

CircuitSense: Automatic Sensing of Physical Circuits and Generation of Virtual Circuits to Support Software Tools

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ABSTRACT

The rise of Maker communities and open-source electronic prototyping platforms have made electronic circuit projects increasingly popular around the world. Although there are software tools that support the debugging and sharing of circuits, they require users to manually create the virtual circuits in software, which can be time-consuming and error-prone. We present *CircuitSense*, a system that automatically recognizes the wires and electronic components placed on breadboards. It uses a combination of passive sensing and active probing to detect and generate the corresponding circuit representation in software in real-time. *CircuitSense* bridges the gap between the physical and virtual representations of circuits. It enables users to interactively construct and experiment with physical circuits while gaining the benefits of using software debugging tools. It also dramatically simplifies the sharing of circuit designs with online communities.

ACM Classification Keywords

H.5.2. Prototyping

Author Keywords

Electric Circuits; Component Recognition; Circuit Virtualization;

INTRODUCTION

The Maker Movement has helped generate significant interest in electronic circuit projects. By 2016, over 1.4 million people participated in Maker Faire events worldwide [8] and Arduino Studio, software for an open-source circuit prototyping platform, has been downloaded over 14 million times [1]. The proliferation of open-source software tools and readily accessible electronic components also helped accelerate this growth.

The breadboard is a solderless plug-board developed in the 1970s. Its simplicity, low cost, and re-usability make it the most popular circuit prototyping approach for education and maker projects. Although breadboard is easy to get started

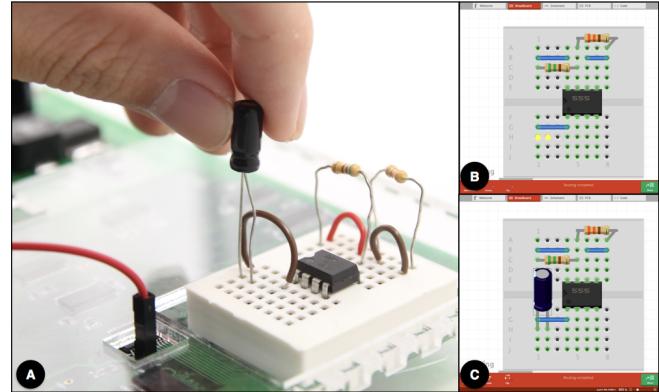


Figure 1. *CircuitSense* is a hardware+software system that facilitates automatic virtualization of physical circuit designs. (A) When developers place wires or electronic components on our *CircuitSense* breadboard, the (B) Pin Location Sensing determines the location (highlighted in yellow) and the number of pins, followed by (C) Component Recognition identifying the type of that electronic component, and *CircuitSense* generates the corresponding software representation ultimately.

on, studies [13] have shown that errors such as mis-wiring, incorrect usage of electronic components, and erroneous circuit designs are common.

Many software tools have been developed for virtual circuit debugging, simulation, and sharing. For example, Toastboard's software [15] allows users to draw circuits on a virtual breadboard, which is then able to detect common breadboard circuit error patterns and propose corresponding solutions. PSpice [11] circuit simulator can verify and debug circuit designs. However, in order to benefit from these software tools, users are required to manually create their circuits in software, which can be error prone and time consuming. Users also need to manually update the circuits to keep the virtual and physical circuits in sync.

To bridge the gap between physical circuits and their virtual representations, we present *CircuitSense*, a system that automatically recognizes the physical wires and electronic components in a physical circuit and generates their corresponding virtual representations. *CircuitSense* consists of two key features: 1) Pin Location Sensing that uses strain gauges to detect the location where all the pins of an electronic component are plugged into a breadboard, 2) Component Recognition that uses active wave signal probing and machine learning to iden-

tify the type of components and its specification. CircuitSense can construct virtual circuits in real time as physical circuits are created. It enables users to interactively construct and experiment with physical circuits while gaining the benefits of using software debugging tools. It also dramatically simplifies the sharing of circuit designs with online communities.

Figure 1 shows our prototype. As components and wires are plugged into our CircuitSense breadboard, the location and the type of the components are recognized and updated as part of a virtual circuit in the Fritzing software. We have demonstrated the capability of our CircuitSense prototype with an experiment, in which 22 different kinds of electronic components were successfully identified, including wires, resistors, capacitors, diodes, regulators, transistors, and 10 popular integrated circuits, with the number of pins ranging from 2 to 8.

