



## Article

# Design and Implementation of a Low-Cost Touchscreen-Based Modern Home Automation System for Residential Energy Management

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## Abstract:

The ever-evolving landscape of embedded systems and the Internet of Things (IoT) has transformed the way homes operate. The aim of this research was to develop and construct a local home automation system that replaced traditional mechanical switches with a digital touchscreen interface. The system design employed an 8-bit 8051-family microcontroller as the control logic and a 4-wire resistive touch panel for user input. For power control and safety, a 4-channel relay module was used to achieve electrical isolation between the low-level control and high-level power loads. The system exhibited almost instantaneous response, with touch-to-load delay much shorter than human response time. The addition of a 16x2 alphanumeric LCD display enabled real-time monitoring, enhancing transparency. Compared to conventional manual switches, the proposed design provided greater convenience, monitoring and safety. The results of the study found that the proposed prototype is a cost-effective, reliable and scalable solution for home automation, especially where network connectivity is not essential and reliability is a critical requirement. This study suggests future work include the addition of wireless communication and sensor networks, to develop the system into a self-monitoring smart home.

**Keywords:** Home Automation, Microcontroller, Touchscreen Interface, Real-time Monitoring

## 1. INTRODUCTION

The concept of home has been revolutionised with the inclusion of “Ambient Intelligence” in which the home environment is aware and responsive to human presence. Today, home automation, once considered a luxury, has become a necessary mechanism to meet global challenges of ever increasing electricity bills, the need for enhanced home security and the need for assisted living technologies (Zamora-Izquierdo et al., 2010). The shift from manual switching to digitized control has been made possible by the availability of low-power and low-cost microcontrollers that serve as the “brain” of the household (Bhatt & Patoliya, 2016). The “smartification” of domestic settings has seen a shift in research towards designing intuitive Human-Machine Interfaces (HMI) to offer users control without technical expertise (Lee et al., 2016).

The development of these systems has involved a plethora of communication and control techniques. In recent

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years, wireless communication has been the most common, with Bluetooth systems providing localised, secure communication for close proximity (Anandhavalli et al., 2015; Asadullah & Ullah, 2017). At the same time, incorporating the Global System for Mobile Communications (GSM) has facilitated remote monitoring over longer distances, enabling users to control their appliances through SMS or telephone calls from anywhere in the world (Ganesh, 2017). While the wireless approach offers flexibility, it can be susceptible to issues such as signal interference, reliance on an external mobile phone and security issues with the user authentication process (El-Hajj et al., 2019). As a result, there is growing demand for dedicated, wires-only tactile devices - such as the touchscreen-based system used in this work - that are highly reliable, have instantaneous responsiveness, and are not vulnerable to network failure (Lee et al., 2016).

Hardware choice is a fundamental aspect of automation. Arduino and Raspberry Pi have been commonly used in previous studies for their open-source development environment and sensor connectivity (David et al., 2015; Patchava et al., 2015; Upton & Halfacree, 2016). But for dedicated control functions where precise timing is essential, 8-bit controllers (such as 8051 and PIC) are still widely used because of their low-power requirement and reliability (Puri & Nayyar, 2016; Gunpath et al., 2017). Such controllers need to interface with low-voltage digital circuits and high-voltage alternating current (AC) loads, often achieved via electromagnetic relays. Isolation is a critical aspect of the system for the user's safety and to prevent the logic circuitry from damage due to electrical transients and back-EMF (Howedi & Jwaid, 2016).

Beyond simple on-off control, the addition of status-indicating components such as LCDs not only improves user interaction, but also provides a means of diagnosing system behaviour. Feedback allows the user to be aware of the condition of the system, enhancing the user experience of automated systems (Imran et al., 2016). Finally, as we move towards the Internet of Things (IoT), these local and standalone prototypes are the starting point for more sophisticated "Fog Computing" applications, in which some processing is done locally (at the edge of the network) to provide resiliency and speed (Ozeer et al., 2019; Froiz-Míguez et al., 2018).

The main research goals of the current study were carefully crafted to consider both the technical and functional aspects of a home controller. First, this study intended to develop a home controller using an 8051-series microcontroller that is capable of multitasking for input readings and output activation. Second, the study intended to design a resistive touchscreen as the HMI to provide a digital alternative to mechanical switches. Third, the study sought to develop a reliable power-control circuit to safely control multiple AC loads (bulbs) via a 4-channel relay. Fourth, a goal was to include a 16x2 alphanumeric LCD for instant feedback of device states. Last, the research intended to assess the overall system performance (response time and switching reliability) to assess the feasibility of the prototype as a low-cost, scalable home automation system.

