Electrical Appliance Control for Smart Buildings Using Real-time Location Tracking and Virtual Environments

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Abstract

Building automation is becoming increasingly popular due to the growing use of the Internet of Things (IoT) framework in the built environment. While there has been a spurt of mobile applications that control electronics in buildings, most of these utilize complex user-interfaces that require multiple interactions to realize user-intent which negatively impacts their adoption. In this paper, we present a framework that provides an intuitive and effective user interface to control electrical devices and fixtures in the connected home of the future. The framework utilizes a handheld point-and-click device that can be used to turn appliances on and off by pointing at them. This functionality is enabled by tracking the location of the device in real time within a virtual building model to determine the user's context and intent.

The position and orientation of the device is used to project a ray in the virtual world to determine the appliance of interest to the user, which is then controlled through the IoT infrastructure. The system is proposed to be implemented using ultra-wideband (UWB) and inertial measurement units (IMU). This research proposes a novel and necessary interface between users and "things" in the IoT paradigm for the built environment that does not require extensive modifications to the appliances itself. Future research will be performed to determine means of incorporating our framework into existing automation efforts such as motion-controlled devices and for defining presets for multiple devices through an extension of the presented framework. Additionally the virtual model also provides a means for tracking and accounting for the electricity usage of the home per device. This utility of the prototype enables sustainable maintenance and operations to optimize the energy-usage of buildings.

Keywords –

Smart homes, Internet of things, Appliance Control, Real-time tracking

1 Introduction

Over the past two decades, significant improvements in sensing and telecommunications has led to the emergence of smart environments [1]. This trend has resulted in the idea of smart homes take root in society, and we are starting to see isolated implementations of increasingly sophisticated tools, devices and systems for home automation. Examples of these innovations include automatic systems for temperature regulation, illumination control, and waste disposal.

The definition of what constitutes a smart/automated home has changed over time due to the rapid development of networking frameworks. Specifically, the growth of Internet of Things (IoT) applications in built environments has led to the increase of inter-connected platforms within the smart home.

According to Mendes et al. [2], a smart home is "A concentrator and disseminator of information and services to cover the totality of a home's functional areas in order to improve the levels of comfort and quality but also to provide a gateway or interface to the exterior by the means of an interaction with other paradigms". De Silva et al. [3] describes the smart home as a "home-like environment that possesses ambient intelligence and automatic control capable of reaction to the behavior of residents and to offer various accommodations (to them)".

It is observed that true home automation is only achieved when an established intelligent space improves overall user experience by simplifying and expediting the process of indoor environmental interaction. Creating an efficiently working intelligent area requires novel ways for humans to be able to communicate with it. An example of such an innovation is the context-aware system infrastructure for indoor location tracking. These technologies improve current smart house frameworks by providing an automated area in which the human location, orientation and gestures can be used to regulate and control appliances in the home.

Current methods of appliance control have improved the ability to exploit the functionality and utility of smart houses. However, these control devices are often expensive, with extensive hardware infrastructure, and inefficient interface operation. Given all of the above, it is the goal of this paper to present an appliance control prototype that fills in efficiency gaps discovered in others by providing an intuitive interface, cost-effective overall design and aesthetically pleasing architecture.

2 Literature Review

Research efforts in the creation of appliance control systems have culminated in mobile and fixed applications that utilize complex procedures that require multiple interactions and the recollection of numerous commands to realize user-intent. Moreover, many current state-of-the art automation systems have the disadvantage of being expensive due to the need for large amounts of physical components for these systems to work for both wired and wireless systems. This section highlights some of the issues with currently available solutions for home automation control.

2.1 Inefficient Interface Design

Based on literature review conducted by the authors, there are three main interface designs used for smart home control devices. These include graphical user interfaces, gesture driven interface, and command line interface. Identified products and prototypes have adequately been able to achieve some level of effective home automation. However certain limitations of these systems have been recognized. Details of these findings are provided in this section.

2.1.1 Graphical User Interface (GUI)

This interface type allows the user to interact with target appliances through graphical icons displayed on a control device. One method used to create GUI interfaces for controllers is with a top-down layout. The design works by providing echelonically arranged icons that allow specific actions to be reached the when the user progresses through the necessary hierarchical levels. When used for home-automation, top-down interfaced controllers typically have display screens that show the different areas of the building which contains all of the appliances or implements that the user could possibly interact with. These zones are made up of several tiers or layers that the user has to go through in order to locate the specific item they would like to communicate with. There are several examples of researchers employing this interface layout to successfully create remote controllers to communicate with appliances.