RELATED WORK

Our CircuitSense prototype enables real-time, automatic sensing of a physical circuit on a breadboard and converting it into a virtual circuit in software. In this section, we discuss circuit prototyping tools for breadboards, computer-aid design (CAD) tools, and electronic component testing and recognition.

Circuit Prototyping Tools for Breadboards

Multimeter, Oscilloscope, and Digilent Electronics Explorer [6] are commonly used to debug breadboards. They require manual probing of the individual components. Toastboard [15] uses an instrumented breadboard to provide voltage sensing and visualization of an entire breadboard's voltage readings including historical data.

Toastboard also provides software-based debugging features, which performs template matching on common circuit error patterns, and suggests corresponding solutions. However, because Toastboard does not detect the physical wires and components in a circuit, this software error checking is available only after users manually draw their circuits using Toastboard's virtual breadboard software. CircuitSense automates the detection of physical circuits, and could be integrated with Toastboard to automatically provide software error checking without requiring any manual effort.

CircuitStack [19] supports rapid circuit prototyping by printing virtual circuits onto circuit papers, and sandwiching them between specially designed printed circuit boards (PCBs) and a breadboard. It automates the process of constructing a physical circuit from a virtual one, whereas CircuitSense automates the exact opposite, which is generating a virtual circuit by sensing a physical one. With CircuitSense, any changes to CircuitStack's physical circuit can be automatically detected, and could be used to keep the virtual circuits in sync, enabling more flexible workflow.

Computer-Aided Design (CAD) Tool for Circuits prototyping

CAD tools help users design, simulate, and share their electronic projects. Fritzing [16] is one of the most popular tools for the maker community. It facilitates drawing circuits on a virtual breadboard, and presents circuit in breadboard, schematic and printed circuit board (PCB) views. It helps

foster an ecosystem in which users documented their projects and shared the digital files with the community.

Tools such as CircuitLab [4], AutoDesk Circuits [2] and PSpice [11] enable developers to construct virtual circuit schematics and verify circuits through simulation. VISIR [17] allows students to wire and measure the electronic circuits remotely on a virtual workbench that automatically replicates a physical circuits.

Eagle [3] and OrCad [10] are designed to aid advanced users to create more robust and compact circuits in the form of PCBs. However, the entire process of creating/modifying schematics and PCB layouts still requires manual operation.

With CircuitSense, the circuit design of the functional breadboard prototypes could be automatically exported into the proper formats and imported into these software tools for sharing, simulation, debugging, and PCB layout.

Electronic Component Recognition and Testing

Some commercial products support the functionality of recognizing electronic components. LCR meter [7] automatically identifies the type of passive electronic components and calculates the resistance, capacitance, and inductance based on the impedance. Multi-function Tester [9] further distinguishes transistor, diode, MOSFET and battery when users plug the pins of a component into the proper locations. In addition, Integrated Circuit (IC) Tester [5] identifies an IC chips by searching its rule-based library, and tests its functionality. However, these products require users to plug individual components into specific instruments, separating from the intended breadboard circuit. CircuitSense provides recognition of multiple components as part of the breadboard itself. Furthermore, these products support either the recognition of IC chips or passive electronic components. CircuitSense supports the recognition of both types, plus wiring, all of which are needed to support the sensing of a complete breadboard circuit.

SYSTEM DESIGN AND IMPLEMENTATION

We designed our system to support the following three functions:

- Pin Location Sensing: detect the location of all of the pins of a wire and electronic component.
- Component Recognition: recognize the type of an electronic component.
- Virtual Circuit Generation: record the components and their pin locations, and create the corresponding virtual circuit representations.

Figure 2 illustrates the procedure of how CircuitSense performs these functions.

Pin Location Sensing

In order to sense the number of pins of a component and its pin locations, we added a strain gauge to each hole of the breadboard.

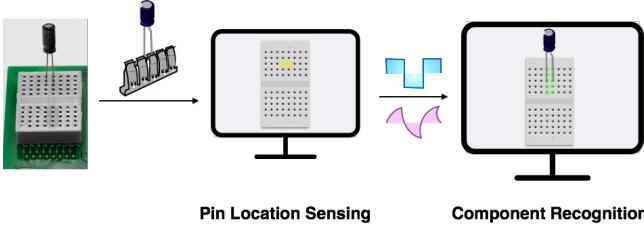


Figure 2. CircuitSense detects the locations of plugged components on the breadboard, identifies the type of components and visualizes them on Fritzing. For example, when users plug a capacitor into our system, Pin Location Sensing first detects the holes occupied by the component. Component Recognition then identifies the capacitor by machine learning classification models, and further calculate its specifications. Finally, CircuitSense display the capacitor on the virtual breadboard of Fritzing.

