INTERNATIONAL STUDIES IN THE FIELD OF ELECTRICAL ELECTRONICS AND COMMUNICATIONS ENGINEERING

March 2024

EDITOR

ASSOC. PROF. DR. HİLMİ ZENK

SERÜVEN YAYINEVİ

Genel Yayın Yönetmeni / Editor in Chief • C. Cansın Selin Temana

Kapak & İç Tasarım / Cover & Interior Design • Serüven Yayınevi

Birinci Basım / First Edition • © Mart 2024

ISBN • 978-625-6319-00-4

Serüven Yayınevi / Serüven Publishing
Türkiye Adres / Turkey Address: Kızılay Mah. Fevzi Çakmak 1. Sokak
Ümit Apt No: 22/A Çankaya/ANKARA
Telefon / Phone: 05437675765
web: www.seruvenyayinevi.com
e-mail: seruvenyayinevi@gmail.com

Baskı & Cilt / Printing & Volume
Sertifika / Certificate No: 47083

INTERNATIONAL STUDIES IN THE FIELD OF ELECTRICAL ELECTRONICS AND COMMUNICATIONS ENGINEERING

March 2024

Editor

Assoc. Prof. Dr. Hilmi ZENK

CONTENTS

CHAPTER 1

EXAMINING MICROPROCESSORS AND MICROCONTROLLERS AND ANALYZING THE FUNCTIONALITY OF TWO MICROCONTROLLERS PRODUCED VIA DIFFERENT COMPANIES

Ahmet TOP[1]

1 Dr.Ahmet TOP
Department of Electrical and Electronics Engineering, Faculty of Technology, Fırat University, Turkey, ORCID ID: http://orcid.org/0000-0001-6672-2119

1. INTRODUCTION

With the discovery of semiconductors in 1948 and the use of transistors in 1950, computers moved to a new extension. Computers that are smaller and consume less energy than before have begun to be produced. In 1970, Intel company designed the microprocessor, which is considered the brain of the computer, as a single integrated circuit. A simple microprocessor system consisting of memory, input/output units and processor was later named microcontroller by integrating the mentioned elements into a single integrated system. Since the trimmed features of the units that make up the microprocessor system are used in the microcontroller system, the cost has decreased, it has become easier to program, and therefore its dimensions have become smaller [1].

Many people are not even aware of microcontrollers, which are found in many devices used in daily life. However, hundreds of millions of microcontrollers are used by the industry every year, and each person sees or uses at least 50 to 100 microcontroller devices on average. According to source [2], microcontrollers are used almost everywhere nowadays; alarm clocks, microwave ovens, dishwashers, washing machines, refrigerators, cars, robotics, mobile phones, photocopiers, air conditioners, industrial machines and credit card POS machines, etc. Microcontrollers; CPU (Central Process Unit) is also introduced as integrated circuit, microcontroller, microcomputer or embedded computer systems. Microcontrollers are constantly being developed and their features and performance are being increased. Apart from their familiar uses, microcontrollers are constantly opening new areas of use in industry and our daily lives [1].

Microcontrollers previously had a structure that had completely digital inputs and outputs and performed control functions digitally. Since only digital input-output controls are insufficient in modern industrial systems, analog signal processing and various environmental control units have begun to be added to microcontrollers produced in recent years. In particular, the widespread use of A/D (Analog/Digital) and D/A (Digital/Analog) converters has encouraged manufacturers to place these units in a single chip [2]. Thus, memory, input/output (I/O) subsystems, RAM, ROM, EPROM, EEPROM, timers, A/D or D/A converters in a single chip can be embedded in many applications of these microcontrollers, directly and alone. It allows them to be used for control purposes with much simpler and cheaper interface techniques than microprocessors [3]. Today, there are many companies producing microprocessors and microcontrollers. The most important of these are Intel, Atmel, Texas Instruments, Philips, Sıemens, Mıcrochip, Hıtachi, Mitsubishi, Analog Devices, Motorola and Renesas Technology companies. According to 1995 statistical reports, Intel has the largest market share, with over 70% market share [3].

In this study, information about microprocessors and microcontrollers, their architectures, memory types, etc. Information was given and the frequently used microcontrollers produced by Microchip and Atmel companies and their features were examined. The application was implemented using the PIC16F877A developed by Microchip and the Arduino Due development platform, a product of Atmel. Analog-to-digital converter (ADC) and digital-to-analog converter (DAC) applications were made with these controllers, and the results were examined both in simulation and experimentally. The software was made using the Micro c PRO program for the PİC16f877A microcontroller and the simulation was made in the ISIS subprogram of Proteus 7 Professional. Arduino Due's interface program was used for its software, the circuit was established and the results were observed on the oscilloscope. Speed performances and programmability of microcontrollers were examined.

2. Microprocessors

A microprocessor is an integrated circuit that is responsible for running programs in a computer system and controls all components centrally [4]. The first microprocessor was Intel's 4004, which was produced in 1971 for a calculator. This is the first general-purpose calculator built for use in processor calculators. It was called a 4-bit processor because the data it could process at a time was 4 bits. Between 1974 and 1976, 8-bit microprocessors, which can be called the first general-purpose microprocessors, were designed [5]. To use microprocessors, some basic components such as memory, input/output units and peripheral units are needed, as seen in Figure 1.

Input / Output unit: It consists of digital, analog and special functions and allows the microprocessor to communicate with the outside world.

CPU (Central Processing Unit): It is the most basic function and organizer of the system. It is called the brain of the computer. It operates in word lengths of 4, 8, 16, 32 and 64 bits to execute instructions, perform calculations and coordinate data.

Memory: Can be RAM, ROM, PROM, EPROM, EEPROM or any combination of these. This unit is used to store programs and data [6].

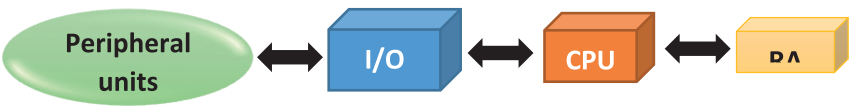


Figure 1. Basic components of a microprocessor system

2.1 Features that Distinguish Microprocessors from Each Other

2.1.1. Word Length

The number of bits that the microprocessor can process in each clock pulse is called word length. During this time, processors interpret instructions or perform operations on data in memory. The word length is equal to the bus length. The processor is defined by the word length it can process in each clock pulse. Processors are classified as four, eight, sixteen, thirty-two and sixty-four bits [1].

2.1.2. Command Processing Rate

Clock signals are needed for microprocessors to operate. The CPU moves to the next processing step at each clock signal. When examining the speed of the processor, it is necessary to look at the clock frequency and command cycle times. Clock frequency is the frequency of the oscillator applied externally to the microprocessor or located inside the processor. Command cycle time is the time taken for any command to complete its task [1].

2.1.3. Addressing Capacity

A processor's addressing capacity is the size of the memory area it can address or directly access. This size depends on the number of address lines of the processor. The number of this line also determines the amount of memory that can be used in the system to be designed [1].

2.1.4. Number of Recorders

Registers in microprocessors are divided into two groups: general purpose registers and special purpose registers. All microprocessors have registers with different features and numbers assigned to different tasks, which we can include in these groups. These registers can be 8, 16, 32 and 64-bit. The number of registers not only makes the programmer's job easier, but also makes the program simpler and more understandable [1].

2.1.5. Different Addressing Modes

Different access methods are used to retrieve the data required to process an instruction from a memory region, to put it in a memory region, or to change it between memory–register or register–register. Different ways of accessing the information that the microprocessor will process are referred to as 'addressing methods'. Having different ways to access data in any memory region in many different ways provides flexibility to the programmer. Some addressing types that make up the addressing modes are: Direct addressing, Indirect addressing, Data-defined addressing, Register addressing, Absolute addressing, Relative addressing, Indexed addressing, Accumulator and implied addressing [1].

2.1.6. Compatibility with Additional Circuits

Circuits to be added to the microprocessor system must operate at least at processor speed. It should be preferred that the memory ICs to be added to the system have the same speed as the processor. Likewise, the speeds and performances of the input and output units installed in the system should be the same or very close to the microprocessor. If the speed of the units installed in the system is lower than the microprocessor, the speed of the microprocessor decreases due to the slowness of other elements [1].

2.2. Communication Ways in the Central Processor Unit

In addition to the lines carrying the commands to be processed in the microprocessor, there are lines carrying the data to be processed and lines carrying the signals that control the interrupt operations. The same lines are used to send the data to be processed to the processor or to transfer the processed data to the appropriate units. All these paths are called communication paths. There are basically three buses used in a microprocessor: data, address and control [1].

2.2.1.Data Bus

The lines used to send data from the central processing unit to the memory and input / output units or to transfer data from these units to the processor are called data buses. Data bus width is directly related to the structure of the microprocessor, microprocessor register width and the word length used. In 8-bit microprocessors, the data bus contains 8 lines, while in 16-bit processors it contains 16 lines. Since the data transmitted to the microprocessor for processing is transmitted over the data bus, or the data processed in the microprocessor is sent to the relevant units over the data bus, two-way communication is possible on the data path [1].

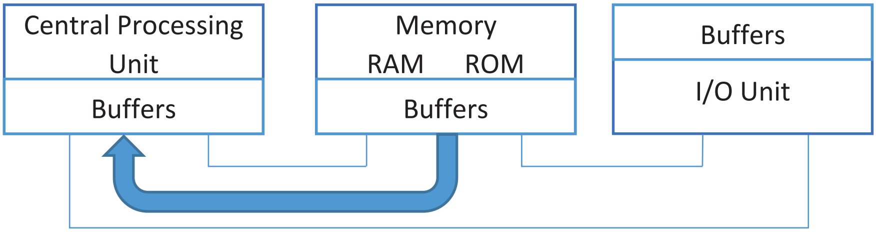


Figure 2. Data transfer from memory unit to processor using bus

The data in the memory that needs to be processed by the CPU is transmitted over the data bus. Buffers are used as shown in Figure 2 in order to keep the data for a short time when placing the data in memory on the lines or transferring the data from the lines to the CPU. Registers are used as buffers. The input/output (I/O) unit is used as an interface to transmit data processed in the CPU to external elements or to send data from external elements to the CPU. The data bus shown in Figure 3 is used to transmit data between the CPU and the I/O unit. The data coming to the I/O unit over the bus is sent to units such as keyboard, monitor, printer and scanner over the bus using buffers, or the information from these units is transferred to the CPU [1].

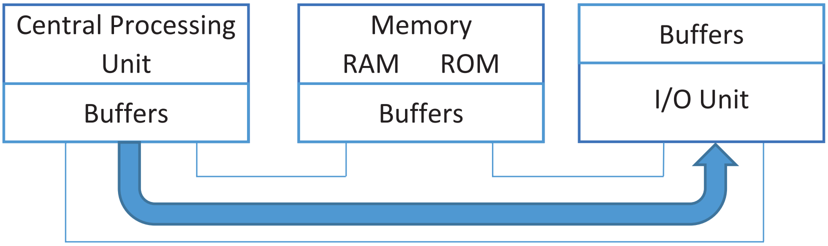


Figure 3. Transmission of data processed in the processor to the I/O unit using the data bus

2.2.2. Address Path

The lines used to carry information representing the address region where data will be received (read) or data will be sent (written) are called address buses. The address bus is unidirectional and has a structure that allows parallel communication. Data processed in the CPU may need to be stored in memory or sent to other elements. In this case, the address of the place where the data will be stored or sent is placed on the address bus with the help of the PC in the microprocessor.

2.2.3. Control Path

The lines used to transmit signals that regulate the relationship between units in the microprocessor system are called control paths. Since the instruction set of each microprocessor and the signals used for certain purposes are different, each microprocessor may have a control path containing a different number of lines.

3. Microprocessor Architectures

3.1. Microprocessor Architectures in Terms of Memory Organization

Microprocessors and microcontrollers are designed on one of two architectures called Von Neuman and Harvard in terms of memory usage. Von Neuman architecture was designed by Princeton University and, as the name suggests, by Harvard University. Although the Von Neuman architecture, which was suitable for the technology of that day, was preferred, as the technology became more suitable in the following years, the Harvard architecture became the standard, especially in microcontroller design, in the late 1970s. Today, there are also microcontrollers (MAXQ family) that include the features of both architectural structures. These microcontrollers have a mixed architecture and achieve performance increases by using the superior features of the two architectures [7].

3.1.1. Von Neuman Architecture

The separation of the processing unit from the memory unit is the most important feature of this architecture. In the 'Von Neuman Architecture', where the same memory is used for commands and data, the general structure of which is given in Figure 4, commands and data are transmitted using the same path. This situation requires data-related communication systems to wait for command-related communication operations in cases where commands and data need to be transmitted. In microprocessors using 'Von Neuman Architecture', after the commands are taken from the memory, they are decoded and the necessary operations are performed and the obtained results are sent back to the memory. During these operations, a phenomenon called bottleneck may occur in the system because the speed of the paths cannot keep up with the speed of the microprocessor. In addition to this drawback, another undesirable process that may occur is that since data and instructions are sequentially located in the same memory, there is a high possibility of these two information being mixed [8].

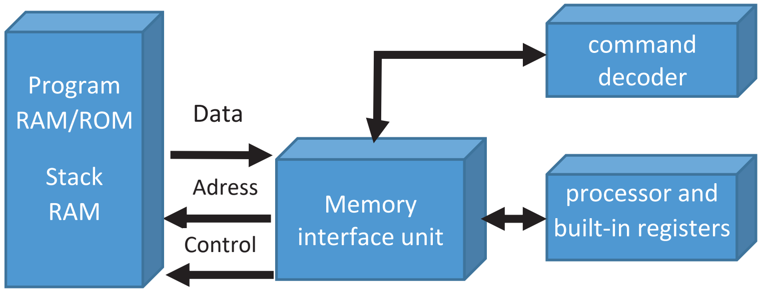


Figure 4. Von Neuman Architecture

A cache system has been developed to eliminate the two detailed drawbacks and to increase the performance of systems using Von Neuman Architecture. Caches are used to bring the commands and data to be processed from the main memory and keep them in a memory close to the processing unit. Commands and data taken from the main memory are placed in separate caches, ensuring parsing and eliminating the bottleneck. Today's personal computers also work on the Von Neuman architecture. There is only one memory (RAM) in the system and all commands and data are stored in the same environment. While the majority of microprocessor systems work in Von Neuman architecture, most microcontroller systems work in Harvard architecture [8].