## 2. LITERATURE REVIEW

Much of the research is centred around the choice and deployment of wireless protocols for home automation. The articles reveal Bluetooth as a popular short-range communication protocol (Puri & Nayyar, 2016; Asadullah & Ullah, 2017; Anandhavalli et al., 2015). Research shows that Bluetooth-based systems can provide economical options for home applications, but are limited in range. ZigBee is another popular protocol, especially for mesh networking in smart homes (Li et al., 2014; Vivek & Sunil, 2015). WiFi-based solutions are widely investigated for their ubiquity and compatibility with existing network infrastructure (Yan et al., 2015; Bhatt & Patoliya, 2016). The studies show a tendency towards multi-protocol solutions for increased system adaptability and coverage (Vivek & Sunil, 2015; Froiz-Míguez et al., 2018). Moreover, the use of GSM and MQTT protocols is explored as alternatives to provide remote monitoring and control (Anandhavalli et al., 2015; Kodali & Soratkal, 2016).

Another notable group of studies relates to microcontroller platform choices and optimisation. The most popular platform is Arduino for its ease of use, cost-effectiveness and open-source community (Baraka et al., 2013; David et al., 2015; Gunpath et al., 2017). Several papers provide detailed Arduino-based examples from simple relay control to complex automation scheduling (Baraka et al., 2013). The Raspberry Pi platform is another significant category, for the greater processing power it offers to support advanced control and analysis (Upton & Halfacree, 2016; Patchava et al., 2015). Recent studies highlight WiFi-capable low-cost ESP8266 and ESP32 microcontrollers (Kodali & Soratkal, 2016; Syafa'Ah et al., 2019; Makhanya et al., 2019). Specialized platforms like PIC microcontrollers are also reported for low-resource applications (Puri & Nayyar, 2016).

Research literature showcases different architectural styles for home automation. Traditional research considers local control using a single controller or hub (Zamora-Izquierdo et al., 2010; Lee et al., 2016). Recent studies

more frequently consider distributed and fog-computing paradigms (Froiz-Míguez et al., 2018; Ozeer et al., 2019), allowing edge processing and low-latency operations in smart homes.

The integration of cloud systems is a recent development, with research considering hybrid local and cloud-based systems (Huang & Tseng, 2016; Kodali et al., 2016). Research highlights the need for local autonomy for system reliability and integration with the cloud for data analytics and remote control. The user interface is a significant area of the research. Economic considerations result in the use of traditional button-based interfaces (Lee et al., 2016). Smartphone apps, especially Android apps, are the most popular user interface tool in the recent literature (Puri & Nayyar, 2016; Asadullah & Ullah, 2017; Shafana & Aridharshan, 2017; Makhanya et al., 2019).

Web interfaces are reported as secondary control interfaces (Huang & Tseng, 2016). The literature suggests growing interest in smart and adaptive interfaces that personalise the user experience and trigger actions based on user preferences (Zamora-Izquierdo et al., 2010; Huang & Tseng, 2016). Voice interfaces and artificial intelligence integration are identified as future trends, but with little practical implementation. Internet of Things (IoT) paradigms are a revolutionary theme in recent years. IoT systems build on existing home automation with connected sensors, actuators and smart gateways (Singh & Ansari, 2019; Badabaji & Nagaraju, 2018; Kodali et al., 2016). Cloud computing integration allows real-time monitoring, predictive maintenance and data analytics for decision-making (Huang & Tseng, 2016; Froiz-Míguez et al., 2018; Ozeer et al., 2019).

The MQTT (Message Queuing Telemetry Transport) protocol stands out as the most commonly used middleware for IoT-based systems, thanks to its lightweight and publish-subscribe model (Kodali & Soratkal, 2016; Froiz-Míguez et al., 2018). Fog computing, which offloads computational tasks to edge nodes, is also increasingly explored to improve responsiveness and minimise bandwidth and communication costs (Froiz-Míguez et al., 2018; Ozeer et al., 2019).

Authentication and security are important themes. El-Hajj et al.'s (2019) survey offers a classification of IoT authentication approaches, tackling basic security issues for smart homes. A number of papers explicitly account for security in their designs (Kaur et al., 2016; Gupta & Chhabra, 2016; Kodali et al., 2016). Access control, encryption and authentication are recognised as critical elements to secure smart home systems against unauthorised access and attacks (El-Hajj et al., 2019). A clear understanding of privacy and data security as a critical element for commercial smart home systems is emerging.

Cost and energy efficiency are identified as design goals. Several studies focus on cost-effective solutions using open-source hardware and open-source software (Baraka et al., 2013; Gunpath et al., 2017; Howedi & Jwaid, 2016). Arduino and Raspberry Pi boards are justified mainly by cost considerations while achieving satisfactory functionality.

Energy efficiency is solved through scheduling algorithms (Baraka et al., 2013), relay control and device activation based on occupancy or environmental conditions (Gupta & Chhabra, 2016). So, cost-effectiveness and energy efficiency are not mutually exclusive design criteria, as per the literature. Sensor integration is a core theme for environmental monitoring and decision making support. We find that the literature identifies a range of sensors such as temperature, humidity, light, motion, and door/window contact sensors (Davidovic & Labus, 2016; Froiz-Míguez et al., 2018). Data collection, management and interpretation are noted as essential operations to support intelligent automation functions (Davidovic & Labus, 2016).