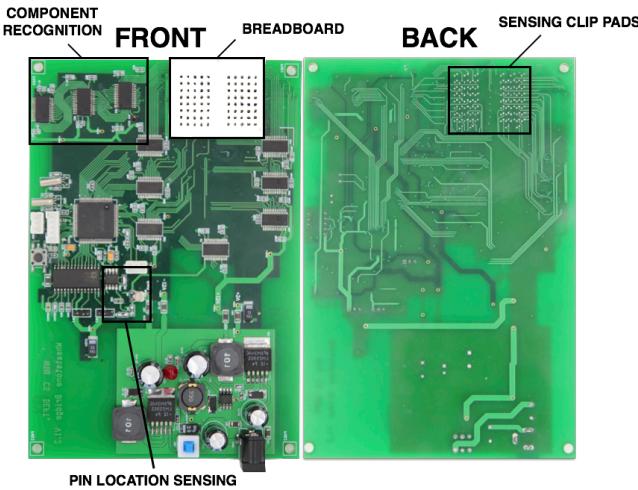


Figure 3. The CircuitSense Printed Circuit Board (PCB). The circuit of Pin Location Sensing includes a Wheatstone Bridge and a two-stage cascading multiplexer. The circuit of Component Recognition consists of 3 multiplexers. The lead wires of Sensing Clips are passed through the holes on PCB and are soldered to the Sensing Clip Pads

Strain Gauges

A breadboard consists of a perforated block of plastic with metal spring clips under the perforations. The metal spring clips, as shown in Figure 4A, are designed to hold a wire lead and component pin to provide reliable electrical connections and also provide tactile feedback to users.

In order to sense the insertion of a wire or a component, we attached strain gauge sensors on every spring clip. When users plug in a wire or a component, the spring clips bend outward slightly, and the bending of the clips results in subtle but noticeable changes in electrical resistance readings of the strain gauges. In our case, the length and width of the strain gauges are 4.0mm and 2.4mm respectively, which match the sizes of a standard breadboard clip. We attached five strain gauges onto a spring clip on alternating sides, as shown in Figure 4B, with a total of three sensors on one side and two on the other.

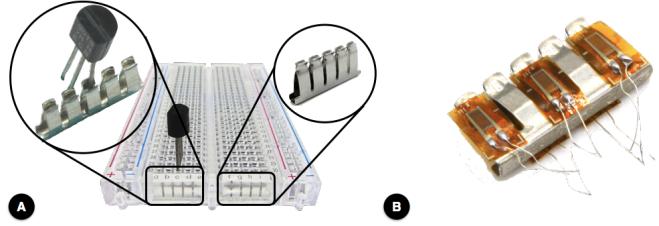


Figure 4. (A) The interior structure of a breadboard consists of rows of tiny metal spring clips, with each corresponding to 5 holes on the breadboard. The spring clips hold a component pin tightly to provide a electrical connection and also tactile feedback to users. (B) A clip with 5 strain gauges attached, with 3 on the front and 2 on the back side, to sense whether component pins have been inserted.

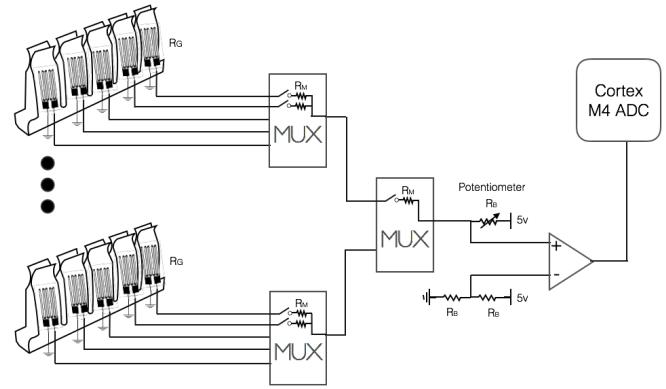


Figure 5. The circuit design of Pin Location Sensing. All sensing clips are connected to two-stage cascade of multiplexers. For measuring the small change in resistance of the strain gauges, the resistance(R_B) of balanced resistor is equal to the sum of two inner resistance of multiplexers(R_M) and the basic resistance of strain gauge(R_G). ($R_B = 2 \times R_M + R_G$). The potentiometer is used for minute adjustment in resistance.