3.1.2. Harvard Architecture

In microprocessor systems using 'Harvard Architecture', where commands and data-related information are stored in separate memories, the paths used to transmit data and commands are independent from each other, as seen in Figure 5. The different paths used for transmission make it possible to transmit data and commands at the same time. In other words, while the command code is read from memory, the data needed during the execution of the command can be read from the data memory [8].

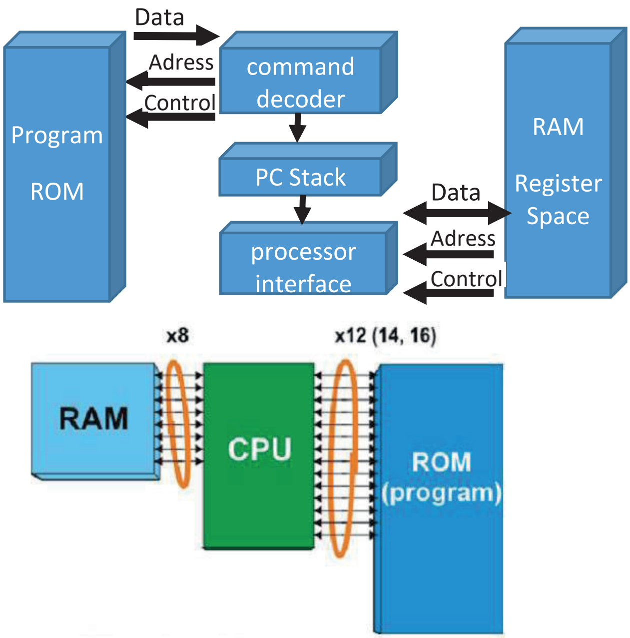


Figure 5. Harvard Architecture

3.2. Microprocessor Architectures in Terms of Command Processing Techniques

With the use of different instruction sets in microprocessors, two different microprocessor /microcontroller architectures have emerged:

- **C**omplex **I**nstruction **S**et **C**omputer -CISC
- **R**educed **I**nstruction **S**et **C**omputer –RISC

3.2.1. CISC Architecture

In the 70s, when Intel's processor series based on the X86 architecture emerged, some scientists who advocated supporting high-level languages by using these elements economically, due to the expensive and limited RAM, came together and developed the CISC architecture. This architecture; It was developed to provide easy programming and active memory usage. Although it makes the design very complex, it simplifies the software [9]. In microprocessor systems developed with the CISC design philosophy, the command processing technique called 'cascaded command processing' technique, in which only one command is processed at a time, is used.

Advantages of CISC Architecture

- Microprogramming is as easy as executing assembly language and is cheaper than the control unit in the system.
- The newly developed microcomputer supports the assembly language of the previous one.
- Fewer commands are used to execute a given task. Thus, memory is used more effectively.
- Since microprogram instruction sets are written similarly to the structures of high-level languages, the compiler does not have to be complex.

Disadvantages of CISC Architecture

- With each developed microprocessor, the instruction code and chip hardware have become more complex.
- The translation time of each command is not the same. Since different commands run at different cycle times, they will reduce the performance of the machine.
- Not all existing commands can be used in a program.
- Flag bits need to be taken into consideration when processing commands. This means additional time. It affects the operation of the microprocessor.

3.2.2. RISC Architecture

RISC architecture was systematically developed by companies such as IBM, Apple and Motorola. As memory speed increased in this architecture and high-level languages replaced assembly language, the main advantages of

CISC began to become obsolete. RISC's philosophy is based on three basic principles [6].

- All commands must be executed in a single cycle:
- Memory should be accessed only with “load” and “store” instructions.
- All execution units must be run from hardware without using microcode [6].

Advantages of RISC Architecture

- They run faster thanks to the reduced instruction set.
- They use fewer chips because their instruction sets are simplified.
- They can be designed more quickly than CISC processors.

Disadvantages of RISC Architecture

- A RISC architecture processor does not support the instruction set of an older microprocessor from the same family.

4. Memory and Memory Types

Memory units are used to store the program that will direct the operation of the computer and the data on which the program will work. In the early days of the computer, mechanical gears and punched cards were used as memory. In electronic computers, relays were first used and later core memories were used. More recently, the memories used are based on semiconductor technology [10].

Semiconductor memories require energy to keep the data written to the memory. Therefore, cutting the supply voltage causes the information to be lost. Various methods have been developed over time to eliminate this disadvantage. Semiconductor memories are divided into two in terms of storing information. Read Only Memory (ROM) and Random Access Memory (RAM) [10].

4.1. Read Only Memory - ROM

Writing information to this type of memory occurs during the production of the memory. These memory types are also called “Factory Mask ROM”. The masks used when making memories from semiconductor materials are prepared in a way that creates the information that the memory should contain. As a result, the memory produced is produced with the desired information. However, it is not possible to delete the information in the memory and reprogram the memory. The fact that ROMs can only be programmed during production and the programs inside cannot be changed can be seen as an important limitation [10].

4.2. Programmable ROM Memory (PROM)

At the moment they are produced, all cells are memories loaded with logic 0 or 1. There is a fuse in each cell. Fuses can be increased through a special method and device. If a cell's fuse is blown, it means that the logical position of that cell has changed. It is also called OTPROM (One Time Programmable ROM) [10]. This type of memory cannot be reprogrammed. It can only be programmed once.

4.3. Erasable Programmable ROM Memory (EPROM)

Programming is done by applying an electrical signal to the memory cells. The saved information is not deleted when the power is cut off. To prevent the program in the "EPROM" from being deleted, the glass window part should be covered with light-proof tape. To rewrite the EPROM memory, the tape on the "EPROM" must be removed and kept under ultraviolet for a certain period. In this way, the information inside can be deleted. Thus, the product becomes reprogrammable and can be used repeatedly to try different programs and operate the device [1].

4.4. Electronically Erasable Programmable ROM Memory (EEPROM)

The most advanced of erasable and programmable memories are electrically erasable memories. In these memory units, a desired value can be recorded in the memory cells and the recorded data remains in memory until a new write operation. Special methods and devices are also used to write data to EEPROMs. In fact, erasing EEPROM means the same as erasing EPROM [10].

4.5. Random Access Memory - RAM

RAM is the unit where all kinds of variables are located and temporary operations are performed during the microprocessor's operation. Since any address is accessed without following a special order, it is called Random Access Memory - RAM. Since RAM-type ICs are used for both writing and reading, the CPU must send reading R (Read) and W (Write) signals when controlling these ICs. In addition, there is an integrated selection (CS = Chip Select) pin that will enable the integrated circuit to become active at any time and it operates with an active low (0 Volt). These memories, each bit of which is a flip-flop circuit, operate with very low power consumption due to their ability to store the information (0 or 1) until a new trigger signal arrives [11].

4.6. Flash Memory

While EEPROM is written in byte-by-byte (2 byte-4 byte) blocks, in FLASH the block size can be variable and larger. For example, while the time required to program 1 byte in EEPROM is 1 ms, the time required for 32 Kbytes in FLASH is 10 ms [10].

5. Microcontrollers

Microcontrollers are control devices that are combined into a single chip by adding at least input-output interfaces and a memory module to microprocessors, and are widely used today, especially in embedded systems. In addition to input-output interfaces and memory modules, microcontrollers can also contain very practical modules that reduce the complexity of applications, such as analog-digital converter, serial input-output interface, pulse signal output, USB connection controller and infrared. These modules differ depending on the selected microcontroller family and model [12].

5.1. Advantages Provided by Microcontrollers

Microcontrollers have some advantages over microprocessors. These advantages can be listed as follows;

- The design and use of a microprocessor system is more complex and costly than a microcontroller system.
- For a microcontroller system to work, it is sufficient to have the element itself and an oscillator source.
- The fact that microcontrollers are small and cheap allows them to be used in all electronic control circuits [1].

5.2. Differences Between Microprocessor and Microcontroller

Microprocessor is a system that works according to the binary number system, processes command sequences, performs arithmatic and logical operations and controls them. Microcontrollers are microprocessor systems that regulate and program input and output units and contain these extra peripheral units [2]. Accordingly, in order to determine the differences between microprocessor and microcontroller, we need to examine the hardware of both and the areas in which they are used [11].

Hardware Comparison: Microprocessors have control units, arithmetic/logical units and memory units. Microcontrollers, in addition to microprocessors, contain various peripheral units such as internal data and code memory, timer/counter, interrupt controller, serial/parallel interfaces, address bus and data bus.

Application Areas: A microprocessor system provides high efficiency when used to execute various user programs, process large amounts of data, and perform sensitive numerical calculations. A microcontroller-based system, on the other hand, is a comprehensive system in which a constant program is executed that does not require reprogramming [13].

5.3. Criteria to Consider in Microcontroller Selection

We can list the criteria to consider when choosing a microcontroller as follows.

Cost and Availability: The primary feature desired when choosing a microcontroller is that the selected microcontroller has a low cost and is widely available in the market [13].

Operating Speed of the Microcontroller: In applications where time is effective, the speed of the product to be selected is very important. The operating speed of the microcontroller depends on the operating frequency, single command processing time and data storage size [13].

Memory Size and Type: Memory size directly affects the program to be written for the application. Nowadays, controllers that use EEPROM or FLASH as program memory, which can be written/erased as many times as desired, are preferred because they enable program development [13].

Number of Input/Output Ports: It is determined according to the needs of the applications.

Number of Timers/Counters: This unit is very important for applications as it is used in many operations that need to be carried out at regular intervals, counting signals connected to external input, adjusting the data transmission speed in serial communication, generating PWM signals, etc. [13].

Analog/Digital Converter: Today, analog/digital converters are required in most industrial applications. Thus, manufacturers make sure that these converters are included in the microcontroller. Two features that should be considered in A/D converters are the number of bits that show the measurement sensitivity and the number of channels that show how many different points it can measure from [13].

Energy Saving: The controller to be selected must have low power and sleep modes.

Development Tools: An important factor is that the assemblers and C compilers used in applications made with the controller are easy to find and have low costs [13].

5.4. Microcontrollers Used in Industry

Many microcontrollers produced today also have interfaces and special-purpose registers such as PWM, ADC, USB, USART, CAN, SPI, and I^2C, depending on their features and types. Microcontrollers, which were initially produced by 'Intel' and 'Texas Instruments' companies, are now produced by many companies (Motorola, Microchip, Hitachi, Siemens, AMD, Intel, Atmel, Dallas Semiconductor, etc.) [1-4]. Today, the usage areas of microcontrollers can be divided into 10 basic groups according to needs [14]. These are the Defense Industry, Space Research Systems, Toys, Automobiles, Home Electronics, Wireless Network Devices, Medical Devices, Control Systems, Robots, Network Systems, etc.

There are at least 4 basic features desired in microcontrollers used in applications. These desired features can be listed according to application areas as in table 1 [14].

Table 1. Features Required from Microcontrollers According to Application Areas [14]

Scope of application	**Desired Features**			
Defense industry	Reliability	Cpu Performance	Memory Performance	Power Consumption
Space Research Systems	Reliability	Cpu Performance	Memory Performance	Power Consumption
Toys	Longevity	Power Consumption	Reliability	Timer/Counter
Automobiles	Reliability	I/O Units	Power Consumption	Timer/Counter

Home Electronics	Memory Performance	Reliability	Longevity	Timer/Counter
Wireless Network Devices	I/O Units	Reliability	Memory Performance	Longevity
Medical Devices	CPU Performance	Memory Performance	A/D Converters	Timer/Counter
Control Systems	Timer/Counter	A/D Converters	Reliability	CPU Performance
Robots	Reliability	Longevity	Timer/Counter	I/O Units
Network Systems	Reliability	I/O Units	Power Consumption	A/D Converters

5.4.1 Microchip PIC Microcontrollers

Since 1990, Microchip has been producing dozens of types of microcontrollers with special hardware add-ons based on 8-bit architecture. This company also released its new microcontroller with 16-bit architecture called dsPIC in 2004. 8-bit microcontrollers use an 8-bit data bus, and 16-bit microcontrollers use a 16-bit data bus. Some companies, such as Microchip, unlike others, add various hardware (ADC, DAC, etc.) that may be required for applications to the microcontroller. Thus, the additional cost of using this hardware externally can be reduced. Advantages of PIC microcontrollers;

- ✓ They are easy to find in the market and have many varieties.
- ✓ The hardware required for programming is very simple and free circuit diagrams are easily available.
- ✓ Software development tools required for programming are provided free of charge by Microchip.
- ✓ Its RISC architecture allows it to be easily programmed with a small number of commands.
- ✓ Availability of paid/free software that allows programming in high and mid-level languages such as Basic and C.
- ✓ Availability of large amounts of sample applications and resources as a result of widespread use

- ✓ Application notes written by Microchip facilitate application development.
- ✓ Producing it with a DIP sleeve structure facilitates card design [6].

5.4.1.1 PIC Architecture

Harvard architecture (RISC structure) is used in microcontrollers produced by Microchip. For this reason, the program and data memory of PIC microcontrollers are separate from each other. Due to their RISC structure, PICs can be programmed with very few commands. The length of the program bus of PIC microcontrollers is variable. Microchip company uses the "word length" criterion when dividing its microcontrollers into families. PIC families differ from each other by their features such as the memory structure used, operating frequency, number of inputs/outputs and special-purpose hardware. Among these technological differences, the primary thing to know is the memory structure [6].

5.4.1.2 PIC Program Memory

PIC microcontrollers are produced with three types of memory structures. These are called ROM, EPROM and FLASH memory. Flash memory type is structurally different from EEPROM. Flash memory structure is more suitable for storing larger amounts of data and its power consumption is less. For these reasons, the program memory in PICs is Flash and the data memory is EEPROM. For PIC microcontrollers with ROM memory, a program is written once during production and the written program cannot be changed again [6].