The literature suggests a move from basic rule-based automation to predictive analytics and machine learning algorithms that can learn patterns from sensor data (Huang & Tseng, 2016; Ozeer et al., 2019). There is also a wide focus on wireless sensor networks due to their scalability over wired systems (Spadacini et al., 2014; Vivek & Sunil, 2015). Although different from overall home automation, various papers discuss smart home automation in the context of surveillance and security (Spadacini et al., 2014; Kodali et al., 2016; Nedelcu et al., 2009). These systems combine motion sensors, video streams, and alert systems to deliver a holistic security monitoring system, in addition to typical automation features.

Distributed monitoring and alarm notifications are examples of features that allow home owners to stay connected to their homes regardless of where they are (Nedelcu et al., 2009; Kodali et al., 2016). The convergence of security and automation functions is a practical integration of these two aspects of the home. Smart remote control systems is a niche area in the field of home automation. The Point-n-Press system is an example of research on universal remote control that integrates control of various heterogeneous appliances through an easy-to-use

interface (Lee et al., 2016). This research theme covers the real-life problem of operating increasingly complex multiple systems in the home.

The evolution of the research over time is evident. Early publications (2009-2014) focused on basic architecture and choice of protocols (Nedelcu et al., 2009; Zamora-Izquierdo et al., 2010; Li et al., 2014; Spadacini et al., 2014). Middle period papers (2015-2017) concentrate on Arduino and Raspberry Pi and mobile apps (David et al., 2015; Lee et al., 2016; Gunpath et al., 2017). The most recent works (2018-2019) are increasingly concerned with IoT paradigms, cloud computing, fog computing and security (Froiz-Míguez et al., 2018; Ozeer et al., 2019; Jabbar et al., 2019).

### **3. METHODOLOGY**

This study adopted an engineering design methodology, starting with the creation of a control architecture for the centralised system as the system diagram illustrates. The system was purposefully divided into four main blocks: the User Interface, the Microcontroller Main Board, the Relay Driver Board and the AC Load Module. This approach enabled the verification of each of the three stages (signal conditioning, logic, and switching) independently, ensuring the overall system integrity and that the analog control from the user via the touchpad was correctly translated in discrete digital commands to the high voltage loads.

The hardware design was designed using a custom KitsGuru prototyping board based on an AT89S52 microcontroller. For reliable instruction execution, the controller was outfitted with a 11.0592 MHz crystal and manual reset circuit. For the sensing stage, a 4-wire resistive touch pad was attached to the X-Y coordinate system and the microcontroller was able to translate pressure into X and Y coordinates by detecting the voltage drops across the membrane. For output, a ULN2003 Darlington Array was used to drive four electromagnetic relays, offering essential galvanic isolation from the sensitive DC logic circuitry from the 230V AC bulb power supply.

The firmware interface was programmed in Embedded C, which operated on a real-time polling loop. When the system was powered up by the DC jack, the microcontroller would initialize the 16x2 LCD display and turn all the relays “OFF” by default. The code then began to monitor the data lines of the touchpad for a signal. When a touch occurred, a software debouncing filter to remove mechanical noise was applied followed by a coordinate mapping algorithm to check if the touch fell within the “ON” or “OFF” boundary. Finally, a toggle function was used to change the state of the GPIO pin, turning on the relay and refreshing the LCD status.

The last step of the methodology included performance testing to ensure the coherence between the user interface and the appliances. The prototype was tested for switching speed to confirm that there was no delay between a touch event and the switching of the corresponding bulb. The algorithm was also tested for reliability by repeatedly activating the interface of each bulb (Blue and Pink) to ensure that there were no issues with high-frequency switching. This sequence of tests confirmed the proper operation of the Human-Machine Interface, and ensured that the status logs on the LCD were always synchronised with the AC Load Module’s state.

### **4. HOME AUTOMATION SYSTEM SYSTEM**

The Modern Home Automation System with a Touchscreen Interface is an embedded system that offers interactive, centralised control of a series of household loads. It uses a digital Human-Machine Interface (HMI) to replace conventional wall switches, giving the user the ability to switch on/off any electrical appliances (represented in this model by four coloured bulbs) through a resistive touchscreen. The control is based on a low-voltage DC circuit that safely switches high voltage AC loads via a series of electromagnetic relays.

This model is a functional prototype of “Smart Home” devices, with a focus on convenience, safety and status feedback. The system’s microcontroller, acting as the brain of the operation, and LCD monitor display the ability of embedded logic to control household energy loads, and provides a modern tactile interface. It is a starting point for the study of sensor, controller and power electronics integration.