Vikram et al. [4] in 2017 designed a Wi-Fi based, low-cost automation system that had a similar GUI arrangement. The interface utilized an Android application and allowed the individual to exercise desired control over the lighting, air regulation and other electronics systems within their vicinity. Prototypes like the one created by Kumar and Sharma [5] also used a top-down interface design when creating a smart home platform that was controlled with both a computer and smartphone. The framework was fabricated to allow a remote user, control and monitor the on/off status of connected appliances within an interior intelligent space.

Despite the adequate functionality of the systems discussed above, their GUI top-down layout has an innate problem. Specifically, these kinds of interfaces excessively prolong actualization of an action in a target by requiring the refining of a user`s intentions before producing results. This procedure ends up defeating the entire purpose of home automation by making it more cumbersome than some traditional manual methods of appliance control. For example, an individual using a home automation device with a top-down interface in a small-sized room may have to go through several menu-screens just to turn off a light fixture. In this situation, flicking a wall switch (which is supposed to be the slower manual method) ends up being the faster way of realizing the user’s desires. Additionally, using top-down design approach creates difficulties when the interface has to be programmatically constructed. When a change has to be made to a menu screen, it is difficult making sure that the alteration is in the right hierarchal position in the top-down arrangement [6]. As a result, moving items across different graphical layers becomes overly convoluted.

To resolve the issues related to top-down interface layouts, different methods to GUI design have been proposed by different entities. One of these approaches suggested by Gamba et al. [6] utilized a reverse approach to the top-down methodology. They suggested a bottom-up strategy to create a different and more simplistic procedure of executing home automation. The goal of the researchers was to start from the thought of the user to affect a target in a zone.

Ultimately they ended up with a three-tier interface layout for reaching target areas. Even though the bottom-up approach is an improvement, it still requires multiple steps before a target appliance can be turned on or off. Moreover, for more complex appliance systems, the categorization of labels is required before the correct device can be chosen. This labeling process further complicates the construction of the system. Also developers have to always worry about arranging labels on a functionality basis. If this is done incorrectly, the system will revert to a top-down platform thereby defeating the overall goal of the proposed three tiered approach.

2.1.2 Gesture and Voice Driven Interfaces (GDI)

Gesture driven interfaces have also been increasing used for indoor intelligent spaces. The interface relies on specific physical gestures done by the user to create an automated response. Devices like the gesture pendant allow the wearer to control elements in the house via hand gestures [7]. Within the home, the pendant was used to regulate entertainment systems and room lighting with movement of the pendant wearers arm. Similar to this device, a smart class room was created by Shi et al. [8].The goal was to improve teaching within a school setting by utilizing video to recognize specific motions that can be used to display information and visuals needed to aid in student learning. Within workplace settings, systems like the Monica project employ gestural identifiers to retrieve and present needed information to employees within an office [9]. Ultimately, this helped streamline work processes by speeding up information recovery. More recently, electronic home-assistants such as Google Echo and Amazon Alexa are enabled with the functionality of control devices in the home using voice commands.

All of the examples listed above work well enough within their respective indoor smart environments. However, there is a fundamental issue with reliability when it comes to gesture and voice-driven systems. Most dependability problems stem from accidental activations. A user may be performing day to day tasks and set-off an automated response by unknowingly gesturing a signal. Contrastingly, in some situations, the user may actually intend to issue a specific command and the system may not respond due to the slightest inaccuracies in the individual's gesture or accent. Since there are not any templates in most of these systems to provide real-time direction on gesture accuracy, the user might have to try (without guidance) slightly changing their input multiple times before performing the right command. Consequently, this situation leads to frustration when the system is in use.

Additionally, a frequent user of the system may experience fatigue when using gesture driven interfaces. Particularly for hand-based gesture driven interfaces, having to do different motions constantly becomes an exhaustive process. This is especially true since most of these motions are not ergonomic, thereby causing muscle fatigue and user discomfort when done for a period. In the case of voice-based interface, the user is expected to verbally describe their intent, which would require them to suitably label each appliance in their home and recollect that label while issue verbal command.