5.4.1.3. General Features of PIC16F877 Microcontroller

- The PIC 16F87X series carries the features of the PIC 16CXX family.
- Harvard architecture was used in PIC- I6CXX:
- They are designed according to RISC architecture.
- External architecture: 40 pins as in Figure 6

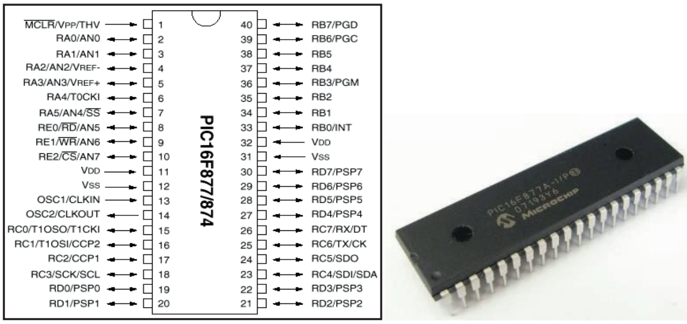


Figure 6 PIC16F87X External Architecture and Appearance

5.4.2. ATMEL AVR Family Microcontrollers

AVR is a RISC-based microcontroller family with Harvard architecture produced by Atmel. AVR, a cheap and fast microcontroller, has advanced features. It has write-erase memory with capacities ranging from 2 KB to 128 KB. The AVR microcontroller structure is designed according to high-level C languages. The AVR microcontroller family is divided into three basic groups [15].

- AT90S microcontrollers
- ATtiny microcontrollers
- ATmega microcontrollers

5.4.2.1. Industrial AVR Series ATmega Microcontrollers

One of the most suitable microprocessors and microcontrollers available today for Industrial Automation is the microcontrollers from the MCS-51 family. The attractive side of these microcontrollers is that each microcontroller from this family is a very small computer, and it directly allows for byte and bit manipulation on each of the input/output pots and the majority of other important function registers. The features that enable the microcontroller-based control card from the MCS-51 family to provide small-sized computer features for industrial automation are the following architectural features contained in only one chip [16].

- ✓ 8/16/32 bit RISC central processing unit (CPU),
- ✓ Built-in EEprom
- ✓ Internal Flash Rom
- ✓ Oscillator that can be selected externally or internally,
- ✓ Can be arranged as bytes or bits, pull-up resistors can be made active or passive
- ✓ Input / Output ports,
- ✓ Static RAM (Internal RAM),
- ✓ External program/data memory (in some microcontrollers),
- ✓ 8/16 bit Timer/Counter/Pwm,
- ✓ Interrupt systems with different vectors that can serve internal and external resources,
- ✓ Serial Port,
- ✓ ISP Port,
- ✓ JTag Port,
- ✓ Protecting programs and data through security bits,
- ✓ Watchdog timer, Brown-out detector,
- ✓ Analog-Digital converter (Adc)
- ✓ Operating frequency up to 20 MHZ,Çalışma frekansına bağımlı (MIPS) çalışma performansı

Atmega8 microcontroller from Atmel, which has the MCS-51 RISC core, has all the above-mentioned architecture.Some of the features of the Atmega8 microcontroller can be summarized as follows: Improved RISC architecture, 32 general purpose registers, 1 instruction execution per clock, 8Kb program memory that can be written by the program, 512 Byte Eeprom, 8 bit timer/counter, 16 bit timer/counter, Byte-based bidirectional serial channel, Programmable serial USART, Master/Slave SPI serial channel, Internal/External Interrupt system. Figure 8 shows the Atmega8 Microcontroller Pin Connection Diagram.

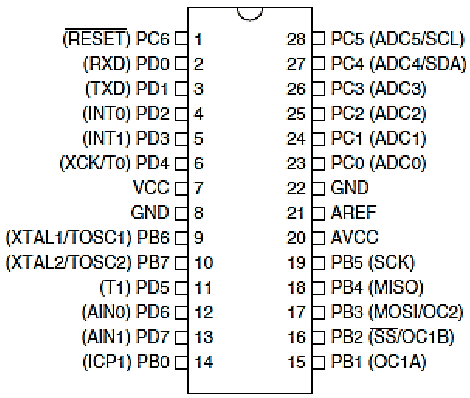


Figure 8 AVR Atmega8 Microcontroller Pin Connection Diagram (PDIP)

5.4.2.2. ATmel AVR Microcontroller Application Areas

According to Source [10], Atmel has become a worldwide leader in design. Microcontrollers produced by Atmel are used in mixed-signal signal processing, security systems, RF control systems, and applications on the control of automotive vehicles [15]. We can list sample applications in the automotive industry as follows [17];

- ✓ Car radio
- ✓ Navigation system
- ✓ Classical balance electronics
- ✓ Key system
- ✓ ABS brake systems
- ✓ Airbag and tire pressure monitoring systems

Microcontrollers produced by ATMEL have a wide market in the field of industrial control. We can list the applications in this field as follows [17];

- ✓ AC and DC motor control
- ✓ Can be used in temperature control and lighting systems.

6. Experimental Setup

Two microcontrollers were used to analyze the performance of microcontrollers. These; Arduino Due is a PIC family product PIC16F877A produced by Microchip and AT91SAM3X8E microprocessor-based controller produced by Atmel. In these applications, an analog signal was given to both integrated circuits and an analog signal was tried to be obtained at the output. The purposes here are;

- ✓ To examine the amplitude and frequency differences between the analog signal applied to the input and the analog signal obtained at the output.
- ✓ To see the delay caused by the reading and writing of microcontrollers
- ✓ The signal given to the analog input is P, PI, etc. in the microcontroller. To examine the ability to perform control algorithms such as

6.1 A/D-D/A circuit with PIC16F877A

To examine the performance of the microcontroller, the ADC conversion feature built into the IC was used. However, since there is no DAC (digital-to-analog converter) feature, the R-2R ladder circuit was used to convert the digital signal back to an analog signal.

6.1.1 A/D Module

All systems naturally found in nature are in analog order. The microcontrollers we use are digital systems. Therefore, to communicate with the outside world and receive data from the outside world, these two systems must somehow understand each other. For this purpose, it is necessary to convert analog signals (heat, light, sound, humidity, voltage, current, etc.) into digital systems that digital systems can understand. There is an ADC module in the PIC16F877A microcontroller. Thus, analog signals can be converted into digital signals thanks to the internal ADC module without using an external circuit or integrated circuit [18].

PIC16F877A microcontroller has 8 ADC input pins (AN0…AN7). An m-bit ADC can sample an analog signal with at most 2^m values. Since the resolution of this ADC module is 10 bits, it can sample with 2^{10}=1024 values. The number of bits of digital information refers to the resolution of the ADC module. The higher the resolution, the better the conversion. The smallest voltage value that the ADC can convert into digital information is called step size and is calculated as in Equation 1;

$$\text{Step Size} = \frac{Vref(+)-Vref(-)}{2^m} \quad (1)$$

According to the catalog values, the positive reference voltage is taken as 5V and the negative reference voltage is taken as 0V. In this case, the step size of PIC16F877A is calculated as in Equation 2.

$$\text{Step Size} = \frac{Vref(+)-Vref(-)}{2^m} = \frac{5V-0}{1024} = 0.0048828125\,V \quad (2)$$

A period of time passes for the conversion of the analog signal at the input of the ADC unit into digital information. The time required to convert an analog signal into digital information is called cycle time. The higher the clock signal frequency to be used for ADC operation, the faster the conversion process. The formula in equation 3 is used to calculate the voltage value of the signal arriving at the ends of the ADC unit.

Signal voltage coming to ADC input = Decimal value of signal * Step size (3)

6.1.2 D/A Module

Since there is no DAC module in the PIC16F877A, this conversion was made using the R-2R ladder-type conversion circuit.

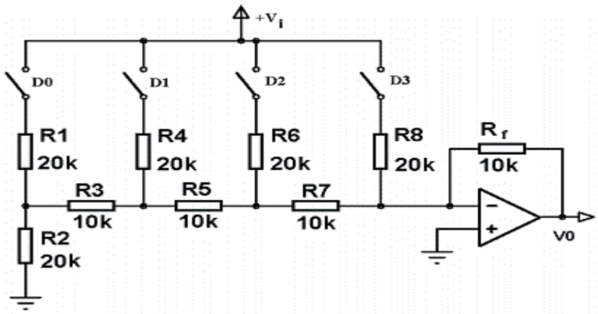


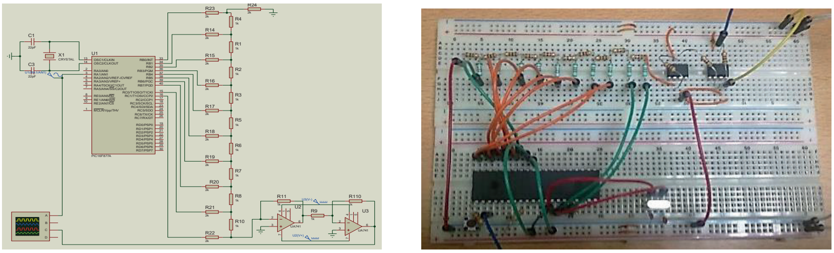
Figure 9 R-2R ladder type 4-bit D/A converter

Since the resistance values in this circuit are listed as R-2R and the output waveform increases in the form of stair steps, these types of converters are called R-2R ladder-type D/A converters. In the R-2R ladder-type DAC circuit shown in Figure 9, the effects of the digital inputs indicated as D0, D1, D2, and D3 on the op-amp inverting input are different. A digital input with a large resistor value in front of it will deliver less current to the op-amp input, and as a result, its effect on the output will be less. D0 is the most unweighted bit and determines the resolution of the circuit. It affects the output by 1/16 of the full-scale value (maximum output). D3 is the most valuable bit and affects the output as half of the full-scale value. The formula giving the output voltage of the circuit is given in Equation 4.

$$\text{DAC output voltage (Vo)} = \frac{-Vref}{16}(Do + 2D1 + 4D2 + 8D3) \qquad (4)$$

6.1.3 Circuit Setup

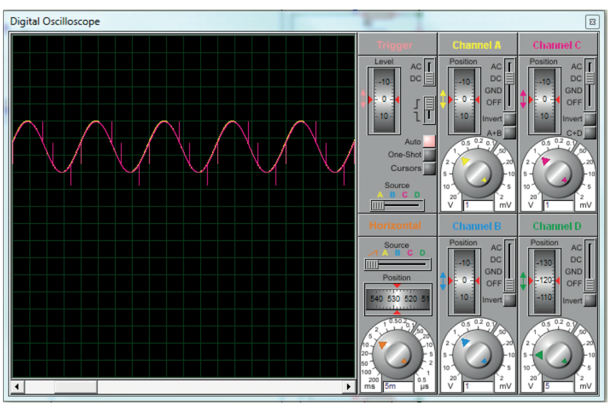
The circuit was first set up in the ISIS interface of Proteus 7 Professional, a simulation program, as shown in Figure 10 (a), and the operation of the circuit and the results were observed.



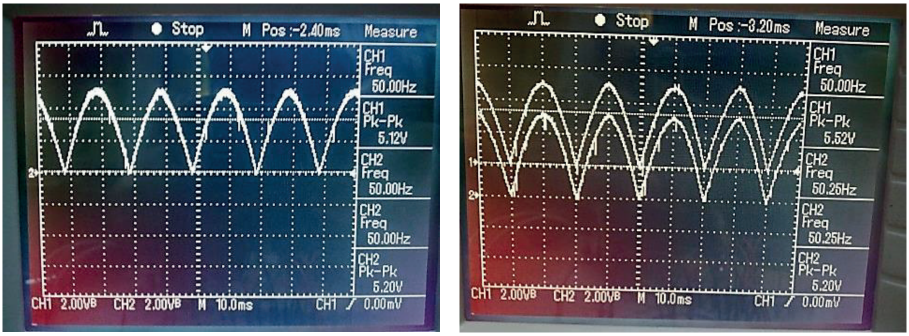
(a) (b)

Figure 10 Setup of the circuit in (a) simulation and (b) experimental study

The circuit includes one PIC16F877A as a microcontroller, two 22pF capacitors and one 20MHz crystal oscillator for the oscillator frequency, 11 2k ohm resistors, 9 1k ohm resistors and two UA741 operational amplifiers for D/A conversion, and An oscilloscope was used to see the results. As the input signal, a sine wave with a frequency of 50 Hz between 0-5V was applied to the circuit. The reason for using two op-amps here is that the op-amp inverter circuit connected to the output of R-2R reversed the voltage. By connecting an inverting op-amp to its output, the voltage was inverted again and correct voltage values were obtained. In the Micro C PRO for PIC program, the program written in C was converted into machine language hex codes and loaded into the PIC. For the experimental study in Figure 10 (b), the hex codes of the program were uploaded to PIC16F877A using Pickit2 and the program interface. The elements in the simulation were used exactly and the results in Figure 11 (b) and (c) were obtained.



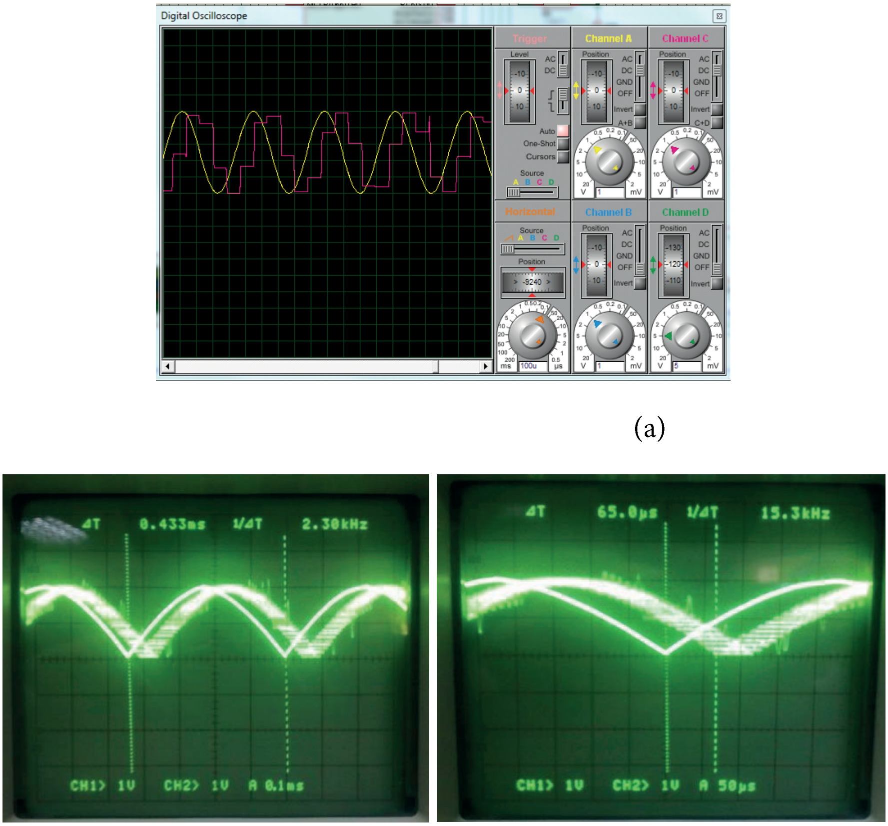
(a)



(b) (c)

Figure 11 Input-output waveforms of the circuit (a) in the simulation, (b) in the digital oscilloscope with the same reference channels, (c) in the digital oscilloscope with different reference channels

While a sine signal with a frequency of 50 Hz and a peak voltage of 1.5 V was applied to the circuit input in the simulation, a full-wave rectified sine signal with a frequency of 50 Hz and a peak voltage of 5 V was applied to the microcontroller input in the experiment, since a negative signal could not be applied to the microcontroller input. When the simulation in Figure 11 (a) and the experimental results in Figure 11 (b) are examined, it is observed that there is no delay between the input and output signal and there is no deterioration in the amplitude value. In Figure 11 (c), the output signal line has been lowered one square on the oscilloscope to better see the difference between the output signal and the input signal. A full-wave rectified sine signal with a frequency of 2.3 kHz, a peak-to-peak sine signal of 5V in the simulation and a peak amplitude of 2V in the experiment was applied to the microcontroller input port. As can be seen in Figure 12, while there was a time delay of approximately 100 microseconds in the simulation and 65 microseconds in the experimental, it was observed that the amplitude of the signal could not be followed exactly.

