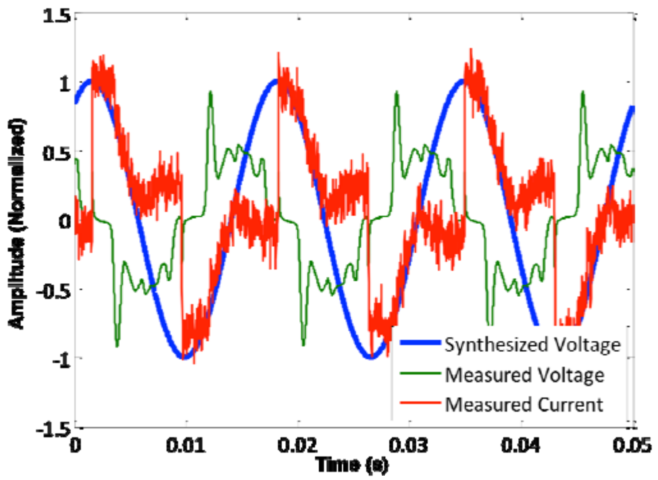

Figure 9. Measured and synthesized SEM waveforms for TRIAC dimmer load.

Experimental Results

In the characterization of our SEM prototype, measurements were completed in a laboratory environment as well as in an example residential installation. **Figure 7** shows the internals of a common residential circuit breaker with a bimetallic strip trip mechanism. The circuit breaker functions in two ways. First there is the bimetallic strip that is sensitive to changes in temperature. As the current flowing through the breaker increases, the temperature of the bimetallic strip increases due to losses in the breaker. That increasing temperature causes the strip to bend due to the different coefficient of thermal expansion of the two metals in the strip. If the strip bends enough, the breaker is tripped. This temperature based method is why it takes time for slightly overloaded breakers to trip. The second method is a magnetic trip where a crude electromagnet can trip the breaker in a single AC cycle if the current is very large (a short circuit). Both of these elements are located in the section of metal running vertically inside the box added to the drawing. We install our sensor on top of the breaker as shown in **Figure 7**.

From our investigations, most thermal and thermal-magnetic breakers have very similar internal geometries and current paths, so the current always is close to the surface of the breaker near the SEM install point. It is important to note that the breakers tested in this work do not contain solenoids for electromagnetic actuation which would increase the magnetic field magnitude around the breaker by 10-20x. If solenoid breakers were to be considered, the design of a high resolution current sensing system would be much easier due to the drastically increased SNR. For this work, we focused on the more challenging but also much more prevalent (in the US) thermal and thermal-magnetic actuated circuit breakers.

Laboratory Evaluation

To characterize the response of our SEM sensor, its voltage and current sense outputs were monitored across a wide range of load currents; the test setup will now be described in detail. Our SEM device was mounted onto the face of a circuit breaker in a bench top breaker panel. The bench top breaker panel is powered with a standard US power plug, which was plugged into the wall through a 20A power meter to provide reference power measurements. Lightbulb loads of various power ratings were switched on to load the breaker with different current magnitudes. The raw SEM voltage and current sense signals were processed in software to calculate real power. **Figure 8** presents the results of this experiment, comparing the output of our SEM sensor with the reference power meter. In this plot, the y-axis is a log scale, and measurement errors are less than 1% of full scale (1 kW) and typically less than 2% of measurement. From this plot, it is apparent that our sensing technique is very effective, showing strong correlation with a reference meter down to load power levels below 10W. Using this same test setup, we also monitored the outputs of our sensing system with a non-linear, TRIAC dimmer load. The time-domain waveforms from this measurement are shown in **Figure 9**, including the synthesized, phase-corrected line voltage signal. TRIAC dimmers (the way modern dimmers are made) utilize a semiconductor device to shut off the current to the load at every zero crossing of the voltage signal (both the rising edge and falling edge zero crossings). The dimmer knob controls the time delay between the zero crossing and the application of current to the load. In **Figure 9** the current is applied to the load half way through the positive or negative half of the AC cycle, so the load receives about half of the full-on power. From this figure, it is clear that the SEM is able to accurately capture the current signature of a load even if the load is highly non-linear.