2.1.3 Command Line Interface (CLI)

Even though considered dated, command line interfaces are still being used by some home automation developers. These interface frameworks work by allowing the user to provide commands in the form of lines of text. These texts then activate a response in target devices. Some mobile telephony technologies utilize command line interfaces to allow human interaction with a smart environment. By definition, mobile telephony refers to the connecting telephones to provide communication over distances. In 2008, Shahriya et al, [10] developed a procedure that utilized mobile telephony to communicate with appliances. This prototype used Short Message Service (SMS) capable mobile phones to provide attention commands that allowed communication with certain appliances within a home. One unique feature of the system is that it only supports Java enabled phones. This may prove to be a problem over the course of the decade due to the decline of manufactured Java enabled phones [11].

A similar telephone based design was proposed by Baig et al. [12] .Their prototype was created to help regulate appliances remotely by using a mobile application that required voice commands. The commands were then converted to line texts that were then transferred to a GSM network. Command line interfaces like the examples listed above have been tested and proven to work. However the major downside of these interface platforms is that they require the recollection of several different commands. Memorizing multiple different commands might prove difficult and overall negatively impacts user experience.

2.2 Extensive Hardware Infrastructure

The hardware requirements for extant home automation systems can pose to be hindrances to their adoptions. This section describes the components necessary for wired and wireless home automation frameworks.

2.2.1 Wired Frameworks

The history of home automation efforts begun first with the development of wired networking protocols. Power line communication frameworks were mostly used to achieve this end. These systems require the alteration of already existing communication lines to transfer both data and electrical power [13]. X10 technology is one of the older innovations that led the way in main stream use of powerline technology for home automation. The system allowed control device interact with target electrical units within the home. Even with this advantage, the inherent wired design of X10 created problems with distance restriction, power phase limitations and overall poor performance due to its unreliability. To resolve these issues, technology like A10 have been created to improve upon X-10 signals while other manufacturers have developed their own unique power line protocols (i.e. Universal Powerline Bus).

Despite these improvements in the utility and functionality of powerline frameworks, the fundamental issue of the system (i.e. requiring extensive hardware infrastructure) remains. This issue presents a problem since it leads to the increase in energy expenditure. Additionally, the need for large amounts of hardware limits the ability to scale the system since the implementation of changes will be difficult.

2.2.2 Wireless Frameworks

Wireless frameworks have recently been gaining popularity in the home automation industry as a more permanent solution to the limitations of current wired systems. Platforms like Z-wave help set the standards for wire-free home automation. Zigbee, which is similar to Z-wave, is another technology that provides great home automation service with great network reliability.

However, these wireless systems (and others similar to them) require receivers attached to their target appliances in order to be controlled by the user. The cost of installing individual receivers on each item increases home automation expenditure.

2.3 Goals of Proposed Prototype

After completing literature review and identifying gaps in the current state of the art, the authors present an alternative methodology that aims to accomplish the following goals:

1. Improved User-Device Interaction

Device aims to simplify user interaction with the smart indoor environment to allow a more straightforward means of communicating with target appliances. Utilizing a simple point-and-click device, the system should prevent users from having to navigate through several different graphical displays before being able to trigger a real-world action. This design should also allow minimal back-end modeling when there is a change in the layout of electrical appliances in a room.

2. Lack of Appliance Modification

Another goal set by the researchers is to create a system that does not require any additional modifications to the functionality of the electrical appliances themselves. The only alteration done will be to the power source of each target appliance. Wireless relay switch systems will be employed to this end.

3. Reduced Infrastructure/Cost

The system utilized ultra wide band wireless technology instead of a wired solution. Doing this should reduce the overall cost of the hardware infrastructure thereby curtailing the need for excessive wiring. Moreover, the proposed framework does not require target appliances to have receivers in order to work; further lowering installation costs. The reduction in infrastructure should also allow for a more aesthetically pleasing design without cables and wires strewn about the home.

4. Scalability

The research aims to create a dynamic prototype that is also scalable. The wireless nature of the prototype allows for the easy implementation of changes when the extension or reduction of the network is required. This is in contrast to wired installations, in which cable extensions are a tiresome affair [14].