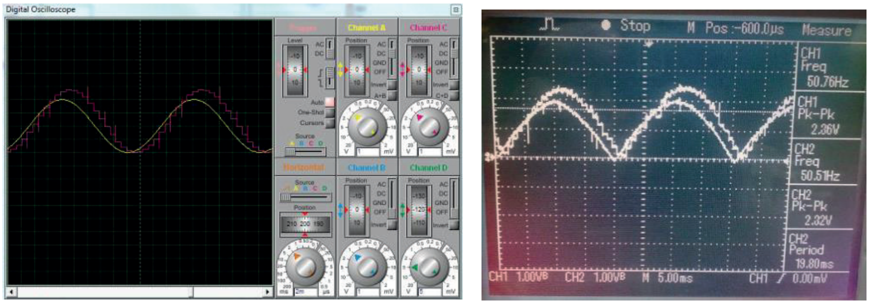


(a)

(b) (c)

Şekil 12 Input-output waveforms of the circuit (a) in the simulation, (b) in the analog oscilloscope with the same reference channels, (c) in the analog oscilloscope with different reference channels

To examine the programmability of the microcontroller and its response to the processing load, the measured analog signal was passed through any PI controller that did not affect the output and was given to the output. In this program, the error signal is calculated by taking the difference between the measured analog signal and the step signal with an amplitude of 1 V, which is accepted as the reference value. To apply PI control, the error is multiplied by the proportional coefficient (Kp) and the integral of the error is multiplied by the integral coefficient (Ki). Additionally, considering that more commands will be added in the future, an empty loop of 100 commands has been created.



(a) (b)

Şekil 13 Input-output waveforms of the circuit with PI controller applied in (a) simulation and (b) experimental

For the program written with PI control commands, the analog input port is 50 Hz in simulation and experimental. The signals in Figure 13 with frequency were applied. When the input and output signals for this situation were examined, it was observed that there were amplitude distortions and time delays of approximately 2 ms in both simulation and experimental. The OP 2300 OP-AMP training set shown in Figure 14 was used for this input signal and the supply voltages of the PIC and op-amps in the circuit.

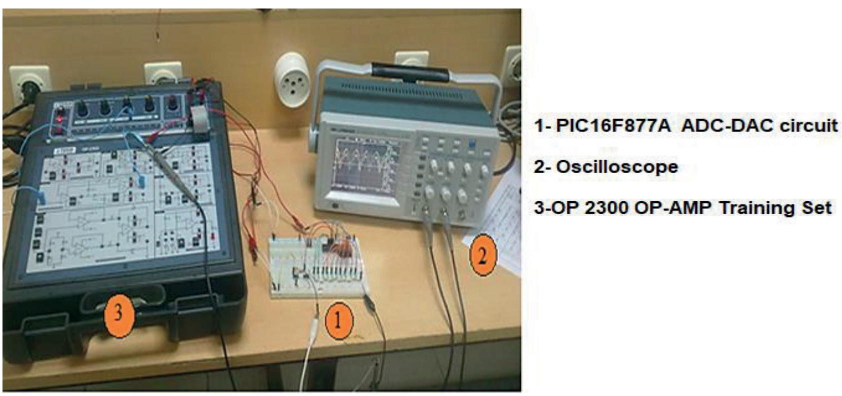


Figure 14 ADC-DAC circuit experimental setup

6.2 A/D-D/A circuit with Arduino Due

Arduino, whose image is shown in Figure 15, is an AT91SAM3X8E microprocessor-based development platform developed by Due Atmel. The specifications of this microcontroller are given in Table 2. Arduino Due has 12-bit DAC and ADC modules in its circuit.

Tablo 2 Arduino Due's features

Microcontroller	AT91SAM3X8E
Operating Voltage	3.3V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-16V
Digital I/O Pins	54 (of which 12 provide PWM output)
Analog Input Pins	12
Analog Outputs Pins	2 (DAC)
Total DC Output Current on all I/O lines	130 mA
DC Current for 3.3V Pin	800 mA
DC Current for 5V Pin	800 mA
Flash Memory	512 KB all available for the user applications
SRAM	96 KB (two banks: 64KB and 32KB)
Clock Speed	84 MHz

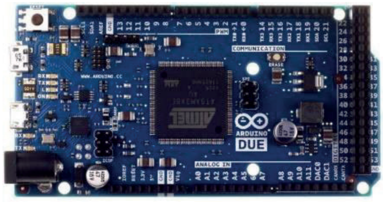


Figure 15 Arduino Due

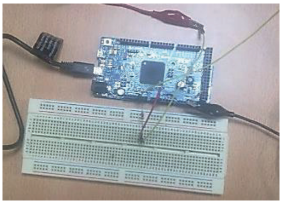
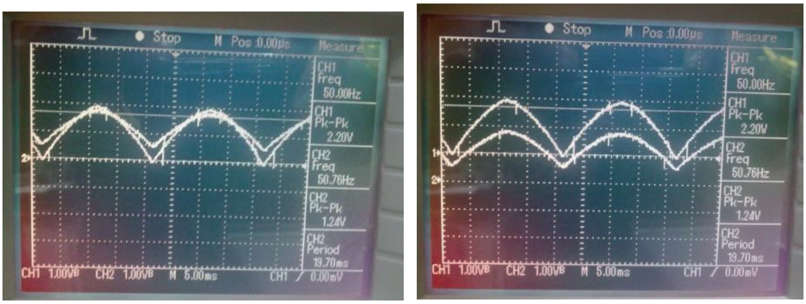


Figure 16 Arduino Due ADC-DAC circuit

Arduino Due is programmed from its C-based interface program via USB. Since it gets its power from USB, no additional power is needed for its operation. Just as seen in Figure 16, the input signal was applied through the resistor and the output signal directly through the resistor was measured with an oscilloscope.

As the analog input, a full-wave rectified sine signal with a peak-to-peak voltage of 2V and a frequency of 50 Hz was applied using the OP 2300 OP-AMP training set, as in the PIC. Without making any changes to the signal in the program, the signal was measured in decimal by connecting it to the ADC pin, multiplied by calculating the step interval, and transferred directly to the output from Arduino's own DAC.



(a) (b)

Figure 17 Arduino Due ADC-DAC input-output waveforms

When the results in Figure 17 are examined, it is seen that there is no time delay in the signal, but there is distortion in the amplitude value. In Figure 17 (b), the signal has been reduced one frame to see the result better. To measure the performance of Arduino, a 2.3kHz frequency full-wave rectified sine signal with the same amplitude value was applied to the ADC pin, as seen in Figure 18. In addition, the same controller and empty loop operations were also carried out in Arduino.

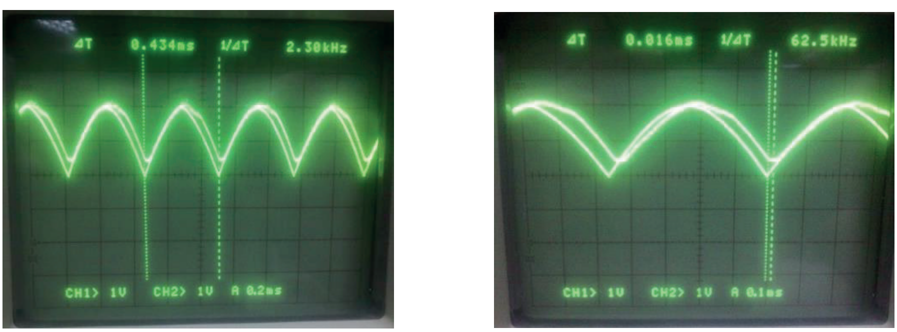


Figure 18 Input-output waveforms with 2.30kHz input signal

When the input and output waveforms were examined, there was no distortion in the amplitude value of the input signal at the output and a delay of 16 micros was experienced. The distortion in amplitude occurred mostly in the parts close to zero.

8. Conclusion

In this study, microprocessors and microcontrollers are defined and information about their architectures, communication paths, memory types, etc. is given. Microcontrollers produced by Microchip and Atmel companies, which are frequently used in the industry, and their features were examined. For performance analysis, two microcontrollers were used: PIC16F877A developed by Microchip and AT91SAM3X8E microprocessor-based Arduino Due development platform from Atmel. Circuits were obtained both in simulation and experimentally, and the results were observed with an oscilloscope.

To observe how fast microcontrollers work, ADC and DAC structures were used to obtain analog signals from their outputs by giving analog signals to their inputs. The purpose of this is to observe how accurately and quickly the microcontroller can transmit a continuous and fast signal of different amplitudes to the output when it comes to its inputs. For this purpose, initially sine signals with a frequency of 50 Hz and a maximum amplitude of 5 V were applied to both microcontrollers. To see the performance difference between the two microcontrollers, the applied sine signal was increased to 2.30 kHz and the results were observed. To examine the programmability of microcontrollers, the applicability of control algorithms such as P, PI, and PID was examined and the PI algorithm was implemented.

PIC16F877A microcontroller was programmed using the C-based Micro c PRO program and examined by establishing a circuit in the ISIS simulation program, which is the interface of the Proteus 7 Professional program. After it was seen that the programs worked correctly, the circuit was established on the breadboard and the results were examined on the oscilloscope. When a 50 Hz sine wave was applied, the input and output waveforms overlapped exactly. However, when the frequency was increased to 2.3 kHz, both amplitude distortions and delays of 65 microseconds were observed. This shows that the microcontroller cannot keep up with the speed of the signal. It shows that even if it is a slower signal instead of such a fast signal, there will still be a delay when many operations are performed and commands are written between the read signal and the signal given to the output. However, these delays and distortions vary in direct proportion to the speed of the signal or the multiplicity of commands. Since the program is written in C language, arithmetic, logical, etc. operations can be written more easily, and it can be programmed more easily and with fewer commands than in assembly language. Therefore, the ability to realize the PI algorithm also shows that advanced control methods can be applied.

Arduino Due's C-based interface program was used for its software, and the circuit was established and the results were observed on the oscilloscope. It was observed that there was no delay in the 50 Hz frequency signal, but there was a delay of 16 microseconds in 2.30 kHz. Since the program is C-based, advanced control algorithms can also be applied to this microcontroller.

In line with the experimental results, it has been seen that Arduino Due with 84 MHz oscillator frequency and 12-bit resolution gives clearer and faster results than PIC16F877A with 20 MHz oscillator frequency and 10-bit resolution. The delay in the PIC was 4 times higher and since its resolution was lower, the output waveform was formed in steps. The advantages of Arduino Due over PIC16F877A can be listed as follows:

- ✓ High working speed
- ✓ Excessive program memory
- ✓ High number of analog channels and resolution
- ✓ High number of inputs/outputs
- ✓ Finding the DAC module
- ✓ Ease of circuit installation
- ✓ Programming can be done via USB even when the circuit is running

REFERENCES

[1] Milli Eğitim Bakanlığı, 2012, Elektrik Elektronik Teknolojisi, Mikroişlemci ve Mikrodenetleyiciler, 523EO0019, Ankara, 67s.

[2] Özcerit, A. T., Çakıroğlu, M., Bayılmış, C., 2008, 8051 Mikrodentleyici Uygulamaları, Papatya Yayıncılık Eğitim, İstanbul, 416s.

[3] Gümüşkaya, H., 2000, Mikroişlemciler ve 8051 Ailesi, Alfa Basım Yayım ve Dağıtım Ltd. Şti., İstanbul, 455s.

[4] Çobanoğlu, B., Mikroişlemciler Dersi, Pic Mikroişlemciler ve programlama ders notu, Sakarya Üniversitesi Teknoloji Fakültesi Mekatronik Mühendisliği Bölümü, 66s.

[5] Soylu E., Öz K., Mikroişlemciler Ders Notu, Karabük Üniversitesi Teknoloji Fakültesi Mekatronik Mühendisliği Bölümü, Karabük, 283s.

[6] Türkoğlu, İ., 2010, Mikro bilgisayarlı sistem tasarımı, Ders Notu, Fırat Üniversitesi Teknik Eğitim Fakültesi Elektronik ve Bilgisayar Eğitimi Bölümü, Elazığ, 157s.

[7] Ünal İ., Mikrodenetleyiciler Ders Notu, Akdeniz Üniversitesi Teknik Bilimler Meslek Yüksek Okulu Elektronik ve Otomasyon Bölümü Mekatronik Programı, 73s.

[8] Çobanoğlu, B., Mikroişlemciler ve Mikrodenetleyiciler II ders notu, Sakarya Üniversitesi Teknoloji Fakültesi Mekatronik Mühendisliği Bölümü, 33s.

[9] Topaloğlu, N., Gürgünoğlu, S., 2003, Mikroişlemciler ve Mikrodenetleyiciler, Seçkin Yayıncılık, Ankara, 304s

[10] Dilmaç, S., 2004, 8051 ve ADuC8xx Eğitim Notları, Elektronik Sanayi ve Ticaret A.Ş., İstanbul, 385s.

[11] Milli Eğitim Bakanlığı, 2006, Mikroişlemci ve Mikrodenetleyiciler, Mesleki Eğitim ve Öğretim Sisteminin Geliştirilmesi Projesi, Ankara, 57s.

