# Daisy-Chaining Embedded Processors for Enhanced Capacitive Sensor Array Resolution

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***Abstract*—Capacitive sensing technology is widely applied in ubiquitous sensing. Its low-power consumption enables it to be used in a wide variety of Industry 4.0 applications. Capacitive Sensors can be combined into Arrays (CSAs) with mutual capacitive sensing to reduce external wiring requirements. For instance, the Texas Instruments (TI) MSP430FR2676 can capture and process data from 8x8 capacitive sensor grids. However, it is limited to supporting only 64 sensors. We propose a design incorporating daisy-chaining of CSAs via the I2C serial protocol to enable support for 256 sensors. We also demonstrate a rapid prototyping implementation of 128 sensors. The extended work we plan is to implement the prototype on custom Printed Circuit Boards (PCB) and maximize data update frequency. This architecture can find relevance in industries like manufacturing and farming, enhancing precision in the interaction between robots and humans/objects.**

**Keywords - Capacitive Sensor Arrays, Soft Robotics, Human-Robot Interaction, Embedded Systems**

## I. Introduction

Capacitance is the ability to hold electric charge. A gap between two objects with different electric potentials causes an electric field to form. Capacitive sensor arrays (CSAs) utilize this physical principle to recognize the electric field over a spatial domain. CSAs consist of a series of capacitors in a grid format. The capacitors electrically couple with one another to create a mutual capacitance grid. When a conductor, such as a human, touches it, the stored electric charge is shunted. A benefit to CSAs is the inherent low power consumption [1]. This means it can be a green technology for various ubiquitous sensing applications.

One useful application of CSAs is in soft robotics. Robotics technology in several industries can save time, fulfill dangerous tasks for humans, and give precision to repetitive motions. Despite this, there are significant issues that can arise. Robotic systems can have poor spatial awareness. For example, in a factory floor setting, where robots work with humans, there is a chance for a loss of control or unanticipated intervention. This can lead to lethal robot accidents such as forcing, clamping, or crushing humans against stationary objects [2]. CSA-based robot skins can create better spatial awareness for robots and lead to safer human-robot interactions.

Another example is in farming applications where robots harvest fragile crops like blackberries. If there is uneven clamping from a robot hand, then the integrity of the berry can be compromised and cannot be sold [3].

An Industry 4.0 goal can be to facilitate spatial awareness in robots by implementing robot skins, which are sustainable due to their low-power consumption. Capacitive Sensor Arrays (CSAs) can be an ideal tool to achieve this goal.

This work aims to create high-resolution CSAs for various applications by daisy-chaining multiple microcontroller (MCU) boards with fast update frequency data communication.

## II. Approach

The project aims to create a high resolution and high update frequency combined CSA grid. To accomplish this, we create a system with multiple individual 8x8 CSAs. Each additional CSA will provide greater data resolution, similar to how 256 pixels show a much greater resolution than 64 pixels on a monitor. We used the TI MSP430FR2676 to support capacitive sensing as it can support the most capacitive channels and is cost-effective [4]. Figure 1 shows the architecture to accomplish high-resolution capacitive sensing.

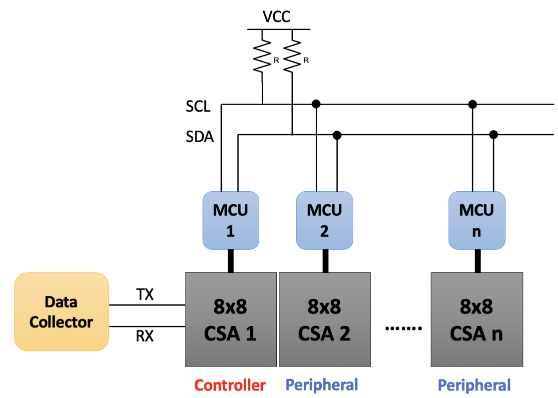
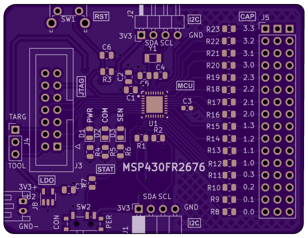



Fig. 1. Daisy-chained architecture comprised of 8x8 CSAs. This supports up multiple devices acting as peripherals.

Data production comes from the capacitive sensor arrays. For simplicity and prototyping purposes, the CSAs used are built according to TI's guidelines for a simple 8x8 CSA grid. Each board has 64 capacitive sensors with 8 transmit lines and 8 receive lines corresponding with capacitive-supporting pins on the MCU. Adding more sensors translates to better data resolution.