3 Methodology

This section details the conceptual design of the proposed framework. The appliance control system is comprised of different components that are that are connected by wireless communication technology. The wireless set-up allows interaction between these device components and enables automation based on commands issued by the user.

To actualize these commands, the user requires input hardware. A microcontroller equipped with a position sensor was used to achieve this end. This data is then fed to a created virtual environment that is a model of the real-world indoor location. The virtual environment determines the user's desires through spatial analysis and communicates with a relay to enable or pre-vent the flow of power to the electrical device.

Discussed in the next few sections are details about the major components of the system and specifics on how they work. Figure 1 further highlights the processes involved to enable the prototype operate.

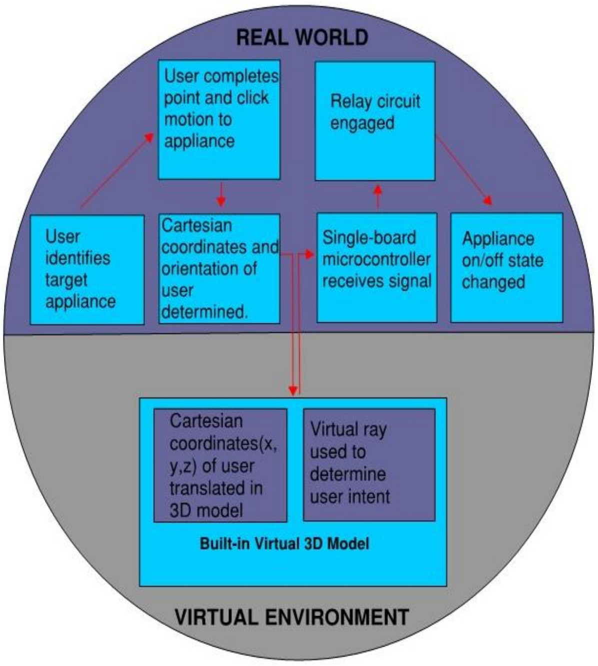

Figure 1. Process Model of Prototype

Figure 2 provides an overview of the components of the entire appliance control system. All physical components of the prototype are displayed with arrows indicating how each of them interacts to produce desired results during use.

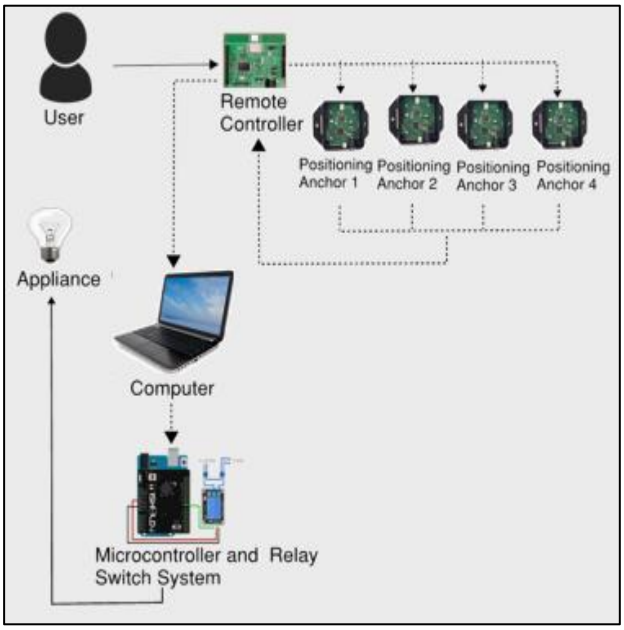

Figure 2. Overview of System Prototype

The systems consists of the following major components:

1. Position and Orientation Tracker

The system uses a position and orientation to provide information of an object or a user within a spatial area. This information is require to determine the user's intent as it will be used to select the appropriate appliance for control.

2. Handheld Remote

The remote device is the medium through the user directly interacts with the electrical appliance control system. The proposed handheld device will be a portable microcontroller with a singular button. This design concept allows for a user-friendly, easy-to-use gadget. This set-up is makes it easier and faster for the individuals to see their desires actualized.

3. Electrical Control System

This hardware component comprises of a microcontroller circuit board with wireless communication capabilities and a relay switch. The relay is necessary to separate the electric current required to power the appliance from that necessary for operating the microcontroller. This component is shown in Figure 4.