[12] Çotuk H., 2008, "PIC Mikrodenetleyiciler için gerçek zamanlı işletim sistemi", Y.Lisans Tezi, TOBB Ekonomi ve Teknoloji Üniversitesi, Bilgisayar Mühendisliği Anabilim Dalı, Ankara, 118s.

[13] Özcerit, A. T., Çakıroğlu, M., Bayılmış, C., 2008, 8051 Mikrodentleyici Uygulamaları, Papatya Yayıncılık Eğitim, İstanbul, 416s.

[14] Goyal, N., 19-21 December 2006, "Grading a Microcontroller: a Travelling Salesman Problem Application", 4th International Conference on Electrical and Computer Engineering ICECE, Dhaka, Bangladesh.

[15] Korbel, S., Janes, V., 2004, Interesting Applications of Atmel AVR Microcontrollers, Digital System Design, Euromicro Symposium, 499-506

[17] http://www.atmel.com/products

[16] Korana, İ., 2006, Atmel Atmega8 Mikrodenetleyici ve Assembler Ders Notu, Konya, 61s.

[18] Çiçek S., 2009, CCS C ile PIC Programlama, Altaş Yayıncılık ve Elektronik, İstanbul, 600s.

CHAPTER 2

INDOOR LOCALIZATION SYSTEMS: SENSORS AND ALGORITHMS

Gökhan KARAÇOBAN[1]

Nurbanu GÜZEY[2]

1 Res. Ass. Gökhan KARAÇOBAN
Department of Astronautical Engineering, Sivas University of Science and Technology
ORCID: 0000-0001-5155-8360
2 Asst. Prof. Nurbanu GÜZEY
Department of Computer Engineering, Sivas University of Science and Technology
ORCID: 0000-0002-6587-2489

1.) INTRODUCTION

Localization is the process of location determination of objects, people, and equipment with respect to predefined reference points (Farid, Nordin, & Ismail, 2013). It can be broadly categorized into outdoor and indoor localization. The Global Positioning System (GPS) is typically used for outdoor positioning. GPS uses satellite radio signals to determine location. Therefore, satellite signals must arrive at mobile agent to be able to determine the position of the mobile agent. However, satellite signals cannot penetrate walls and other barriers. Consequently, GPS is ineffective indoors (Asaad & Maghdid, 2022). Hence, different localization systems are needed to determine location indoors. These systems are called indoor localization system.

With the development of Internet of things, indoor localization systems find wide-ranging applications in both civilian and military sectors. Indoor localization systems are used in hospitals, smart offices, shopping malls, museums, and they also play a crucial role in military operations by providing the precise location of soldiers (Zafari, Gkelias, & Leung, 2019). Thus, they facilitate the process of strategic decision-making, mission planning and adaptability in operations (Ferreira, Fernandes, Catarino, & Monteiro, 2017). Hospitals are generally overcrowded with patients and workers. Patients who do not know where treatment rooms are and any other places inside the hospital can face with difficulties with finding these places. This difficulty can possibly cause stress over patients and being late for their appointments. Also, health workers can find out the treatment rooms, operating areas and hospital assets quickly using indoor localization systems and can help patients without losing time (Zafari et al., 2019).

Museums and galleries offer a window into the rich tapestry of human history. People can visit museums in their free time. Visitors can find specific halls and exhibits easily to visit using indoor localization systems. Therefore, visiting the museum becomes more dynamic and informing with the help of using indoor localization systems. Furthermore, museum directors want to evaluate the behavior of museum visitors with the purpose of realizing which exhibit is the most visited (Zafari et al., 2019).

Indoor localization systems are also used in military applications. They play crucial role in achieving safety and successful military operations. Military operations can be carried out in complex indoor environments such as tunnels or buildings where GPS signals may be blocked or degraded. In these cases, indoor localization systems that do not require GPS signals ensure that military personnel can maintain situational awareness and coordinate effectively even in such challenging environments (Ferreira et al., 2017). Furthermore, unmanned aerial vehicles (UAV) are frequently used in military operations due to their ability to perform various missions without risking human lives. They are used for discovering and surveillance the indoor military area. By that way, UAVs enhance the military's understanding of the operation area by providing aerial views of terrain, obstacles, and infrastructure. This helps soldiers to take informed decisions, prepare resources and adjust tactics effectively during operations. Hence, operation success increases by using UAVs (Gargalakos, 2021). On the other hand, UAVs have to move on the operation area autonomously to carry out their missions. Therefore, autonomous navigation systems are required for UAVs to perform their missions in indoor area (Chang, Cheng, Manzoor, & Murray, 2023). However, autonomous navigation systems need the location data of UAV. This location data is provided using indoor localization systems (Zhilenkov, Chernyi, Sokolov, & Nyrkov, 2020). Therefore, UAVs need localization systems to carry out their military missions. For that reason, developing accurate and reliable indoor localization systems are so crucial to carry out military operations more successfully. When considering the broad spectrum of applications for indoor localization systems, it is obvious that their significance lies in their capacity to greatly facilitate daily military activities and military operations, thereby improving the quality of life.

2. SENSORS AND ALGORITHMS USED FOR INDOOR LOCALIZATION

Sensors and localization algorithms are two important part of an indoor localization systems. Different sensors are used for indoor localization systems. Sound based and radio frequency (RF) based sensors can be used for indoor localization systems. The most frequently used RF based sensors are Wi-Fi, Bluetooth, radio frequency identification (RFID), Zigbee and ultrawideband (UWB) sensors (Asaad & Maghdid, 2022). Moreover, ultrasonic sensor is sound-based sensor. Sensor measurements are done using measurements methods and these measurements are used in localization algorithm to determine the location of an object. These measurement methods are time of arrival (TOA), time difference of arrival (TDOA), angle of arrival (AOA), two way ranging and received signal strength (RSS) (Asaad & Maghdid, 2022). Localization algorithms are chosen based on measurement methods. For example, when angle of arrival of sensor signal is measured, triangulation algorithm has to be used for localization. When TOA, TDOA or two-way ranging method are used for sensor measurement, trilateration or multilateration algorithm have to be used for localization. On the other hand, there is some algorithms that are used for indoor localization. Some of these algorithms are trilateration algorithm, multilateration algorithm, triangulation algorithm, fingerprinting algorithm and Kalman filter based algorithms (A. Yassin et al., 2017).

Wi-Fi is one of the most frequently used technology for indoor localization. This is because, most of indoor area have Wi-Fi access points. Also, telephones and computers are Wi-Fi enabled. Therefore, it is easy to reach and used this access points for localization. The range of operating frequency band of Wi-Fi signal is between 2,5 GHz and 5 GHz for IEEE 802.11b and IEEE 802.11a. standards, respectively (Asaad & Maghdid, 2022). RSS measurements are used in Wi-Fi based indoor localization systems. Wi-Fi access points are placed indoor area and they emit RF signal. These signals make coverage area in indoor area. When mobile agent that has Wi-Fi receiver enters the coverage area, it receives Wi-Fi signal and calculates RSS value of signal. Then, this RSS value is converged to distance data between Wi-Fi access point and mobile agent by using path loss formula and used in trilateration or multilateration algorithm to determine the location of mobile agent. Another localization algorithm that can be used with Wi-Fi technology is fingerprinting algorithm. RSS measurements of Wi-Fi signals can be used in fingerprinting algorithm to localize objects (Asaad & Maghdid, 2022).

The advantage of using Wi-Fi technology for indoor localization is that Wi-Fi signals is easily accessible. Also, Wi-Fi consumes low power. Moreover, the cost of Wi-Fi based indoor localization system is cheap as well (Xia, Liu, Yuan, Zhu, & Wang, 2017). On the other hand, there are number of disadvantages of using Wi-Fi based indoor localization systems. First, RSS measurement error is high in indoor area. Indoor area contains walls and different objects. Wi-Fi signal encounters the problem of diffraction, attenuation, reflection, scattering (M. Yassin & Rachid, 2015) and multipath propagation when it is transmitted to receiver due to walls and other objects that are in indoor area. These problems result in fluctuations of RSS value and increases measurement error (Zayets & Steinbach, 2017). Therefore, localization error increases dramatically due to measurement error. Secondly, in Wi-Fi based indoor localization systems, RSS measurements have to be stored in database to be used in fingerprinting algorithm but, the storage of data is an additional cost and loss of time (Mok & Retscher, 2007).

Another indoor localization technology is Bluetooth which includes MAC and physical layers specifications to connect different wireless devices. Bluetooth technology has Bluetooth Low Energy (BLE) version. BLE is more energy efficient compared to Bluetooth (IEEE 802.15.1) technology and BLE signals can cover the indoor area up to 100 meters (Zafari et al., 2019). The frequency of Bluetooth signal is 2,4 GHz. Interference happens between Wi-Fi and Bluetooth signals since they use same frequency band (Shoemake, 2001). Therefore, localization accuracy decreases due to measurement error results from interference. Another disadvantage of using Bluetooth technology is that Bluetooth signals are prone to noise. Therefore, the accuracy of Bluetooth based indoor localization system is low. When

Bluetooth signals encounter the problems of diffraction, scattering, multipath propagation and reflection issues, measurement error increases dramatically. As a result of increasing measurement error, the localization error also increases (Zafari et al., 2019). On the other hand, there are various advantages of using Bluetooth technology which are low energy consumption, high coverage area of Bluetooth signals and high throughput cost.

Bluetooth emits RF signal and they create coverage area in indoors. When mobile agent enters the coverage area of Bluetooth signals, it receives signal. Then, the distance between Bluetooth transmitter and mobile agent is calculated using some measurement methods such as, TOA, TDOA or RSSI measurement. This distance data is then used in multilateration algorithm to determine the location of mobile agent (Pratama, Abdurohman, & Putrada, 2021).

RFID is a promising technology for indoor localization system. RFID technology is used in various applications such as asset tracking, people localization, warehouse management, supply chain network (Farid et al., 2013). RFID sensor includes tag and anchor. There are two types of RFID tag which are passive tag and active tag. An active tag includes internal power unit which supplies power to the tag. In contrast, passive tags do not contain internal power source and the size of passive tag is smaller than active RFID tags (Bouet & Dos Santos, 2008). RFID tag is attached to the mobile agent that is desired to be localized and RFID anchors are placed at indoor area. RFID anchors emit RF signal and these signals make coverage area in indoor place. RFID tag becomes active when RFID tag enters the coverage area and sends RF signal to RFID anchors. Then, RFID anchors receive this RF signal and calculates RSS value of this signal and RSS value is converged to the distance data between mobile agent and RFID tags by using path loss model (Li, Ai, Tateno, & Hachiya, 2019), to be used in localization algorithms to determine position.

Different localization algorithms can be used for RFID based indoor localization. First of all, trilateration and multilateration algorithms are utilized for localization. The distance data between mobile agent and RFID anchors is used in trilateration (Sohan et al., 2019) and multilateration (Costin & Teizer, 2015) algorithm to determine the location of mobile agent. Nevertheless, RSS measurement error is high indoor area due to object and obstacles placed at indoors. Therefore, localization error using trilateration and multilateration algorithm is quite high for RFID based indoor localization systems. Another localization algorithm used for RFID based indoor localization is fingerprinting algorithm. Fingerprinting algorithm consists of two stages which are offline and online stages. In offline stage, RSS measurements are collected from all RFID anchors located at different places in indoor area. These RSS measurements are called as fingerprint and recorded in database. Then, they are used as a reference to be compared with the RSS values that is obtained in online stage. In online stage, RSS measurements obtained from the mobile agent are compared and matched with the RSS fingerprints to obtain location information of mobile agent (Sesyuk, Ioannou, & Raspopoulos, 2022). However, localization error of fingerprinting algorithm is high due to RSS measurement error of RFID sensor. Indoor area contains walls, barrier and obstacles. When RFID signal encounter this obstacles, reflection, diffraction, multipath fading happens and act as measurement noise (Donelli & Manekiya, 2018). Therefore, RSS measurements fluctuates due to measurement noise which results in measurement error and the localization accuracy of fingerprinting algorithm decreases dramatically. This is a disadvantage of fingerprinting algorithm and RFID sensor. On the other hand, there are number of advantages of RFID based indoor localization systems. First of all, power consumption of RFID sensor is low. Furthermore, the cost of RFID sensor is also low. Finally, the response time of RFID based indoor localization system is low (Farid et al., 2013).

Zigbee is another sensor used for indoor localization. Zigbee uses 868 MHz frequency band in Europe (Mellios et al., 2014). Zigbee sensor has transmitter and receiver parts. Receiver is placed on mobile agent that is desired to be localized. Transmitters are placed in reference points and sends

RF signals to indoor area. These signals make a coverage area in indoors. When mobile agent enters to coverage area, RF signals are received by receiver and RSS value is obtained. Then, RSS values can be used in fingerprinting algorithm to determine the location of mobile agent (Wisitpongphan, 2013).

The advantages of using Zigbee sensor for indoor localization are low cost and low power consumption (Dong, Xu, & Zhuang, 2019). Nevertheless, there are various disadvantages of using Zigbee sensor. Firstly, Zigbee is vulnerable to signal interference from other signals that use same frequency band (Farid et al., 2013). In addition, Zigbee sensor provides RSS measurements. However, in non-line of sight (NLOS) situation due to obstacles located indoors, Zigbee sensor's signals reflect, scatter and diffracts. Therefore, RSS measurements have high measurement error which result in high localization error. Moreover, Zigbee sensor uses narrow-band channels, which results in low frequency diversity that makes Zigbee signals more sensitive and vulnerable to signal interference (Azevedo & Santos, 2022). When there are other RF signal sources which have same frequency with Zigbee sensor signal, interference happens between Zigbee signal and other RF signals. Therefore, high measurement and localization error occur.

UWB sensor is one of the most widely used sensors for indoor localization systems. UWB sensors use short pulses to transmit data. UWB sensors use large bandwidth which is more than 500 MHz. The frequency range of UWB signal is between 3,1 GHz and 10,6 GHz (Zafari et al., 2019). UWB sensor has tag and anchor. UWB anchors are placed at reference points in indoor area and UWB tag is attached on mobile agent. UWB tag sends UWB signal to anchors. Then, TOA, TDOA or TOF are calculated to determine distance between UWB anchor and tag. Also, RSS measurements can be used in fingerprinting algorithm to estimate location of mobile agent using UWB sensor (Zafari et al., 2019).