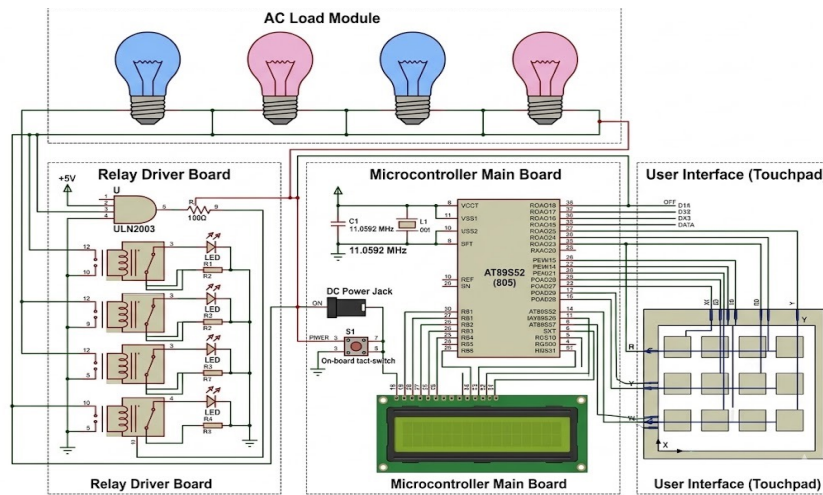


Figure 1: Schematic Design and System Interconnections for the KitsGuru Touchscreen Home Automation System

## 5. ARCHITECTURE AND SCHEMATIC DESIGN

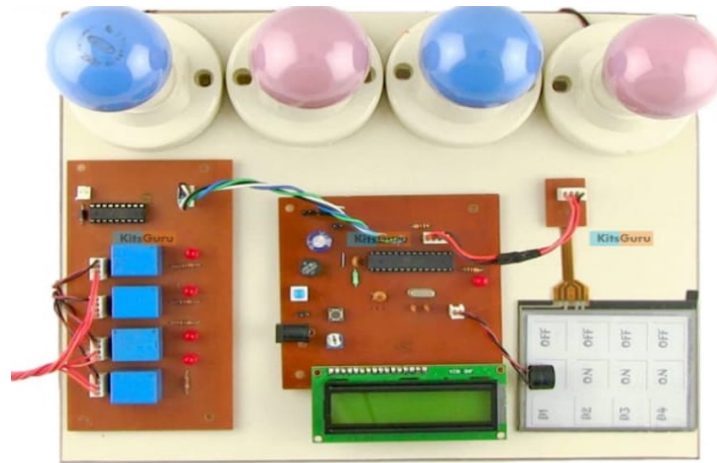


Figure 2: System Components

The system is a complete electronic package that shows current load switching techniques. It is made up of three main interlinked components: the User Interface (the touchscreen), the Controller (the central microcontroller board), and the Output Interface (the relay bank and light bulb holders). The system is physically assembled on a wooden or acrylic base to provide secure assembly between the modules. It works by translating a user's touch on a resistive touch membrane into a digital input that is then translated to control electromechanical "switches" in order to close the AC circuit for the four different colored bulbs.

According to the 40-pin Dual In-line Package (DIP) chip on the board, this version of the model uses an 8051-series Microcontroller (like AT89S52) or an 8-bit AVR family of microcontrollers. As opposed to a computer like a Raspberry Pi, this microcontroller is a special control chip. It is used in this type of automation due to its real-time execution, low power requirements, and it has enough General Purpose Input/Output (GPIO) pins to interface with the touchscreen, LCD, and relay drivers, while not needing an operating system.

The "sensor" in this project is the Resistive Touchscreen. It is connected to the microcontroller through 4 wires (X+, X-, Y+, Y-). When a press occurs, the microcontroller creates a voltage gradient across one of the layers and reads the voltage on the other. This voltage is sampled and converted to a digital value using an ADC (Analog-to-Digital Converter). The software converts these values into coordinates on a reference grid, thus transforming the printed sheet below the glass into an interactive keyboard.

The 16x2 Alphanumeric LCD serves as the system's feedback and status indicator. It converts the binary system states to a human-readable format. When the system is powered on, it usually shows a "System Ready" or "Welcome" message. When in use, each time a bulb is switched on or off using the touchscreen, the LCD

promptly displays the status of the load (e.g., “L1: ON, L2: OFF”). This serves as a feedback to the user that their touch input has been acknowledged by the controller and the action has been carried out.

The design is based on a two-rail power supply for safety. The microcontroller and logic gates are powered by a DC power adapter which regulates 5V or 12V. But the bulbs are connected to a high-voltage AC supply. To protect the microcontroller, the circuit includes a buffer, in the form of a ULN2003 Darlington Transistor Array. This ensures that the “flyback” voltage from the relay coils does not damage the microcontroller. The PCB traces are sized to allow the current needed to turn on the relays while not over-heating the Control Board.

The system’s control logic is implemented via a Sequential State Machine in the firmware. The controller is in a constant “Idle” state, scanning the touchscreen pins for a change in voltage level. The logic then moves to a “Decision” state, where the coordinates are compared with a memory map of the four buttons. If this match is made, the controller will send a “High” signal to the relay driver for that button. The logic is “latched” which means if the light was NOT on, the touch makes it turn on and stays on until the same coordinate is touched again to switch it back off.