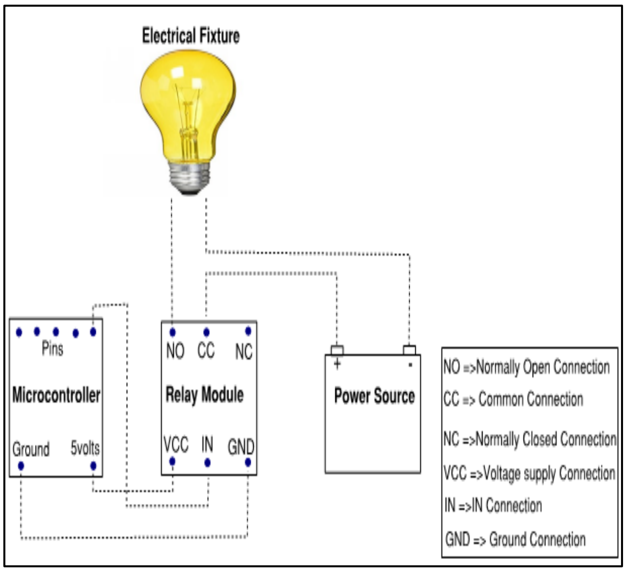

Figure 4. Circuit Diagram of relay/electrical control system.

1. Virtual Environment

A virtual environment was created as part of the main component of the of the appliance control prototype. The virtual environment will act as the medium that translates the user's intentions. The position and orientation of the handheld device is used to project a ray in the 3D environment to determine the appliance of interest to the user, which is then controlled through the IoT infrastructure. The pre-built virtual environment has the benefit of serving as a virtual reflection of the real-world location.

4 Case Study

A case study was performed to test a prototype of the system proposed for appliance selection. This involved selecting a suitable room with multiple electronic fixtures and performing the following steps as described in this section.

4.1 Virtual Environment Creation

After a room was selection, its geometric and spatial dimensions were obtained using a laser measurer. Care was taken to ensure that all measurements were highly accurate and were precise representations of the structural design of the room. Additionally, the spatial location of the light fixtures were determined and recorded. This spatial information was used to create a virtual model of the room.

To create the virtual environment, the research goals demanded a dynamic platform that allowed easy replication of any layout changes that might occur in the real word. Typically for architectural design work, building information modeling tools like Revit are used to graphically depict as-planned and as-built models of building structures. However for the purpose of this research, employing Revit for three dimensional design work would have proved limiting due to the software's long rendering time and lack of interactivity during walkthroughs [15]. To prevent this issue, a game engine, was used to create the virtual environment. Specifically, Unity 3D was the gaming tool utilized. Its programmable interface and cross platform ability made it the ideal tool required for the project [16]. Additionally the ability of the game engine to allow easy alteration to virtual elements means that unexpected changes in the real-world location can readily be replicated in the virtual environment to maintain a high degree of accuracy.

4.2 Positioning Tracking Technology Installation

Monitoring the location of the user required the installation of ultra wideband (UWB) tracking technology and motion sensors. To this end, UWB anchors were utilized to help determine the user's context within the confines of the testing location. This hardware is comprised of four anchor/sensors and a remote device.

To begin the installation procedure the four anchors were placed across the room at exact locations on walls.

To ensure the anchors positioned optimally they were placed at elevated points within the line-of-sight of the user. Care was also taken to ensure that all sensor hardware was spread around the user at different heights per anchor to improve coordination between anchors and boost their ability to deter-mine the 3D spatial location of the user. Additionally, anchors were placed far away from metallic objects to prevent diminished performance of the anchor's antenna.

Next, a tag was configured to enable communication with the anchors. The tag works by determining its location relative to the installed anchors in the room. This location dictating feature is facilitated through the creation of a coordinate system based on the spatial relationships between each anchor. One anchor is selected to be the origin point of the coordinate system. Going off this origin point, two other anchors are then set as the y-axis and x-axis. Once all the axes have been substantiated, manual measurements using a laser was conducted to determine for each anchor, their heights from the ground and their relative location on the created coordinate plane. Results obtained from these measurements represented the x, y and z coordinates of each sensor. Since all of these devices were distributed in a non-linear form around the location, the newly created coordinate system conformed to the rooms shape and orientation.