Sensor Reading Circuit Design

In order to sense the small changes in electrical resistance of all the strain gauges, we designed a circuit to scan all the sensors, as shown in Figure 5. It consists of a Wheatstone bridge, one two-stage cascade of 16-to-1 multiplexers (ADG1606, Analog Device) and an instrumental amplifier (AD8228, Analog Device). A chained set of multiplexers controlled by an ARM Cortex-M4 microcontroller is used for sampling the large number of sensors. Once a sensor becomes one of the 4 resistors on the Wheatstone bridge and the strain-induced change in resistance will result in the variation of output voltage, which ranges from 0.3mV to 0.5mV when the lead of a component inserts into a sensing clip. The instrumental amplifier gain is set to 100 for measuring the small changes in voltage. Finally, we connected the output voltage of the amplifier to an 12-bit Analog to Digital Converter (ADC) in the microcontroller.

Breadboard Prototype

For our current prototype, we built a small breadboard with 8 rows and 10 columns and a total of 80 sensing clips, as shown

in Figure 3. The sensing clips were soldered to our custom PCB for electrical connections to each row. Because of the large number of lead wires of the strain gauges, we simplified the wire routing by having the lead wires of strain gauges pass through the holes on the PCB and soldered them to the copper pads on the backside. We then connected each pad to the multiplexer cascading circuit. Finally, CircuitSense read the value of each sensing clip at the sampling rate of 10kHz. In order to identify all the pins of a component, we grouped new pins that are inserted within a small time window, currently set to 2 seconds.

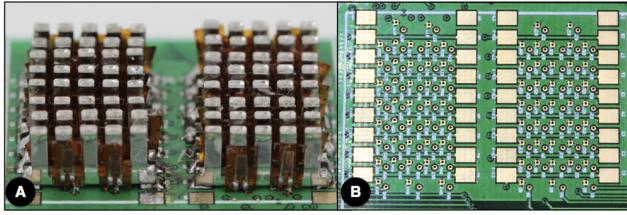


Figure 6. The sensing clips. (A)The lead wires of strain gauges were passed through holes on PCB and soldered on the copper pads next to the holes. Each pad was connected to a multiplexer cascading system, which transmits the sensing value to our Pin Location Sensing system. (B) 8 * 2 sets of sensing clips.

Component Recognition

CircuitSense identifies the type of components by performing active wave signal probing and applying machine learning classification.

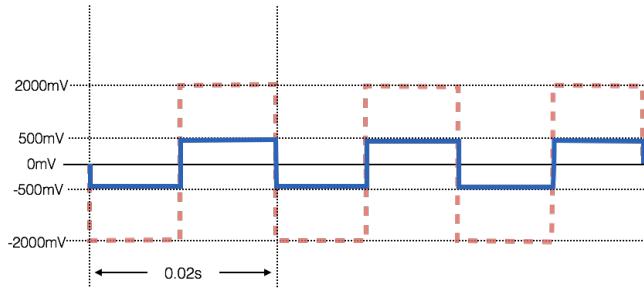


Figure 7. The square wave signal in Component Recognition. The period of the square wave is 0.02 seconds and the amplitude is initially set to 500mV (Blue) which can be adaptively increased to the maximum voltage, 2000mV (Red).

Active Probing

We designed an active probing technique that collects features of components without causing damages to circuits. We use square waveform as stimulus, which would be transformed after passing through electronic components. We also adaptively adjust the voltage amplitude for components that require a higher operating voltage.

Once we detect that a component has been plugged in, we start sequential probing for all 2-combinations of pins of that component and record the results. Our system would sequentially select one pin to probe with the square waveforms, select another pin to connect to ground, and collect data from every pin of that component.

The following formula shows the relationship between the number of collected waves and the number of component pins.

$$\#Wave = \binom{\#Pin}{2} \times \#Pin$$

For a 2-pin component, we collect $1 \times 2 \text{pin} = 2$ response waves, for a 3-pin component we collect $3 \times 3 \text{pins} = 9$ response waves, etc.