## **6. HARDWARE COMPONENTS & IMPLEMENTATION**

The model is a single automation prototype design, with three primary printed circuit boards (PCBs) sitting on a base. In the middle, the Logic Unit comprises the microcontroller and power supply. The Relay Execution Board on the left contains relays and output connections. To the right is the Input Interface, containing a resistive touch screen with a printed command sheet. The modular design facilitates fault tracing and uses ribbon cables and jumpers instead of bulky wires to connect signals.

The four blue blocks on the board on the left are Electromechanical Relays, but they resemble buttons. But in many educational versions of the kit, the board also has small Tactile Micro-switches or jumpers for manual override or reset. In this design, the “blue blocks” are used as switches for the AC loads. When triggered by a 5V signal from the microcontroller, the coil in the relay creates a magnetic field that attracts an armature (a piece of metal), closing the circuit to the bulbs without requiring physical contact with high-voltage components.

The system uses a 4-Channel Relay Module for 5V DC control. Generally, each relay can handle 10A at 250V AC or 30V DC. The modules also have Freewheeling Diodes (such as 1N4148) to prevent back EMF when the relay coil is switched off. The design also includes LED Status Indicators for all channels, so that you can tell which relay is “closed” (energized) even if the bulb is not connected or even if it is burned out.

The LCD is a usual JHD162A 16x2 Character LCD. It has a 5V supply and an HD44780 controller protocol. It includes a green LED backlight to be visible in dimly lit environments and is 16 pin, with data lines (\$D0-D7\$), Register Select (\$RS\$), and Enable (\$E\$). In this model, its main purpose is as the System Debugger and Status Monitor, converting the microcontroller’s logic into text such as “Light 1: ON” or “Awaiting Touch”.

The main microprocessor is an 8-bit Microcontroller, probably the AT89S52 (8051). It has 8KB of Flash memory, 256 bytes of RAM and 32 I/O pins. It has a clock frequency set by an external 11.0592 MHz crystal, a common clock speed for these models as it enables accurate baud rates for serial communication. This chip handles the ADC conversion of the touchscreen input and the incremental triggering of the relays.

In this particular case, the wiring is done according to a port mapping standard. The Touchscreen is usually wired to the Analog pins (or external ADC chip) to detect voltage drops. The LCD is typically connected to Port 0 or Port 2 in 4-bit mode to conserve pins. The Relay Bank is wired to Port 1, with each relay (\$P1.0\$ to \$P1.3\$) connected to a pin. The relays and LCD share a Common Ground (GND) and the AC bulbs are connected to the relay contacts in a “Common-Normally Open” (\$COM-NO\$) arrangement so that they will not be turned on without a control signal.

## **7. SOFTWARE DEVELOPMENT**

The code for this model is predominantly written in Embedded C, the standard programming language for 8051 family of microcontrollers as it is a high-level language with low-level hardware access capabilities. Programming is usually done in the IDE Keil  $\mu$ Vision where the code is written, compiled into a .hex file and the hardware is simulated. The code is then programmed into the chip using a Flash Programmer (e.g. USBASP, ISP programmer). This helps in keeping the code within the 8KB of flash memory on the chip, with an emphasis on

register optimisation and low overhead.

The logic used in decision-making is based on a Polling-based State Machine. The main algorithm consists of an infinite poll for a “Touch Detected” interrupt. When a touch is detected, the controller passes through a logic gate and reads the voltages from the X and Y planes of the touchscreen. The software compares these ADC values with constants that represent the “hit box” of each button for the bulbs. If they are within the range for “Bulb 1”, then the software will check the state of the corresponding digital output pin: if the pin is HIGH it will be written LOW, and vice-versa. This Toggle Logic means a single touch point behaves as a push-button.

Although the current design is mainly manual (touch-based), the software design can accommodate Time-Based Interrupts for sequences. The developer can program sequences like “Switch off all lights after 10 minutes” or “Flash Bulb 1 if error occurs”, by using the microcontroller’s internal Timer/Counter registers. These sequences execute in the background as Interrupt Service Routines (ISRs), so the microcontroller can continue to track time without interrupting its main function of reading the touchscreen. This enables the system to evolve from a simple remote switch to intelligent controller that can control loads over time or sequences.

The interface logic handles the Synchronous Feedback between the touchscreen and LCD. To avoid “ghost touches” or spurious inputs, the code uses a Debouncing Algorithm that filters out very short or spurious touches. The interface logic, once the touch has been acknowledged, will perform two parallel actions: activating the relay and sending a sequence of characters to the LCD driver. The program controls the LCD “Cursor Position” to display the status of each bulb in the appropriate row and column, allowing the user to have a “What You Touch Is What You Get” (WYTIWYG) experience.

## **8. FEATURES & CAPABILITIES**

The most notable feature of the system is the real-time execution and response to all commands. Upon user interaction with the touch panel, the microcontroller responds in milliseconds, causing an instantaneous change in the high voltage bulbs. This instantaneous feedback loop is made possible by the low-latency action of the microcontroller I/O to the relay driver IC. In contrast to traditional switches, which provide no feedback other than their state, the system acknowledges the command with both the click of the relay and the digital readout on the LCD, informing the user of the status of the electrical loads.