UWB sensor signals have different frequency spectrum due to large bandwidth. Frequency diversity provides UWB sensor some advantages. It provides crucial advantages to UWB sensor, especially in the difficulties that are encountered frequently and increases localization error dramatically in indoor localization systems such as signal reflection, diffraction, scattering and multipath propagation. In NLOS condition, even if some UWB sensor signals can reflect, scatter and diffract when encounter with obstacles, another UWB signals that have different frequency can penetrate these obstacles and arrive at receiver. Incoming signals to receiver are adequate for localization. Therefore, UWB sensors do not need line of sight between receiver and transmitter. This provides a great advantage to the UWB sensor, especially in indoor localization applications. Moreover, UWB sensor is resistant to multipath propagation because they do not need direct line of sight. UWB signals can penetrate obstacles. Therefore, they can pass through obstacles and do not reflect and scatter. For that reason, UWB signal are more immune to multipath propagation than other sensor signals such as Wi-Fi, Bluetooth and RFID. Furthermore, UWB sensor is immune to signal interference. This is because, even if some UWB signals can interfere with other RF signals, other UWB signals that have different frequency with other RF signals do not interfere with them. Hence, these signals can arrive at UWB receiver without interference. Therefore, measurement error of UWB sensor is low even in there is other RF signal sources that causes interference in environment. For that reason, interference does not cause high measurement error for UWB sensor. In addition, UWB sensor is robust to signal jamming, which is a significant problem especially in military operations. Sensor signals can be jammed during military operations to make fail localization and navigation systems of UAV and military agents. The success of military operation decreases significantly, if navigation and localization systems fail. For that reason, UWB sensor is the most advantageous and suitable sensor for military operations among other sensors such as RFID, Bluetooth and Zigbee. On the other hand, there are some disadvantageous of UWB sensor. Firstly, the cost of UWB sensor equipment is high. Secondly, even if UWB sensors are more resistant to signal reflection and scattering problem, they also encounter with that problems that result from metallic objects.

Beside RF based sensors, there are also sound based sensors used for indoor localization systems. The example of sound-based sensor is ultrasonic sensors. Ultrasonic sensors use sound waves (Zafari et al., 2019). Ultrasonic sensors consist of transmitter and receiver parts. Ultrasonic transmitters are placed at reference point in indoor area. Ultrasonic receiver is placed on mobile agent that is desired to be localized. Ultrasonic transmitters emit ultrasonic waves. These waves are received by receiver. Then, different measurement methods such as TOF, AOA or TDOA are used to determine the distance between mobile agent and ultrasonic transmitters (Ijaz, Yang, Ahmad, & Lee, 2013). After that, this distance data is used in localization algorithms to determine location such as lateration, triangulation and fingerprinting algorithms. Ultrasonic sensors have narrow band signals. Therefore, there are some disadvantages of ultrasonic sensors. They are more vulnerable to signal interference than RF based sensors. In addition, the sound velocity changes a lot which results in high measurement error (Ijaz et al., 2013). Furthermore, sound waves fade away when encounter with walls and barriers located indoors. Therefore, high measurement error occurs when using ultrasonic sensors. For that reason, localization error of ultrasonic based indoor localization systems is quite high. On the other hand, there are a few advantages of using ultrasonic sensors for indoor localization. Power consumption and the cost of ultrasonic sensors is low (Ijaz et al., 2013). Compared to RF-based indoor localization systems, the errors of indoor localization systems using ultrasonic sensors are much higher. For that reason, RF based sensors are more advantageous and suitable for indoor localization.

There are some challenges indoors that decreases the accuracy of indoor localization systems. Some of these challenges are signal interference, multipath propagation and NLOS situations. They are encountered with these challenges in harsh indoor environments frequently.

Interference is serious issue for indoor localization systems. Indoor environments consist of different signal sources such as telephone, computer, TV, Wi-Fi etc. When the frequency of the sensor signal used to determine the location is the same as the frequency of other signals in the indoor environment, signal interference occurs. Therefore, measurement error increases since this interference effects as measurement noise. As a result, localization accuracy decreases. For instance, RSSI measurements fluctuate because of signal interference and this fluctuation causes significant localization error especially in complex indoor environments (Azevedo & Santos, 2022). In that case, some filters such as Kalman filter have to be used to filter measurement noise due to RSS fluctuation in order to increase localization error (Shen, Hwang, & Jeong, 2020).

Multipath propagation is another problem for indoor localization. There are different objects and obstacles that closes the line of sight between sensor receiver and transmitter. The line of sight can be reduced or blocked completely due to objects and obstacles. In that case, sensor signal is encountered with obstacles and reflects, diffracts. Then, the reflected signal can encounter with another obstacle and reflect again when hitting on obstacle. Therefore, reflected signals follow different paths to arrive at receiver. This situation is called as multipath propagation (Obeidat et al., 2019). Multipath propagation leads to measurement error and this error causes localization error. For example, multipath propagation leads RSS values to have large fluctuations (Obeidat et al., 2019). Another example of negative impact of multipath propagation is that time of arrival and time difference of arrival measurements have large errors (Gentner & Jost, 2013). When signal is encountered with multipath propagation, the time of arrival of signal to arrive at receiver changes. Therefore, measurement errors occur. As a result, localization error increases due to measurement error.

Another problem encountered in the indoor localization process is NLOS situation which is the weakening or complete loss of line of sight between the sensor transmitter and the target object. When sensor signal collides with obstacles, the signal reflects, diffracts and sensor measurements become inaccurate.

Sensors have to be chosen accurately and effectively to cope with these challenges faced with indoor area. Therefore, some metrics have been defined in literature to choose appropriate sensor for indoor localization system. These metrics are accuracy, cost, power consumption and coverage area of sensor signal. The term of accuracy defines how sensor measurement error is low. Also, power consumption identifies sensor consume how much power to operate. Finally, coverage area defines the area which is covered by sensor signal (Alarifi et al., 2016).

When ultrasonic, Wi-Fi, Bluetooth, RFID and UWB sensors are compared in terms of accuracy, the most accurate sensors are UWB (Zafari et al., 2019) and ultrasonic sensors (Crețu-Sîrcu et al., 2022). However, the accuracy of ultrasonic sensor is high in short distances and short coverage area (Hazas & Hopper, 2006). When the localization is desired to carried out in large area, the accuracy of ultrasound sensor decreases sharply. This is because, ultrasound sensors have narrow frequency band. When the area is increased, ultrasound sensor signals encounter more obstacles and signal reflects and diffracts more. Diffraction and reflection of sensor signal result in large measurement noise. Furthermore, ultrasound sensors cannot tolerate this disadvantage and have poor performance since the frequency diversity is very low in ultrasound sensor due to narrow frequency band that they have (Hazas & Hopper, 2006). On the other hand, the accuracy of UWB sensor is high even in long distance and large area since UWB sensors have wide bandwidth and frequency diversity due to wide bandwidth. The accuracy of UWB sensors is high even in NLOS condition. Even if some of the UWB sensor signals encounter with diffraction, scattering and reflection more in long distance due to more obstacles, other signals that have different frequency can pass through these obstacles without reflection and scattering. Therefore, measurement error of UWB sensor is low even in large and wide area. For that reason, UWB sensor is the best for indoor localization among other sensors mentioned above in terms of accuracy.

When sensors are compared in terms of coverage area, sensors with the widest coverage area are UWB and Wi-Fi. Nevertheless, Wi-Fi uses RSS measurements to localize objects. RSS measurements fluctuates a lot in indoor area due to signal interference. Also, Wi-Fi signals attenuates when encounter with obstacles. Therefore, RSS measurements have large error. Consequently, even if both Wi-Fi and UWB sensor signals have large coverage area, UWB sensor performs better than Wi-Fi. When sensors are compared in terms of power consumption, the power consumption of UWB, Bluetooth, RFID and ultrasonic sensor is lower than Wi-Fi. Finally, when sensors are compared in terms of cost, Bluetooth and RFID sensors are cheaper than other sensors (Deak, Curran, & Condell, 2012).

Coverage area and accuracy are the most important criteria to be able to design effective and high-performance indoor localization systems. Therefore, they have to be considered more to choose an appropriate sensor for indoor localization. When sensors are compared in terms of coverage area, the most advantageous sensor is UWB sensor. Moreover, when sensors are compared in terms of accuracy, UWB sensor is the best among Wi-Fi, Bluetooth, RFID, Zigbee and ultrasonic sensors. Compared to other sensors, UWB sensors have significant advantages. UWB sensor can transmit high amounts of data with low energy consumption. UWB sensor signal is more resistant to signal interference due to wide bandwidth that UWB sensors have. Furthermore, they have high coverage area and positioning accuracy. Moreover, UWB has impulse radio short pulses which result in detection of multipath component easily (Basiri et al., 2017). This is an advantage of UWB sensor offer. However, other RF based sensors cannot cope with multipath propagation. Therefore, all these advantageous of UWB sensor puts forward UWB sensor from other RF based sensors. As a result, UWB is the most appropriate sensor for indoor localization systems.

Some measurement methods are used for modelling sensor measurements. These methods are TOA, TDOA, AOA, TWR and RSS (Farid et al., 2013). TOA methods calculate the time which signal travels from sensor tag that is attached on mobile agent to anchors. TOA is used to calculate distance between mobile agent and anchors. To calculate distance, the time of arrival of signal is multiplied by speed of light (Farid et al., 2013). In this method, sensor tag and each of sensor anchors have to be synchronized each other so that the arrival time of the signal can be measured accurately.

Therefore, when they are not synchronized each other, significant measurement error occurs.

Another measurement method is the TDOA method. In this method, the difference between the arrival time of the signal sent to each anchor is used. Based on the difference between the arrival time, the difference between the distance of the object to each anchor is calculated. Then, hyperbolas are drawn around each reader by considering the distance differences of the object to each reader, obtained from the arrival time difference. The intersection point of these hyperbolas is the location of the target object (Liu, Darabi, Banerjee, & Liu, 2007). Disadvantages of this method, TDOA measurements are highly inaccurate in indoor area due to signal reflection, scattering and multipath propagation problems.

AOA method can also be used for sensor measurement. In this method, arrival angle of signal to anchor is utilized. The signal sent by the sensor transmitter is detected with the help of the antenna in the receiver. Both the phase of the signal sent by the transmitter to the receiver and the phase of the signal received by the receiver are determined by the transmitter and receiver. Since the phase of the signal received by the receiver and the phase of the signal sent by the transmitter are known, the phase difference between these signals can be determined. By using this phase difference data, the wavelength of the signal and the distance between the sensor transmitter and receiver, the arrival angle of the signal can be found (Botler, Spork, Diwold, & Romer, 2020).

TWR method uses time of flight (TOF) of the signal between receiver and transmitter (Liu et al., 2007). In TWR method, sensor tag sends signal to transmitter and the chronometer on sensor tag starts working. When transmitter gets signal, it sends back signal to tag after processing time. Then, sensor tag turns off its chronometer when receive the signal back and the time for signal to travel between tag and transmitter is found. The processing time of signal is subtracted from the time for signal to travel between tag and transmitter and divided by two to calculate TOF. Since, sensor signal moves with speed of light, the TOF is multiplied by the speed of light to calculate distance between transmitter and receiver. The advantage of TWR method is that TWR does not require time synchronization between receiver and transmitter. However, measurement errors result from signal reflection and scattering are disadvantages of TWR method.

Another measurement method is RSS. In the RSS method, when the target object enters the coverage area of anchor, the tag becomes active and sends a signal to the anchor. When the anchor receives the signal, RSS value is measured and used in the path loss model to obtain the distance between the target object and the anchor. This distance is then used in multilateration or trilateration algorithms to determine object's position (Booranawong, Sengchuai, Buranapanichkit, Jindapetch, & Saito, 2021). Additionally, RSS measurements can also be used in the fingerprint algorithm to localize object (Ijaz et al., 2013). When sensor signal encounter with obstacles in indoor area, signal reflects and scatters. Therefore, RSS measurements fluctuate and have high measurement error. This is a serios disadvantage of RSS based measurement methods.

Sensor measurements are processed in localization algorithms to determine object's location. Different localization algorithms can be used such as trilateration, multilateration, triangulation and fingerprinting algorithms. Also, filter-based algorithms such as particle filter, extended Kalman filter (EKF) and unscented Kalman filter (UKF) can be used as well.

Circle geometry is used in trilateration algorithm to determine location. 3 sensors are required to determine position in 2D coordinate system. The location coordinates of each sensor are the center of each circle that is drawn for each of sensors. The distance between each of the anchors and the tag represents the radius of circle. Then, 3 circles are drawn by using radius and the center for each sensor and intersection point of these circles represents location.

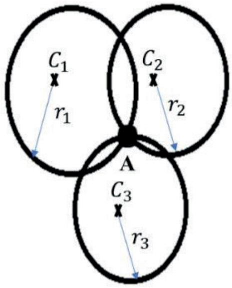


Figure 1: Trilateration algorithm

The geometric demonstration of trilateration algorithm is given in Figure 1. C_1 , C_2 and C_3 are the location of each sensor and represent the center of each circle. Moreover, r_1 , r_2 and r_3 are radius of each circle. They represent the distance between mobile agent and each of the sensor respectively. Circle 1 is drawn by using C_1 and r_1. Similarly, circle 2 is drawn by using C_2 and r_2. Finally, circle 3 is drawn by using C_3 and r_3. Intersection point of these 3 circles represent the location of mobile agent. Therefore, A represents the location of mobile agent in Figure 1.

Trilateration algorithm has some disadvantages. The circles drawn for each sensor often do not intersect at any point, or in some cases, more than one intersection point can emerge. Therefore, the location of mobile agent cannot be determined using trilateration algorithm. Moreover, even just one intersection point emerge, high positioning errors can occur due to high measurement error. Therefore, trilateration algorithm is vulnerable to measurement noise and cannot tolerate measurement noise. Hence, large localization errors occur when trilateration algorithm is used.

Another localization algorithm is multilateration. Circle geometry is used in multilateration algorithm as well. The difference between trilateration and multilateration algorithm is that more than 3 sensors can be used in multilateration algorithm.

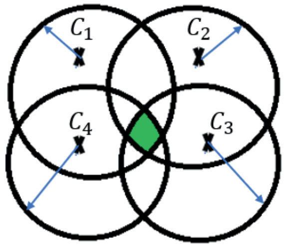


Figure 2: Multilateration algorithm

The geometric demonstration of multilateration algorithm is given in Figure 2. 4 sensors are used for localization in Figure 2 and C_1 , C_2, C_3 and C_4 are the center of each circle which represents the location of each sensor. Also, r_1 , r_2, r_3 and r_4 are radius of each circle which represent the distance between mobile agent and each of sensors, respectively. 4 circles are drawn by using each radius and center data and the location of mobile agent is in the intersection area of 4 circle. Multilateration algorithm suffers from high measurement error. The localization accuracy of multilateration algorithm decreases significantly due to high measurement error.