In our prototype, the probing signal is generated using waveform generator AFG3022C. The frequency of the wave was set to 50Hz, which was a balance between fast detection time and the range of detectable components. Higher frequency leads to faster data collection times, but has shorter time for charging and discharging which may result in more limited range of detectable components. Furthermore, in order to activate electronic components while preventing damages, the initial voltage range is set to -500mV to 500mV (peak-to-peak amplitude of 1V).

However, some 2-pin components, such as LEDs and beepers, may require a higher operating voltage than the initial 500mV or they would appear to be an open circuit. For these kinds of components, we use an adaptive approach to adjust the voltage amplitude, by gradually increasing 500mV from the initial amplitude until the system detects output waves, which indicates that the component is at or near its operating voltage.

In summary, CircuitSense uses active, non-destructive wave signal probing with 50Hz square waveform and adaptive voltage amplitude for 2-pin components, as shown in Figure 7.

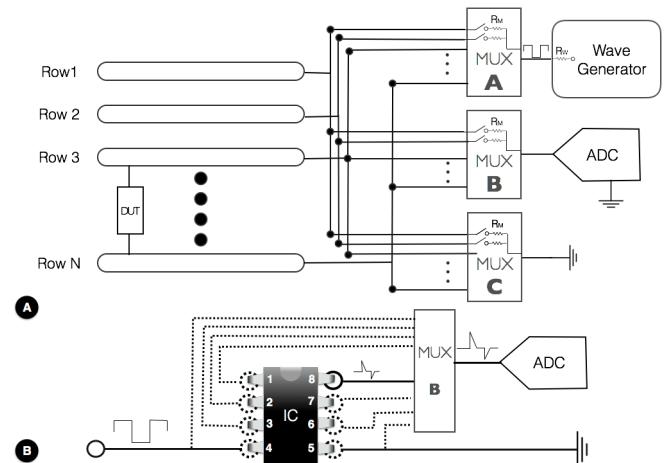


Figure 8. Hardware design for Component Recognition System (A) Each Row of Breadboard is connected to 3 multiplexers respectively for squared-wave input, data collection device and ground. (B) Multiplexer B switches between 8 pins of IC to retrieve waves passed to ADC.

Probing Circuit Design

In order for every pin on our breadboard to be able to probe and read the response waves, we designed a circuit containing three high-performance analog multiplexer (ADG426, Analog Device) and one high-speed Analog to Digital Converter

(AD1674, Analog Device). Three analog multiplexers, A, B, C, are connected to each row for the square wave input, data collection device, and ground, respectively, as shown in Figure 8A.

When a component has been inserted into our breadboard, our system would: 1) control Multiplexer A to connect one of the pins to the wave generator, 2) control Multiplexer C to connect one of other pins to ground, and 3) control Multiplexer B to sequentially connect the ADC to each pin of the component, and collect 2000 samples at 75000 Hz. The scanning circuit is shown in Figure 8B.

Component Classification

Our goal is to support real-time classification of common electronic components used in breadboard circuits, including wires, resistors, diodes, beepers, transistors, and integrated circuits. We would also like to identify additional properties like the resistance, capacitance, and inductance of a component, as well as the model number of an IC.

After collecting the response waves of a component, we extract statistical features from both the frequency domain and time domain of each wave, including mean, peak, median, variance and standard deviation. Furthermore, we compute the cepstrum [14] on each wave, which is the result of taking the inverse Fourier transform (IFT) of the logarithm of the estimated spectrum of a signal, and represents information about the rate of change in the different spectrum bands. We then use a collection of Random Forest Classifiers to classify the components, where a classifier is created and used based on the number of pins a component has.

To better understand the changes in response wave characteristics of common breadboard components, we select a list of components that span a variety of types and properties, including wires, resistors, diodes, beepers, transistors, and integrated circuits. The components are shown in Figure 9. In our experiments, CircuitSense successfully classified the type of 2-pin components, as well as recognized the model number of 3-pin components and ICs with 100% accuracy.