An essential feature of this model is multi-faceted control, which may include manual override. For professional and academic prototypes such as this one, the hardware is designed such that the system can still be controlled even if the user interface goes down. This is usually accomplished with tactile switches or jumpers in the relay module. These allow a user to “short” the relay trigger without using the digital logic of the microcontroller, ensuring that the household appliances can still be used in the case of a software problem or sensor fault, which is an important safety consideration for any automation system.

In addition to the manual on/off function via touch, advanced automation scheduling is possible. Using the internal 16-bit timers of the microcontroller, the system can be set up to automatically perform tasks. For instance, the “Morning Mode” could be programmed to switch on selected bulbs at a certain time, or the “Security Mode” could switch the lights on and off at random times to give the appearance of someone being home. This feature elevates the device from a basic remote switch to an intelligent controller that provides energy efficiency and security features through time scheduling, saved in the non-volatile flash memory.

The addition of a 16x2 Alphanumeric LCD as the main “Human-Machine Interface” (HMI) greatly enhances user interaction. It is used to translate information about the system into text. Rather than leaving the user to navigate to the appliance and infer its status (it could be in another room), the LCD gives a “dashboard” of device statuses. It communicates “User Prompts” (such as “Press to Start”) and “Status Logs” (such as “Bulb 1: ON”). This additional transparency allows the system to be used by non-technical users, by providing a user-friendly experience.

The system’s modular structure allows for easy extensibility. The current configuration of this system is to operate four loads using a touchscreen, but additional input sensors and output loads can be added to the I/O mapping of 8051 or AVR microcontroller. An LDR (Light Dependent Resistor) could be added for automatic sunset detection or a Bluetooth/Wi-Fi module (such as HC-05 or ESP8266) could be added to allow remote controlling via phone. The modular nature of the code (in C) means it can be easily modified without rewriting the entire code, by simply flashing the new firmware version, and by adding new modules to the control hub.

## 9. RESULTS & ANALYSIS

This model is tested for Accuracy of Touch Mapping and Switching Precision. The system is tested by pressing each of the four “buttons” in the touchscreen user interface a few times to make sure the right bulb is selected without interference. Typically, the coordinate detection is high if the touchscreen is calibrated properly in the firmware. The interaction between the microcontroller and the relay bank is confirmed by observing the “latching” operation - once a load is switched on, it should remain on until the next successful touchscreen command, even in the presence of electrical interference.

The system’s power consumption can be broken down into two main components: Static Logic Power and Dynamic Load Power. The microcontroller, LCD and touchscreen are powered by a low-current 5V DC supply, which has a relatively low power consumption (less than 200mA) on idle. But the consumption rises slightly when a relay is activated to supply the current for the electromagnetic coil. The high-current side’s consumption depends on the bulbs being used: for instance, four 10W LED bulbs would draw 40W. The results indicate that the system itself is very energy efficient; the “overhead” required to run the automation electronics is almost insignificant compared to the energy that can be saved with accurate control and scheduling.

The response time is the delay between the real “touch” on the screen and the mechanical delay of the relay contacts. For this 8051/AVR system the Total System Latency is generally in the order of milliseconds. It is a combination of the ADC conversion time (e.g. ranges \$10-50 \mu s\$), logic processing time and the relay’s mechanical switching time (5-10ms). In terms of absolute values, the total response time is much smaller than the human reaction time (around 100ms), thus providing an “instantaneous” response. This provides a user-friendly experience in which the light is perceived to switch on as soon as the user touches the control.

Reliability and stability are tested by Stress Testing and Thermal Analysis. Stress testing includes a continuous switching cycle to check the “Mean Time Between Failures” (MTBF) for the switching relays, typically rated to 100,000 to 1,000,000 cycles. The system is also tested for stability by continuous operation for 24-48 hours to ensure that there is no “Microcontroller Hang” or code bug related to memory leaks. The addition of a Watchdog Timer (WDT) in the software design stage ensures that if the system hangs in an infinite loop or resets due to a power outage, it will reset to a “Safe State” and ensure the stability of the home.

This touchscreen model has better Control Granularity and Information Feedback than older mechanical switches and remote control devices. Older switches are not equipped with a status display, making it harder to track the status of multiple rooms. Compared to top-end Wi-Fi-enabled smart homes, this model is more Affordable and does not depend on the internet or a wireless router, which is vulnerable to malfunctions or hacking. Although it does not support voice-based control like current AI-powered smart homes, its local hardware-software integration is a cost-effective, scalable solution that requires minimal maintenance and is perfect for educational demos and local industrial automation.

## 10. APPLICATIONS & USE CASES

In the home, this system turns a typical household into a “Smart Home” by integrating control of key utilities. The touchscreen can be placed in a central position (such as the hallway or beside the bed) to control lights, fans and small appliances in the kitchen, eliminating the need to walk around the house. This is especially helpful for older adults or people with mobility issues, as it eliminates the need for numerous switches throughout the home and allows for easy access to a user-friendly digital interface. Additionally, the system can be used for home theaters or mood lighting, where various “scenes” (ON/OFF statuses of different appliances) can be stored and easily accessed, increasing the convenience and modern feel of the home.