Triangulation algorithm is another localization algorithm used for indoor positioning. Angle of arrival measurements are used in triangulation algorithm. Angle of arrival is acquired by using directional antennas. Transmitted signal is detected with the help of antenna in the receiver and the phase of the signal is determined. The phases of the signals sent and received by the transmitter and receiver are determined and thus the phase difference can be calculated. The arrival angle of the signal sent from the transmitter to the receiver can be found by using the phase difference, the wavelength of the signal and the distance data between the sensor transmitter and receiver. The direction of radio wave propagation is determined by angle of arrival measurement. This radio wave propagation is used to determine the location of mobile agent in triangulation algorithm. Radio waves are received through the antenna in the sensor receiver. Transmitter is located on mobile agent and transmits radio waves each of receivers. However, the direction of radio waves propagation and angle of arrival of signal to each receiver are different since the sensor receivers are located in different positions. Therefore, the emitted waves intersect with each other and the coordinate of this intersection point expresses the location of the mobile agent. Triangulation algorithm is inappropriate for indoor localization. This is because, angle of arrival measurements is highly inaccurate due to signal reflection and diffraction problems. When signal encounter with obstacles, arrival angle of signal changes. Consequently, localization error of triangulation algorithm increases dramatically due to inaccurate angle of arrival measurements.

Fingerprinting algorithm is another approach for indoor localization. RSS measurements are used in fingerprinting algorithm. Fingerprinting algorithm consists of two stage which are offline and online. In offline stage, RSS fingerprints are collected from multiple transmitters and stored in a database. In online stage, when mobile user moves, it receives signals from multiple transmitter and RSS value is determined. RSS values collected during the online stage is compared with RSS fingerprints to determine location of mobile agent (Ijaz et al., 2013).

RSS value fluctuates due to signal interference. Moreover, when signal encounters obstacles, it reflects, scatters and diffracts. Therefore, signal attenuates and RSS measurements become highly inaccurate indoors. For that reason, fingerprinting algorithms suffer from high localization errors due to RSS measurement error. To improve localization accuracy of fingerprinting algorithm, some filters must be used to reduce measurement noise on RSS measurements (Subhan, Hasbullah, Rozyyev, & Bakhsh, 2011).

Kalman filter based algorithms are used to determine location in indoor area. The most used Kalman filter based algorithms are extended Kalman filter (EKF) and unscented Kalman filter (UKF). There is also, linear Kalman filter algorithm but it is not used in practice frequently because it requires linear motion and measurement models. However, these models are high nonlinear in real world scenarios. EKF and UKF are so famous algorithms for localization thanks to their high positioning performance (Zhang, Zhang, Cui, & Gulliver, 2012). These algorithms produce the optimal state estimate, where the process and measurement noise are white Gaussian noise. Therefore, localization accuracy of EKF and UKF algorithms is much higher than other positioning algorithms such as multilateration, trilateration, fingerprint and triangulation algorithms. Also, Kalman filter based algorithms are more advanced than other algorithms.

EKF is a Bayesian filter used to estimate system states. EKF algorithm is used to estimate location in indoor localization problems. There are some assumptions which EKF algorithms uses for state estimation. Firstly, initial systems state and initial state covariance matrix should be known. Also, measurement and process noise are white Gaussian noise with 0 mean and certain variance. Furthermore, state variables that identify target movement and state equation is Markov process. EKF algorithm produces optimal state estimation under these assumptions (Huang & Wang, 2006). The equations of EKF algorithm are given below (Bar-Shalom et al. 2001).

Let's define the system with dynamics given below.

$$x(k+1) = f(k)x(k) + Bu(k) \quad (1)$$

where, $x(k)$ and $x(k+1)$ are the system state at time k and $(k+1)$, respectively. $f(k)$ is state transition matrix that helps the system to pass from the k to $k+1$. Also, $u(k)$ is the process noise with zero mean additive white Gaussian noise and B is the process noise coefficient matrix.

EKF algorithm consists of prediction and update steps. In the prediction state, the movement of the subject is predicted. Also, the covariance matrix for this state prediction is predicted.

$$\widehat{\mathrm{X}}(\mathrm{k}+1|\mathrm{k}) = \mathrm{F}(\mathrm{k})\widehat{\mathrm{X}}(\mathrm{k}|\mathrm{k}) \quad (2)$$

$$\mathrm{P}(\mathrm{k}+1|\mathrm{k}) = \mathrm{F}(\mathrm{k})\mathrm{P}(\mathrm{k}|\mathrm{k})\mathrm{F}(\mathrm{k})' + \mathrm{Q}(\mathrm{k}) \quad (3)$$

In Equation 2, $\widehat{\mathrm{X}}(\mathrm{k}|\mathrm{k})$ is the state estimate at time k and $\widehat{\mathrm{X}}(\mathrm{k}+1|\mathrm{k})$ is the state prediction at time $k+1$. Also, F is the state transition matrix and it describes how the state changes from step k to k+1.

State prediction contains some uncertainty. This uncertainty is called as state prediction covariance and modelled a given in equation 3. In Eq 3, Q(k) is process noise covariance, F is state transition matrix, $P(k|k)$ is state covariance at time k and $P(k+1|k)$ is state prediction covariance. Process noise covariance is an important parameter of EKF algorithm since it effects Kalman gain.

In prediction step of EKF algorithm, sensor measurement is also predicted. To predict sensor measurement, Eq.4 is used.

$$\hat{Z}(k+1|k) = h[k+1, \hat{X}(k+1|k)] \tag{4}$$

The difference between sensor measurement and measurement prediction is called as innovation and modelled as in equation 5. In Eq. 5, $Z(k+1)$ is sensor measurement at time $k+1$.

$$V(k+1) = Z(k+1) - \hat{Z}(k+1|k) \tag{5}$$

Innovation involves some uncertainty because of measurement prediction used in calculation of innovation. This uncertainty is called as innovation covariance or residual covariance and calculated as in equation 6.

$$S(k+1) = R(k+1) + H(k+1)P(k+1|k)H(k+1)' \tag{6}$$

In Eq.6, H is the Jacobian matrix and is calculated as in equation 7 below. Also F is the Jacobian matrix of state transition matrix.

$$H(k+1) = \frac{dh(k+1)}{dx}|x = \hat{x}(k+1|k) \tag{7}$$

$$F(k) = \frac{df(k)}{dx}|x = \hat{x}(k|k) \tag{8}$$

In the update step, state prediction is updated using sensor measurements. In this step, Kalman gain is calculated using equation 9. Kalman gain indicates that how much EKF algorithm trust sensor measurements when updated predicted state. Therefore, choosing Kalman gain optimally is important for state estimation with small error.

$$W(k+1) = P(k+1|k)H(k+1)'S(k+1)^{-1} \tag{9}$$

After Kalman gain is calculated, updated state estimate and updated state covariance are calculated by using equation 10 and equation 11, respectively.

$$\hat{X}(k+1|k+1) = \hat{X}(k+1|k) + W(k+1)V(k+1) \tag{10}$$

$$P(k+1|k+1) = P(k+1|k) - W(k+1)S(k+1)W(k+1)' \tag{11}$$

EKF algorithm is used when state or sensor measurement equation are nonlinear. In the EKF algorithm, these nonlinear functions are linearized by using the Taylor series. Jacobian matrix is calculated with Taylor series expansion. The Taylor series expansion has infinite terms. However, this expansion is expressed with only the first two terms and the Jacobian matrix is calculated. Therefore, linearization errors occur due to expressing an expansion with infinite terms with only its first two terms. This situation reduces the performance of the EKF algorithm and causes the filter divergence in cases where nonlinearity is high. Consequently, this is a significant disadvantage of the EKF algorithm. On the other hand, the UKF algorithm is used as a solution to these problems caused by linearization occurring in the EKF algorithm (Huang & Wang, 2006). The UKF is another type of the Kalman filter algorithm used for state estimation in nonlinear systems. It's particularly useful in scenarios where the system dynamics are highly nonlinear. UKF algorithm works based on unscented transformation (UT) which is used for calculating the mean and covariance of random variable (Wan & Van Der Merwe, 2000). In the UT, sigma points are selected from the probability density function of the random variable to be estimated. These sigma points are expressed with mean and covariance values. Because a random variable is expressed by the first two moments, which are mean and variance. A sample space is created with the selected sigma points. By passing these sigma points through the state transition function and propagating in time, the equations of the UKF algorithm are run and estimates of the mean and covariance values of the random variable are obtained. This random variable is the state variable which generally contains position and velocity of the mobile agent that is desired to be localized. The mean of random variable represents the location and the covariance represents estimation of covariance. Therefore, when the random variable representing this state variable is estimated with the UKF algorithm, the state variable consisting of the position and velocity components of the object is estimated, and thus the position of the object is estimated. Since the location of the object whose location is desired to be determined is also a random variable in a statistical sense, the average value of the random variable obtained as a result of the UKF algorithm is the location estimate of the mobile agent and the covariance value is the estimation covariance.

The formulas involved in the UKF algorithm are given below (Wan & Van Der Merwe, 2000). Initial states and initial state covariance matrix have to be determined at the beginning of UKF algorithm. The algorithm initialized with defining these parameters.

Initialization of UKF Algorithm:

$$\hat{x}_0 = E[x_0] \tag{12}$$

$$P_0 = E[(x_0 - \hat{x}_0)(x_0 - \hat{x}_0)^T] \tag{13}$$

$$\hat{x}_0{}^a = E[x^a] = [\hat{x}_0{}^T 0\ 0]^T \tag{14}$$

$$P_0{}^a = E[(x_0{}^a - \hat{x}_0{}^a)(x_0{}^a - \hat{x}_0{}^a)^T] = \begin{matrix} P_0 & 0 & 0 \\ 0 & P_v & 0 \\ 0 & 0 & P_n \end{matrix} \tag{15}$$

Sigma Points:

$$\chi_{k-1}^a = [\hat{x}_{k-1}^a \quad \hat{x}_{k-1}^a \pm \sqrt{(L+\lambda)P_{k-1}^a}] \tag{16}$$

Time Update:

$$\chi_{k|k-1}^x = F[\chi_{k-1}^x, \chi_{k-1}^v] \tag{17}$$

$$x_k^- = \sum_{i=0}^{2L} w_i^{(m)} \chi_{i,k|k-1}^x \tag{18}$$

$$P_k^- = \sum_{i=0}^{2L} w_i^{(c)} [\chi_{i,k|k-1}^x - x_k^-][\chi_{i,k|k-1}^x - x_k^-]^T \tag{19}$$

$$\Upsilon_{k|k-1} = H[\chi_{k|k-1}^x, \chi_{k-1}^n] \tag{20}$$

$$y_k^- = \sum_{i=0}^{2L} w_i^{(m)} \Upsilon_{i,k|k-1}^x \tag{21}$$

Measurement Update:

$$P_{\tilde{y_k}\tilde{y_k}} = \sum_{i=0}^{2L} w_i^{(c)} \left[\Upsilon_{i,k|k-1}^{x} - y_k^{-}\right]\left[\Upsilon_{i,k|k-1}^{x} - y_k^{-}\right]^{T} \quad (22)$$

$$P_{x_k y_k} = \sum_{i=0}^{2L} w_i^{(c)} \left[\chi_{i,k|k-1}^{x} - x_k^{-}\right]\left[\Upsilon_{i,k|k-1}^{x} - y_k^{-}\right]^{T} \quad (23)$$

$$\kappa = P_{x_k y_k} P_{\tilde{y_k}\tilde{y_k}}{}^{-1} \quad (24)$$

$$\hat{x}_k = x_k^{-} + \kappa(y_k - y_k^{-}) \quad (25)$$

$$P_k = P_k^{-} - \kappa P_{\tilde{y_k}\tilde{y_k}} \kappa^{T} \quad (26)$$

where x^a is equal to $[x^T \quad v^T \quad n^T]^T$ and χ^a is equal to $\left[\chi^{x^T} \quad \chi^{v^T} \quad \chi^{n^T}\right]^T$.

Main formulas involved in the UKF algorithm for state estimation describe how to choose and propagate the sigma points, predict the next state, and update the state estimate based on measurements using Kalman gain. Sigma points are chosen around the current state estimate to capture the uncertainty in the state as given in Equation 16. In time update step or prediction step, covariance matrix and next state of the system are predicted using process model and sigma points are propagated through this model for prediction. In measurement update step, state prediction is updated using sensor measurements and UKF algorithm produces its state estimate. Also, state estimation covariance is updated. For that, Kalman gain is used. The Kalman gain indicates how much UKF algorithm gives weight to sensor measurement and state prediction to produce state estimate. Since, Kalman gain determines the estimation accuracy of UKF algorithm, it is important to choose Kalman gain optimally for state estimation with low error.

The difference between the EKF and the UKF stems from the fact that the mean and covariance values of the random variable are advanced differently in time within the algorithm. In the EKF algorithm, the Jacobian matrix is calculated by expanding the Taylor series to linearize non-linear functions. However, in the UKF algorithm, while the initial state variables of the object and the initial covariance values of these state variables are advanced in time, no Taylor series expansion or Jacobian matrix calculation is performed. In the

UKF algorithm, the initial state variables and the initial covariance values of these state variables are propagated in time using the unscented transformation method to obtain an estimate. Therefore, in the UKF algorithm, there are no errors due to linearization and hence the estimation error of UKF algorithm is lower than EKF algorithm. As a result, UKF algorithm performs better than EKF algorithm for indoor localization problems.

Another algorithm that is used for indoor localization is particle filter. The Particle Filter (PF) is a recursive Bayesian filter used for estimating the state of a dynamic system. It's useful when the state-space model is nonlinear and/or non-Gaussian. The formulas of PF algorithm are given below (Gustafsson, 2010).