Residential Installation

Our SEM system was installed on a breaker in a home to test the sensor in a real-world environment with various load types and transients. The breaker panel used for this test was also outfitted with a TED 5000 whole house meter, serving as the reference for calibration and measurement validation. **Figure 10** shows a photo of the hardware installed on a breaker in the circuit breaker panel. A laptop receiving 802.15.4 wireless SEM sensor data, executing Python DSP software, and uploading data to an sMAP server [6] was placed in a room adjacent to the breaker panel.

The SEM was installed on the dwelling's kitchen circuit, and, contrary to common practice and modern code, all appliances in the kitchen utilize this single circuit. Calibration of the sensor was completed by plugging different resistive loads into a kitchen wall outlet (with other loads static), and monitoring changes in the output of the SEM and TED meter. This established a calibration coefficient mapping the SEM's output to real power values. For the same model of circuit breaker, installations on multiple breakers can be accomplished with less than 5% error without recalibration. Several residential circuit breaker models were tested and were measured with less than 10% error without recalibration (i.e., using the same calibration as similar, single pole breakers). However some breakers (tandem breakers in particular) have significant variability model to model and require calibration for reasonable errors. The coefficient was then programmed into the laptop's python script for subsequent logging of real power data. A plot of the power data from both the SEM-metered kitchen circuit and the reference TED meter over a period of 8 hours is shown in Figure 11. It can be seen that the SEM sensor is accurately measuring power for loads with non-unity power factor. The difference in the trends of the two curves shown is due to load changes on other circuits in the residence because power was also used in the rest of the house during this test.

Figure 10. Photo of installation of SEM on a residential circuit breaker panel. The wireless interface board is mounted at the bottom of the panel and SEMs are mounted to five breakers.

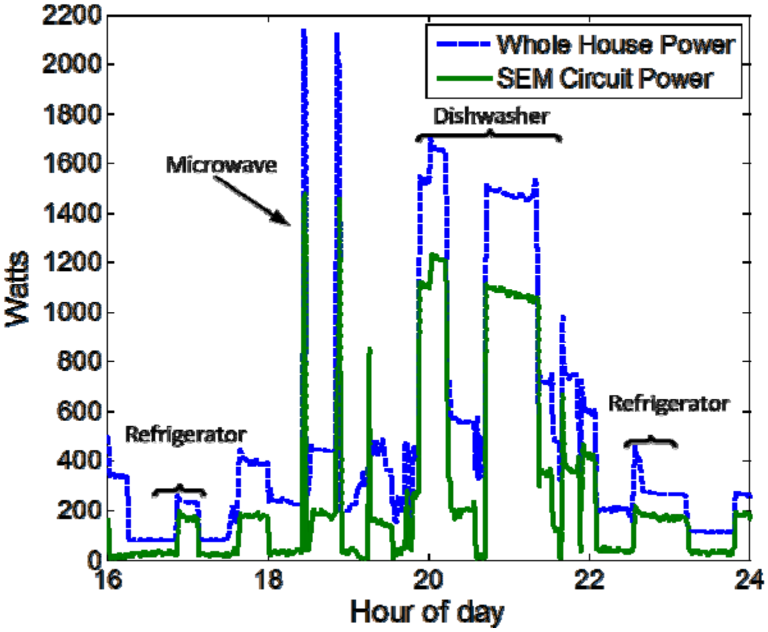

Figure 11. Whole house and kitchen circuit SEM meters' 8-hour energy data.

Conclusion

We have presented a new sensor system for building submetering at the circuit breaker panel that solves many issues inhibiting the widespread adoption of current electricity metering technologies. Our solution includes cost effective hardware that is suitable for installation without an electrician and is easy to produce. We estimate the installed cost of our system to be a fraction of the cost of other available solutions. Through the measurements presented in this paper, we have shown that our sensor accurately measures real power and works well in a residential installation with various types of loads. We believe the fundamental limitation in this system is due to the commercial hall effect sensor SNR at the magnetic field strengths of interest, introducing a measurement resolution vs. update frequency tradeoff. Future work in this area will include improving the quality of the electronics packaging and wiring for a more robust deployment, submetering many circuits simultaneously, and algorithms that automatically perform calibration based on exogenous information and analysis of sensor data.

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