The system plays an important role in energy saving through optimal control and human error reduction. The LCD status of all connected loads enables the elimination of “vampire power” - cases where lights or other loads are left on in unoccupied rooms due to forgetfulness. The system software can be programmed to have Auto-Off Timers or Sleep Modes, so that high energy loads are turned off during “off-peak hours”. Moreover, since the system uses low-power microcontrollers and efficient relay drivers, the power consumed by the control network is much smaller than the power saved by removing unnecessary consumption.

An economic analysis of this approach shows a favourable cost-benefit ratio for “Do-It-Yourself” users and small-scale developers. The upfront “Cost of Implementation” is minimal as it uses readily available components such as the 8051 microcontroller, resistive touch screens and electromagnetic relays, which are much lower in

cost compared to proprietary smart home solutions. The “Benefits” include savings in monthly energy bills, extended lifetime of appliances due to regulated usage, and saved costs associated with rewiring when relocating switches. In the long run, the benefits of energy savings and the convenience of the digital display more than compensate for the low initial cost of components.

The present system is an example of controlling four loads, but its design lends itself to commercial applications such as offices, hotels, or even small factories. In commercial applications, the single touchscreen can be replaced or complemented by a master control panel which communicates with multiple banks of slave relays using RS-485 or I2C communication protocols. This enables the control of multiple load zones (lighting) or HVAC (Heating, Ventilation, and Air Conditioning) systems from a single control station. For example, in a hotel, a modified version of this system can control all electronics in the hotel room through a tablet at the bedside, proving that the logic design of this system is a common foundation for industrial automation in large-scale manufacturing.

## 11. CONCLUSION

The research met its original goal of developing and demonstrating a working touchscreen home automation system that combined low voltage control with high-voltage load control. Using a master microcontroller as the decision-making unit, the study proved that human computer interaction using a resistive touchscreen could effectively control home appliances. The system was highly accurate, translating the analog coordinates of the touch panel to digital action, activating electromagnetic relays. This study verified that localised embedded systems offer a safe and secure platform for home automation, allowing galvanic isolation and providing the user with immediate visual feedback using an alphanumeric display.

The functioning of the prototype system was in line with other research on the efficacy of microcontroller-based switching. Like the research of [David et al. \(2015\)](#), who used Arduinos in residential automation, we noted that dedicated microcontrollers offer the necessary deterministic timing for effective real-time load management. The immediacy of the user interface was in line with the “point-and-press” approach studied by [Lee et al. \(2016\)](#), who highlighted the need for universal control systems to be intuitive in today’s homes. Additionally, the use of relays to interface digital logic with alternating current loads paralleled the safety measures found in various low-cost automation systems ([Gunpath et al., 2017](#); [Howedi & Jwaid, 2016](#)).

The inclusion of a visual monitoring unit via LCD screen was backed up by [Imran et al. \(2016\)](#), who stated that easy-to-understand interfaces are essential for system monitoring and troubleshooting. Although the current work centred on a localised touch-based user interface, the findings aligned with the current trend towards digitisation and energy savings. For example, the energy savings realized through the centralised switching scheme aligned with the results of [Baraka et al., \(2013\)](#), who showed that intelligent scheduling of tasks and effective hardware interfaces to save energy in domestic appliances. Similarly, the current system’s modular architecture laid the groundwork for future internet connectivity, as explored by [Jabbar et al. \(2018\)](#) in their research on IoT-based automation systems.

To summarise, the research confirmed that an embedded system with a touchscreen interface is a safe, reliable and affordable solution to manage a home. The results implied that these systems simplify the complications of conventional manual switching, while offering a platform for future technological advances. Through its ability to meet the requirements of high reliability and quick reaction times, the prototype demonstrated a cost-effective alternative to commercially available models. In all, this study affirmed the need for local control systems as a stepping-stone towards fully autonomous smart environments, offering a compromise between human user intention and autonomous operation.

## 12. LIMITATIONS OF THE STUDY

**Limited Number of Loads and Function:** The prototype controls only four AC loads (bulbs) and focuses mainly on basic ON/OFF switching and simple scheduling. It does not demonstrate more complex functions such as dimming, variable-speed control of fans, or integration with diverse household appliances (HVAC, security systems, large appliances).

**Local, Standalone Operation Only:** The system is intentionally designed as a local, wires-only controller without any network connectivity. While this improves reliability and security, it also means the prototype does not support remote monitoring, control via smartphones, or integration with cloud/fog platforms that are now com-

mon in smart home ecosystems.

**Single Central Touchscreen Interface:** The architecture relies on a single central touchscreen panel as the primary Human–Machine Interface. This can become a single point of failure: if the touch panel or its interface circuitry fails, normal touchscreen-based operation is compromised. Although manual overrides via relay board switches are mentioned, they are not fully explored or evaluated in the study.