The MSP430FR2676 MCU collects the data, and can support up to 64 mutual capacitive sensors for data acquisition [5]. Increasing the resolution requires daisy-chaining boards together. Daisy-chaining is the act of wiring multiple devices together in a linear series. This novel approach enables higher resolution and fast data acquisition speeds. When multiple boards are linked, we consider the first board the controller (master), and each additional device with a CSA acts as a peripheral (slave) [6]. The data is then communicated via the serial Inter-Integrated Circuit (I2C) protocol, which is a serial protocol that consists of a controller sending a clock (SCL) signal and a data (SDA) signal to peripherals. Each signal line is pulled high to $V_{CC} = 3.3$V. In the I2C protocol, communication relies on the controller sending conditions and waiting for peripheral acknowledgments.

When the data is collected on the controller, it is sent to a data collector via the Universal Asynchronous Receive Transmit (UART) protocol with one transmit line (TX) and one receive line (RX). A data collector can be any device capable of broadcasting data for visualization (e.g., Wi-Fi connected MCU, or single-board PC).




(a) CapSense PCB Front


(b) CapSense PCB Back

Fig. 2. (a), (b) Show the front and back of the custom PCB designed for Capacitive data acquisition equipped with features such as JTAG programming, I2C communication, and battery or USB power.

## III. Preliminary Results

We used rapid prototyping to link one controller and one peripheral for proof of concept. We have realistically achieved 128 capacitive sensors by daisy-chaining two 8x8 CSAs. One MSP430 was designated as the controller and the other as the peripheral. When data is sent to the controller, it is sent to a data collector via the UART protocol. Figure 3 shows the implementation of the setup.

When the controller and peripheral communicate, CSA data is sent in packets of 8 bytes, with each bit representing the state of each row in the CSA. It was measured that each packet of data was sent in 627.8 microseconds. Table I shows the estimated number of supported devices for each theoretical update frequency.

| Update Frequency (Hz) | Est. Packet Time (ms) | Est. No. of Devices |
|---|---|---|
| 30 | 33.33 | 52 |
| 60 | 16.67 | 26 |
| 120 | 8.33 | 13 |

TABLE I
Maximum supported devices each update frequency for 8 bytes of data.

This assumes only 8 bytes of data is sent containing either on or off-state positions. If we want more information, we can include data about proximity from a conductor. Then, each packet will contain 64 bytes of data. Since 8 bytes takes 637 microseconds, a packet of 64 bytes will take 5.09 milliseconds.

| Update Frequency (Hz) | Est. Packet Time (ms) | Est. No. of Devices |
|---|---|---|
| 30 | 33.33 | 6 |
| 60 | 16.67 | 3 |
| 120 | 8.33 | 1 |

TABLE II
Maximum supported devices each update frequency for 64 bytes of data.

Our work is ideal for 8 bytes of data, however the implementation cannot support 64 bytes of data. The controller sets clock line to 125 kHz, which means the system is capable of sending $\sim$12.5 kilobytes of data every second. Future work will include data compression techniques to be able to reach this mark.

## IV. Future Work

This work was the basis for a long-term application of soft materials for robotics. The results of the rapid prototyping can be implemented on a custom Printed Circuit Board (PCB), as shown in Figure 2. Additionally, using conductive material, laser-engraved CSAs can be printed in many different configurations. To further advance this CSA-based robot skin, the MCU units can eventually feed data into a Field Programmable Gate Array (FPGA), which is reconfigurable hardware that possesses rapid processing speeds. This can enable high resolution robot skin capable of quick data communication and processing.

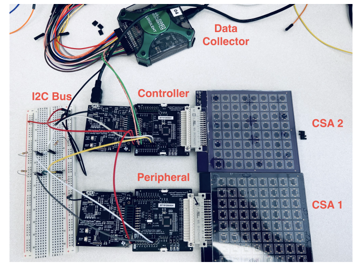



Fig. 3. Proof of concept of daisy-chained architecture comprised of two 8x8 CSAs, one controller and peripheral.

## V. Conclusion

This paper explored the development of a capacitive sensor array (CSA) for enhanced spatial awareness in robotic systems. The proposed architecture employs a daisy-chained arrangement of 8x8 CSAs, utilizing TI MSP430FR2676 boards to emulate high-resolution robot skin.

Preliminary results demonstrate a proof of concept on linking a controller and peripheral to achieve 128 capacitive sensors. Data communication occurs through I2C protocol, with each CSA data packet transmitted in 4.638 milliseconds. The data from both CSAs are then transmitted to a data collector via UART. Ongoing work involves the application of custom PCBs along with conductive and flexible material for scalable CSAs with fast data transfer.

## VI. Acknowledgements

This work is funded by the University of Arkansas Honors College Research Grant. This material is based upon work supported by the National Science Foundation under Grant No. 2237945.

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