	2-pin Component	3-pin Component	IC
Components	Wires Resistors (50 -1000Ω) Capacitors (1-100μF) Inductors (0.01 -1H) Diode (1N4001) Beepers	LM317 - Regulator LM337 - Regulator TIP120 - NPN TIP122 - NPN TIP31C - NPN TIP32C - PNP	MC34063 - Regulators ICL7660S - Converter 24LC256 - 256K I2C MCP3002 - ADC LM358 - Amplifier MAX492 - Amplifier KA34063 - Controller DS1302 - TimeKeeping NE555N - Timer MSGEQ7 - Graphic Equalizer
Accuracy	100%	100%	100%

Figure 9. The recognizable components types and the discriminative accuracies grouped into three categories by the number of pins.

CircuitSense is capable of not only identifying the type of electronic components but also supporting identifying specific

component properties, such like resistance, capacitance, and inductance. Following sections explain the types of components and the calculation based on Figure 10.

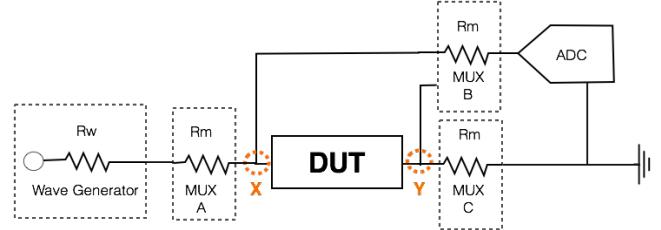


Figure 10. The circuit diagram illustrates the measurement configuration of 2-pin components. The square signal wave is applied to the device under test (DUT) through the inner resistors of a wave generator and a multiplexer. In our experiment, we sequentially collected the data at two ends of DUT, point X and Y.

Wires

For wires, the probing and the response waveforms are identical, with a small phase shift due to interleaved scanning. The equivalent circuit is a voltage divider circuit which leads to the response signal waves only changing in the amplitude as shown in Figure 11C.

Resistors

The response signal waves of the resistors are similar to wires according to Voltage Divider Rule. We further measured the resistance (R_x) based on the response signal at the point X in Figure 11B in the following formulation:

$$\frac{V_{out}}{V_{in}} = \frac{R_x + R_m}{R_m + R_w + 2 \times R_m}$$

where R_m is the inner resistance of multiplexer, and R_w is the inner resistance of wave generator. In our system, the measurable range in resistance is from 50 ohms to 1000 ohms, which is limited by the resolution of ADC. The measurement error is no more than 5%.

Capacitors

In the case that DUT is a capacitor, the probing signals are transformed by the charging and discharging of capacitance (Figure 11D). The whole circuit is equal to a standard RC circuit. According to Kirchhoff Circuit Laws, we measured the capacitance on the wave of point Y in Figure 10 by the relation of voltage and charging time:

$$C \frac{dV(t)}{dt} + \frac{V_0}{R} = 0$$

Where $V(t)$ is the voltage on the test point of Y, which can be measured from ADC, V_0 is the charged voltage and R is the total resistance. After solving the differential equation, the formulation is the following:

$$V(t) = V_0 e^{-\frac{t}{RC}}$$

Then apply logarithm on each side of the equation:

$$\log(V(t)) - \log(V_0) = -\frac{t}{RC}$$

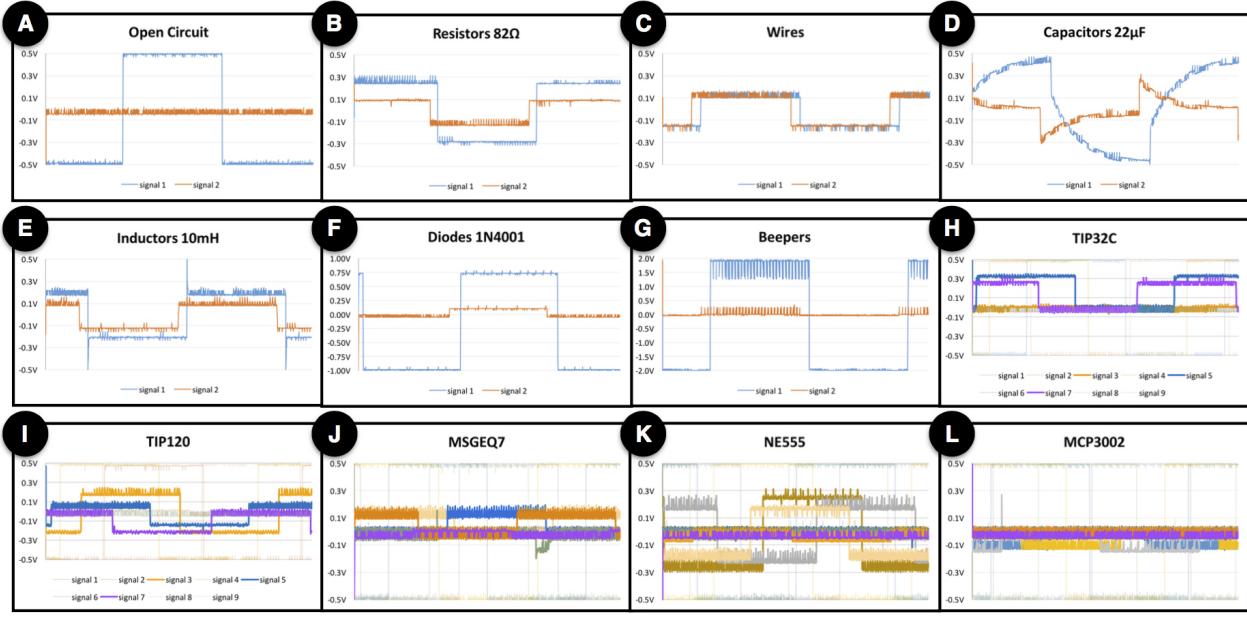


Figure 11. The response wave signal on example components. For 2-pin components (A) to (G), the signal 1 and signal 2 respectively equals to the signal collected at point X and Y in Figure 10. Different colors represent different signals retrieved with probing.

From this equation, we can observe the linear relationship between $\log(V(t))$ and t , and its slope is $-1/RC$. Because the total resistance is known, we apply linear programming, which can decrease the effect of noise in the circuit, on $\log(V(t))$ to get the value of slope for calculating the capacitance(C). Limited to the speed of ADC, the measurable range of capacitance of CircuitSense is $1\mu F$ to $100\mu F$. The measurement error for capacitance is within 15%.

Inductors

Inductors transformed the probing signal into the waveform shown as Figure 11E.

We calculated the inductance on the wave of point X in Figure 10 based on the following relationship:

$$V(t) = (V_2 - V_1)e^{-\frac{tL}{R}}$$

V_1 is the initial voltage, V_2 is the voltage after influenced by the inductor. Then applying logarithm:

$$\log(V(t)) - \log(V_2 - V_1) = -\frac{tL}{R}$$

Finally, linear programming was also used to measure the slope in order to estimate inductance. The range of measurable inductance is from $10mH$ to $1H$, which is still limited by the speed of ADC.

Diodes and Beepers

For several components including diodes and beepers, the response waves will be an open circuit if the input voltage is lower than the working voltage, which is impossible to determine them. When the adaptive voltage of probing is over

the operating voltage, the diodes and beepers will response different waveform, shown as Figure 11F and Figure 11G respectively. However, the polarity of diode and beepers will result in the effect of response waves. Hence, we also added the data of the inverse polarity to our trained-model.

Transistors and Regulators

In the category of 3-pin components, we selected six 3-pin components, LM317, LM337, TIP120, TIP122, TIP31C, TIP32C, including two CMOS linear voltage regulators, three NPN transistors with different specifications, and one PNP transistor. The response wave signal from two example 3-pin components are shown in the Figure 11G, which are obviously different from each other.

Integrated Circuits

As integrated circuits were widely used in electronic projects, we choose ten 8-pin integrated circuits including six most popular IC from SparkFun [12]. 8-pin integrated circuits are probed slightly differently from other components due to excessive 2-combinations of pins, which would lead to longer collecting time. Alternatively, we only collect 2-combinations on the opposite row of ICs. That is, we probe only four combinations (1,8), (2,7), (3,6), and (4,5) of the integrated circuit shown in Figure 8 and collect data from every pin as well.

Software

CircuitSense virtualizes physical circuits into circuit diagrams on Fritzing. The recognized components and physical wires would be automatically placed at the corresponding locations on a virtual breadboard. In addition, we provide an interface

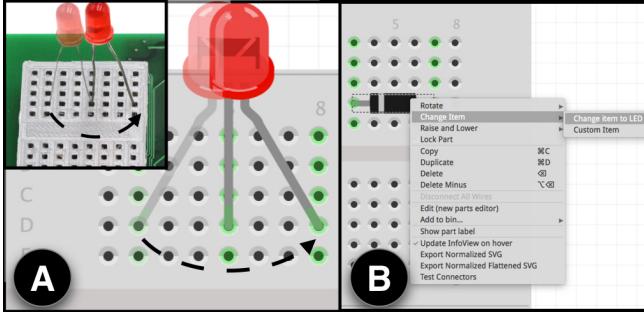


Figure 12. (A) When one lead of the component is detached and attached to another hole on the breadboard, CircuitSense will automatically modify the pin location on the virtual breadboard. (B) For the components can't be distinguished such like LED and diode, users can right-click on the component, and select the correct type of component.

for modifications which enables users to replace the components with other homogeneous components.