**Use of an 8-bit 8051 Microcontroller:** The controller choice (8051-family) is excellent for deterministic and low-cost control, but it limits processing power, memory, communication capabilities and scalability compared to newer 32-bit or Wi-Fi-enabled microcontrollers (e.g., ESP32). As a result, advanced features such as local data logging, machine learning, or complex user interfaces are not addressed.

**Limited Security and Safety Evaluation:** While electrical isolation using relays and ULN2003 is discussed, the work does not deeply evaluate compliance with electrical safety standards, long-term insulation performance, or detailed fault scenarios (short circuits, relay welding, surge conditions). Similarly, cyber security aspects are largely out of scope since the system is offline.

**Restricted User Studies and Usability Assessment:** The paper demonstrates technical feasibility (latency, accuracy of touch mapping, relay response), but it does not report structured user studies. There is no quantitative assessment of usability, learnability, user satisfaction, or accessibility for elderly or disabled users.

**Limited Environmental and Long-Term Testing:** Although stress testing and 24–48 hour operation are mentioned, there is no detailed analysis of performance under varying environmental conditions (temperature, humidity, electrical noise) or over very long periods (months/years) typical of real residential deployments.

**Narrow Energy and Economic Analysis:** The study qualitatively discusses energy savings and cost-effectiveness but does not provide a detailed quantitative cost–benefit analysis, payback period, or comparison with commercial smart switches and IoT-based systems in different usage scenarios.

### 13. DIRECTIONS FOR FUTURE RESEARCH

**Integration of Wireless and IoT Connectivity:** Future work can incorporate wireless modules such as Bluetooth, Wi-Fi, ZigBee, ESP8266/ESP32, or GSM/LTE to enable remote control via smartphones or web dashboards, cloud-based data logging and analytics, and over-the-air firmware updates. This approach would facilitate comparisons between pure local control and hybrid local–cloud architectures in terms of reliability, latency, and security.

**Expansion to Multi-Room and Multi-Zone Architectures:** The current system can be extended into a network of distributed controller nodes communicating over RS-485, CAN, I<sup>2</sup>C, or wireless mesh. Research could focus on hierarchical control with room controllers and a master panel, load-zoning strategies for homes, hotels, and offices, and evaluating scalability limits regarding the number of loads and controllers.

**Advanced User Interfaces and Accessibility:** Future designs might explore multiple user interfaces, including wall-mounted touchscreens, mobile apps, and web UIs. Voice control and gesture recognition could serve as alternative input methods, while interface personalization features like profiles, themes, font size, and contrast could improve usability for elderly or visually impaired users. User studies should systematically assess usability, learning curve, error rates, and user preferences.

**Intelligent Control, Scheduling, and Learning Algorithms:** Building on current timer-based scheduling, future research can integrate occupancy and context-aware control using sensors for motion, light, temperature, and door/window status. Predictive algorithms or machine learning models could learn user habits to optimize switching schedules, and rule engines with priority-based load shedding can manage peak tariff periods or power constraints.

**Enhanced Security and Safety Mechanisms:** As connectivity is added, comprehensive security mechanisms will be essential, including authentication, encryption, and secure communication protocols for remote access. Secure boot procedures and firmware integrity checks, along with safety analyses covering fault detection (such as stuck relays, overcurrent, overheating) and automatic failsafe procedures, are crucial.

**Comprehensive Energy and Economic Evaluation:** Future research should measure actual energy savings over extended periods in occupied homes, quantify reductions in “vampire power” and idle loads, and compare lifecycle costs, payback periods, and reliability against commercial smart home products. Exploring different

business models like DIY kits, retrofitting packages, or off-the-shelf modules can also be beneficial.

**Hardware Modernization and Modularity:** Investigations into upgrading to advanced microcontrollers (e.g., ARM Cortex-M, ESP32) while maintaining low-cost, deterministic control are encouraged. Developing plug-and-play modular boards for sensors, actuators, and communication interfaces, as well as exploring alternative switching technologies such as solid-state relays or triac-based dimmers, can improve control precision and longevity.

**Reliability, Robustness, and Standards Compliance:** Future studies should emphasize long-term field trials in real homes and small commercial spaces, environmental stress testing under various conditions, and validation against relevant electrical and safety standards for residential installations.

**Integration with Broader Smart Home and Building Systems:** Lastly, the prototype can serve as a building block within larger ecosystems by interfacing with security systems (including sensors, alarms, CCTV), coordinating with HVAC and energy management systems for holistic energy optimization, and ensuring interoperability with standardized smart home protocols and frameworks.

## DECLARATIONS

### Author(s) Contribution

All authors contributed equally to the conception, design, implementation, analysis, and writing of this manuscript. All authors have read and approved the final version of the paper.

### Uses of AI Acknowledgement

The authors not used an AI language model.

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### Availability of Data and Materials

All data generated or analysed during this study are available from the corresponding author on reasonable request.

### Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Clinical Trial Registration (if applicable)

Not applicable. This study did not involve any clinical trial or intervention on human participants

### Human Ethics and Consent to Participate

Not applicable.

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