With the coordinate points set, the microcontroller is initialized by uploading it with code written in C language. The previously measured x, y and z points of each anchor is put into this code and algorithm uses this information to find the relative location and orientation of the handheld remote device.

This relative positioning algorithm works by treating the anchors as reference frames in a three-dimensional space and used these set points to determine the real time coordinates of the user as they move around the room. To read the orientation of the users pointing motion, the code was further expanded to communicate with an embedded gyroscopic and accelerometer sensors in the remote controller. Given the tri-axis nature of these sensors the absolute orientation or rotation of the device can be extracted. To do this, quaternions are utilized. The Quarternions which are represented by 4 parameters provide mathematical notation to represent rotation state of an object. Next, all of this data is communicated to the game engine software thereby allowing the real-world orientation and spatial location of the remote device to be visually replicated in the created 3D environment.

4.3 Relay Installation

For this step in the set-up process, a relay was installed to provide the means of controlling the appliance by leveraging electromagnetic fields to open and close the switches. The researchers performed following procedures to complete the relay-microcontroller framework:

4. Required components were identified and gathered for use. These components included a micro-controller circuit board and a 5V relay module.
5. Next, the connections between the controller circuit board and the relays were set-up. Using wiring, the board is connected to an inlet pin of the relay. Next the power supply pin (5V) and ground pin of the board is linked to the relay module.
6. The third step involves the relay connections to the ac current power source and the chosen light fixtures. The relevant relay terminals required to achieve this end are as follows:
    - Common connection: The central terminal of the relay. It was connected to the power source of the ac current.
    - Normally open: This connection is a switch for the circuit. Like the name suggest it stays open in its initial state. Closing it however allows current to flow to the light bulb, thereby turning it on.
    - Normally Closed: This connection is opposite to the normally open. When opened its interrupting the current flowing through the light bulb thereby turning it off.

Ultimately, the microcontroller was programmed to regulate the on/off state of the relay based on a received wireless signal.

4.4 Prototype Testing

Once all of the requisite components of the prototype had been set up, testing began. The test location was a simple rectangular shaped room in an office building.

A user was then given the point and click device to regulate the on/off state of each light fixture. To ensure that the prototype worked to maximum efficiency, the area of room was divided into 10 equal sized rectangular sectors. Then the tester was placed in each rectangular sector in the room and allowed to press the button that controlled the electrical appliance at different angles. Doing this helped the researchers ascertain the accuracy of the motions sensors in determining the user's context in the chosen location. Additionally selecting different areas of the room to activate the light fixtures, helped in calibrating the orientation-determining feature of the system to maximum efficiency. A distribution schema of 10 was selected to make it easier to obtain a percentage of accuracy for the prototype.

Figure 4 and 5 respectively show the real world use of the hand held controller and its replication in the virtual world.

Figure 4. Real-world testing of handheld point and click device.

Figure 5. 3D Virtual model replicating the user's action

5 Results and Discussion

As expected, the completed prototype was fully functional for each sector throughout the room. The single button feature of the device created a direct method for the individual to interact with the test area. Also utilizing a simple design provided a shallow learning curve for the user to understand how to operate the device and expedited the process of target appliance response.

The system was created using ultra-wideband technology as the basis for wireless communication therefore curtailing the need for excessive components. This setup makes the prototype less physically extensive than wired systems for home appliance control.

Moreover using multi-connected electricity relay systems and a virtual environment for target identification further reduced the need for additional hardware components traditionally used in popular wireless platforms (i.e. receivers). Consequently this design allows for a more affordable, easily scalable and easily changeable prototype. All of these results and features of the final product meet the goals set by the authors and show the overall benefits of utilizing the proposed system for appliance control.

The concept of indoor-positioning innovations and context aware systems was introduced earlier in the paper to set up a simple positionally aware appliance control device. The proposed prototype was successfully created by integrating microcontroller circuitry, wireless communication, electrical relay switches, and virtual environments. Testing the limits of the created platform revealed its suitability in reaching all performance and design goals set in this research paper.

This research can enables applications within the field of home automation. The use of the prototype can be expanded by integrating an electricity usage monitor to track the power consumption of individual electronic appliances within the home. Doing this will encourage the user to adopt environmentally friendly behavior and aid them in managing their home by providing a means to regulate energy consumption (and thereby utility expenses) of the home.

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