Circuits Construction and Modification

Once the start button on the modified Fritzing UI is clicked, the connection between the hardware and the software is established. CircuitSense then starts detecting the whole circuits and rendering the recognized components and wires on the virtual breadboard. In order to continuously update the modifications of user-created circuits, CircuitSense not only add the plugged components to the virtual breadboard but also remove the unplugged components from it. Our system tracks the whole building process of the physical circuit and synchronizes it with the virtual representation on Fritzing.

User Revision

To address the issues of unrecognizable component types and homogeneous components such as a LED and diode, we also provide the function for users to select the correct type of components. For example, When a LED is inserted into our breadboard, our system will identify it as a diode due to the homogeneity between two components. For revision, users can right-click the diode on the virtual breadboard, and selected the "Change Component" option in the menu (Figure 12B), which contains a list of similar components to choose. Then the users can change select the type "Led" to complete the circuit diagram. If the component is not in the list, the users can also select "Custom Item" to input the name of the expected component.

DISCUSSION

We discuss the limitations and future work of CircuitSense, as well as the impact to Maker Community and Electronic Engineering.

Expanding Recognizable Components

To broaden the range of detectable components, we plan to explore several approaches to enhance our system. First, the recognizable component types and models currently depend on pre-trained models. We plan to implement a real-time model training system, which supports users adding new components into the database for classification model training. Second, higher speed and resolution of Analog-Digital-Converter

(ADC) enables a broader measurable range of resistance, capacitance, and inductance. Third, some components require a higher voltage to operate, such as motors and high-voltage diodes. These components can not be recognized if the probing voltage is lower than the operating voltage. We plan to develop a system that can increase voltage while limiting the maximum current in order to prevent component damage.

Parallel Circuits

Our current prototype only supports components in parallel circuits with user participation. By first placing all the components used in the parallel sections onto the breadboard without connecting them to the main circuit, the components will be recognized correctly. Users can then complete all the parallel connections with wires. As a fallback mechanism, users can revise any incorrectly sensed components. In order to support parallel circuits without user participation, we plan to design a new PCB capable of isolating and connecting individual components.

Scaling the Breadboard

Currently, the breadboard in our proof-of-concept prototype is only 8 rows and 2 columns, which is smaller than those of a normal breadboard. For general use, we plan to scale the size of the breadboard and explore ways to improve location sensing. For example, using customizable inkjet layers such as [18] attached on the strip of clips and adhered on the board with copper tape. Also, as the number of cascading multiplexer will increase, the inner resistance would also change. We will need to adjust the balanced resistor within Wheatstone bridge to ensure the system works properly.

Benefits from CircuitSense

CircuitSense brings several advantages into circuit prototyping. First, the auto-construction of virtual software files facilitates circuit file management and circuit version control. Users no longer need to record the physical circuit projects on their own and can easily manage different versions to trace back the revision history. Second, CircuitSense significantly accelerates and simplifies the sharing of circuit designs with online communities. Third, while building the physical circuits, users can simultaneously benefit from the functionality, such as circuit simulation and debugging, supported by software tools. These advantages illustrate how CircuitSense enhances the prototyping experience through real-time physical-to-virtual circuit sensing and synchronization.

CONCLUSION

In this paper, we presented CircuitSense, a hardware+software system that achieves the automatic virtualization of physical circuit design on traditional breadboards. CircuitSense comprises two systems: 1) Pin Location Sensing, for detecting the placing of electronic components on breadboard with reinforced spring clips inside, and 2) Component Recognition, which performs an active low-voltage probing to retrieve the wave signals and then identifies the component through Random Forest Classifier models. We show that CircuitSense is able to recognize 22 different kinds of electronic components at an accuracy of 100%. Furthermore, CircuitSense supports

one of the most common software assistant tools, Fritzing, by real-time generating the corresponding software diagram.

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