Initialization of PF Algorithm: In this step, a set of particles are generated and initial weights are assigned.

$$x_i \sim p_{x_0} \quad i = 1, \dots, N \text{ and } w_{1|0}^i = \frac{1}{N} \tag{27}$$

Measurement Update: For $i = 1, \dots, N$

$$w_{k|k}^i = \frac{1}{c_k} w_{k|k-1}^i p(y_k | x_k^i) \tag{28}$$

N is the number of particles, in equations 27 and 28. Also, in equation 28, c_k is the normalization weight and calculated as given in equation 29.

$$c_k = \sum_{i=1}^{N} w_{k|k-1}^i p(y_k | x_k^i) \tag{29}$$

Estimation: In estimation step, the filtering density, which is $\hat{p}(x_{1:k} | y_{1:k})$ is calculated as given below. Also, the mean is calculated by using Equation 31.

$$\hat{p}(x_{1:k} | y_{1:k}) = w_{k|k}^i \delta(x_{1:k} - x_{1:k}^i) \tag{30}$$

$$\hat{x}_{1:k} \approx \sum_{i=1}^{N} w_{k|k}^i \, x_{1:k}^i \tag{31}$$

Resampling: In every time step, N samples are taken and replaced with the set $x_{1:k}^{i}$. The probability of taking sample i is $w_{k|k}^{i}$. $w_{k|k}^{i}$ is set to $\frac{1}{N}$.

Time Update: In time update step, the estimation of PF algorithm is produced. Also, importance weight which is $w_{k+1|k}^{i}$ is updated for the next iteration of the algorithm.

$$w_{k+1|k}^{i} = w_{k|k}^{i} \frac{p(x_{k+1}^{i}|x_{k}^{i})}{q(x_{k+1}^{i}|x_{k}^{i}, y_{k+1})} \quad (32)$$

The PF algorithm essentially maintains a set of weighted samples or particles that represent the probability distribution of the system's state. By propagating these particles through the motion model, updating their weights based on sensor measurements, and resampling them according to their likelihood, the PF provides an estimate of the system state.

3. CONCLUSION

In this chapter, different sensors and algorithms used for indoor localization is discussed. Wi-Fi, Bluetooth, RFID, Zigbee, UWB and ultrasonic sensors have been compared each other in terms of some criteria such as, accuracy, coverage area, cost and power consumption. UWB sensor is the most suitable sensor for indoor localization among other sensors. This is because, UWB sensor signal has large bandwidth. The signals of UWB sensors have frequency diversity due to large bandwidth. Therefore, UWB sensors are resistant to multipath propagation, signal interference, reflection and scattering due to frequency diversity. Moreover, some algorithms such as trilateration, multilateration, triangulation, fingerprinting and filter-based algorithms are discussed for indoor localization. The accuracy of trilateration, multilateration, triangulation, fingerprinting algorithms is low because they cannot tolerate measurement error. Therefore, these algorithms are not appropriate for indoor localization since the accuracy of these algorithms is low. On the other hand, filter-based algorithms such as, EKF, UKF and particle filter perform better than other algorithms. Filter based algorithms can filter measurement noise and provide much more accurate localization in complex indoor environment. Also, among filter-based algorithms, UKF algorithm provides higher accuracy than EKF algorithm. In addition, particle filter is advantageous when uncertainties have non-Gaussian or multimodal distributions. It uses a set of particles for state estimation. This allows particle filter to handle with complex distributions that might arise in indoor localization scenarios better than EKF and UKF algorithms.

REFERENCES

Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M., & Al-Khalifa, H. (2016). Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances. *Sensors*, *16*(5), 707. https://doi.org/10.3390/s16050707

Asaad, S. M., & Maghdid, H. S. (2022). A Comprehensive Review of Indoor/Outdoor Localization Solutions in IoT era: Research Challenges and Future Perspectives. *Computer Networks*, *212*, 109041. https://doi.org/10.1016/j.comnet.2022.109041

Azevedo, J. A., & Santos, F. E. (2022). Performance Evaluation of Directional Antennas in ZigBee Networks under NLOS Propagation Conditions. *Electronics*, *11*(13), 2032. https://doi.org/10.3390/electronics11132032

Bar–Shalom, Y., Li, X. R., Kirubarajan, T. (2001). *Estimation with Application to Tracking and Navigation.* America: Wiley – Interscience Publication, 386.

Basiri, A., Lohan, E. S., Moore, T., Winstanley, A., Peltola, P., Hill, C., Figueiredo E Silva, P. (2017). Indoor location based services challenges, requirements and usability of current solutions. *Computer Science Review*, *24*, 1–12. https://doi.org/10.1016/j.cosrev.2017.03.002

Booranawong, A., Sengchuai, K., Buranapanichkit, D., Jindapetch, N., & Saito, H. (2021). RSSI-Based Indoor Localization Using Multi-Lateration With Zone Selection and Virtual Position-Based Compensation Methods. *IEEE Access*, *9*, 46223–46239. https://doi.org/10.1109/ACCESS.2021.3068295

Botler, L., Spork, M., Diwold, K., & Romer, K. (2020). Direction Finding with UWB and BLE: A Comparative Study. *2020 IEEE 17th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*, 44–52. Delhi, India: IEEE. https://doi.org/10.1109/MASS50613.2020.00016

Bouet, M., & Dos Santos, A. L. (2008). RFID tags: Positioning principles and localization techniques. *2008 1st IFIP Wireless Days*, 1–5. Dubai, United Arab Emirates: IEEE. https://doi.org/10.1109/WD.2008.4812905

Chang, Y., Cheng, Y., Manzoor, U., & Murray, J. (2023). A review of UAV autonomous navigation in GPS-denied environments. *Robotics and*

Autonomous Systems, *170*, 104533. https://doi.org/10.1016/j.robot.2023.104533

Costin, A. M., & Teizer, J. (2015). Fusing passive RFID and BIM for increased accuracy in indoor localization. *Visualization in Engineering*, *3*(1), 17. https://doi.org/10.1186/s40327-015-0030-6

Crețu-Sîrcu, A. L., Schiøler, H., Cederholm, J. P., Sîrcu, I., Schjørring, A., Larrad, I. R., Madsen, O. (2022). Evaluation and Comparison of Ultrasonic and UWB Technology for Indoor Localization in an Industrial Environment. *Sensors*, *22*(8), 2927. https://doi.org/10.3390/s22082927

Deak, G., Curran, K., & Condell, J. (2012). A survey of active and passive indoor localisation systems. *Computer Communications*, *35*(16), 1939–1954. https://doi.org/10.1016/j.comcom.2012.06.004

Donelli, M., & Manekiya, M. (2018). Development of Environmental Long Range RFID Sensors Based on the Modulated Scattering Technique. *Electronics*, *7*(7), 106. https://doi.org/10.3390/electronics7070106

Dong, Z. Y., Xu, W. M., & Zhuang, H. (2019). Research on ZigBee Indoor Technology Positioning Based on RSSI. *Procedia Computer Science*, *154*, 424–429. https://doi.org/10.1016/j.procs.2019.06.060

Farid, Z., Nordin, R., & Ismail, M. (2013). Recent Advances in Wireless Indoor Localization Techniques and System. *Journal of Computer Networks and Communications*, *2013*, 1–12. https://doi.org/10.1155/2013/185138

Ferreira, A. F. G., Fernandes, D. M. A., Catarino, A. P., & Monteiro, J. L. (2017). Localization and Positioning Systems for Emergency Responders: A Survey. *IEEE Communications Surveys & Tutorials*, *19*(4), 2836–2870. https://doi.org/10.1109/COMST.2017.2703620

Gargalakos, M. (2021). The role of unmanned aerial vehicles in military communications: Application scenarios, current trends, and beyond. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, 154851292110316. https://doi.org/10.1177/15485129211031668

Gentner, C., & Jost, T. (2013). Indoor positioning using time difference of arrival between multipath components. *International Conference on Indoor*

Positioning and Indoor Navigation, 1–10. Montbeliard, France: IEEE. https://doi.org/10.1109/IPIN.2013.6817908

Gustafsson, F. (2010). Particle filter theory and practice with positioning applications. *IEEE Aerospace and Electronic Systems Magazine*, *25*(7), 53–82. https://doi.org/10.1109/MAES.2010.5546308

Hazas, M., & Hopper, A. (2006). Broadband ultrasonic location systems for improved indoor positioning. *IEEE Transactions on Mobile Computing*, *5*(5), 536–547. https://doi.org/10.1109/TMC.2006.57

Huang, B., & Wang, Q.-G. (2006). Overview of emerging bayesian approach to nonlinear system identification.

Ijaz, F., Yang, H. K., Ahmad, A. W., & Lee, C. (2013). Indoor positioning: A review of indoor ultrasonic positioning systems.

Li, T., Ai, S., Tateno, S., & Hachiya, Y. (2019). Comparison of Multilateration Methods Using RSSI for Indoor Positioning System. *2019 58th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, 371–375. Hiroshima, Japan: IEEE. https://doi.org/10.23919/SICE.2019.8859906

Liu, H., Darabi, H., Banerjee, P., & Liu, J. (2007). Survey of Wireless Indoor Positioning Techniques and Systems. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)*, *37*(6), 1067–1080. https://doi.org/10.1109/TSMCC.2007.905750

Mellios, E., Goulianos, A., Dumanli, S., Hilton, G., Piechocki, R., & Craddock, I. (2014). Off-body Channel Measurements at 2.4 GHz and 868 MHz in an Indoor Environment. *Proceedings of the 9th International Conference on Body Area Networks*. Presented at the 9th International Conference on Body Area Networks, London, Great Britain. London, Great Britain: ICST. https://doi.org/10.4108/icst.bodynets.2014.257000

Mok, E., & Retscher, G. (2007). Location determination using WiFi fingerprinting versus WiFi trilateration. *Journal of Location Based Services*, *1*(2), 145–159. https://doi.org/10.1080/17489720701781905

Obeidat, H., Alabdullah, A. A. S., Ali, N. T., Asif, R., Obeidat, O., Bin-Melha, M. S. A., Excell, P. (2019). Local Average Signal Strength Estimation for Indoor

Multipath Propagation. *IEEE Access*, *7*, 75166–75176. https://doi.org/10.1109/ACCESS.2019.2918178

Pratama, M. R. W., Abdurohman, M., & Putrada, A. G. (2021). Vehicle Blind Spot Area Detection Using Bluetooth Low Energy and Multilateration. *2021 9th International Conference on Information and Communication Technology (ICoICT)*, 165–169. Yogyakarta, Indonesia: IEEE. https://doi.org/10.1109/ICoICT52021.2021.9527516

Sesyuk, A., Ioannou, S., & Raspopoulos, M. (2022). A Survey of 3D Indoor Localization Systems and Technologies. *Sensors*, *22*(23), 9380. https://doi.org/10.3390/s22239380

Shen, Y., Hwang, B., & Jeong, J. P. (2020). Particle Filtering-Based Indoor Positioning System for Beacon Tag Tracking. *IEEE Access*, *8*, 226445–226460. https://doi.org/10.1109/ACCESS.2020.3045610

Shoemake, M. B. (2001). *Wi-FI (IEEE 802.11b) and Bluetooth17.*

Sohan, A. A., Ali, M., Fairooz, F., Rahman, A. I., Chakrabarty, A., & Kabir, Md. R. (2019). Indoor Positioning Techniques using RSSI from Wireless Devices. *2019 22nd International Conference on Computer and Information Technology (ICCIT)*, 1–6. Dhaka, Bangladesh: IEEE. https://doi.org/10.1109/ICCIT48885.2019.9038591

Subhan, F., Hasbullah, H., Rozyyev, A., & Bakhsh, S. T. (2011). Indoor positioning in Bluetooth networks using fingerprinting and lateration approach. *2011 International Conference on Information Science and Applications*, 1–9. Jeju Island: IEEE. https://doi.org/10.1109/ICISA.2011.5772436

Wan, E. A., & Van Der Merwe, R. (2000). The unscented Kalman filter for nonlinear estimation. *Proceedings of the IEEE 2000 Adaptive Systems for Signal Processing, Communications, and Control Symposium (Cat. No.00EX373)*, 153–158. Lake Louise, Alta., Canada: IEEE. https://doi.org/10.1109/ASSPCC.2000.882463

Wisitpongphan, N. (2013). Wireless Sensor Network Planning for Fingerprint Based Indoor Localization Using ZigBee: Empirical Study. In P. Meesad, H. Unger, & S. Boonkrong (Eds.), *The 9th International Conference on Computing and*

InformationTechnology (IC2IT2013) (pp. 83–92). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-37371-8_12

Xia, S., Liu, Y., Yuan, G., Zhu, M., & Wang, Z. (2017). Indoor Fingerprint Positioning Based on Wi-Fi: An Overview. *ISPRS International Journal of Geo-Information*, *6*(5), 135. https://doi.org/10.3390/ijgi6050135

Yassin, A., Nasser, Y., Awad, M., Al-Dubai, A., Liu, R., Yuen, C., … Aboutanios, E. (2017). Recent Advances in Indoor Localization: A Survey on Theoretical Approaches and Applications. *IEEE Communications Surveys & Tutorials*, *19*(2), 1327–1346. https://doi.org/10.1109/COMST.2016.2632427

Yassin, M., & Rachid, E. (2015). A survey of positioning techniques and location based services in wireless networks. *2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES)*, 1–5. Kozhikode, India: IEEE. https://doi.org/10.1109/SPICES.2015.7091420

Zafari, F., Gkelias, A., & Leung, K. K. (2019). A Survey of Indoor Localization Systems and Technologies. *IEEE Communications Surveys & Tutorials*, *21*(3), 2568–2599. https://doi.org/10.1109/COMST.2019.2911558

Zayets, A., & Steinbach, E. (2017). Robust WiFi-based indoor localization using multipath component analysis. *2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, 1–8. Sapporo: IEEE. https://doi.org/10.1109/IPIN.2017.8115943

Zhang, L., Zhang, H., Cui, X. R., & Gulliver, T. A. (2012). Ultra Wideband Indoor Positioning Using Kalman Filters. *Advanced Materials Research*, *433–440*, 4207–4213. https://doi.org/10.4028/www.scientific.net/AMR.433-440.4207

Zhilenkov, A. A., Chernyi, S. G., Sokolov, S. S., & Nyrkov, A. P. (2020). Intelligent autonomous navigation system for UAV in randomly changing environmental conditions. *Journal of Intelligent & Fuzzy Systems*, *38*(5), 6619–6625. https://doi.org/10.3233/JIFS-179741

CHAPTER 3

MIT APP INVENTOR: OVERVIEW, INTRODUCTION, AND APPLICATION DESIGN EXAMPLE

Ahmet TOP[1]

1 Dr.Ahmet TOP
Department of Electrical and Electronics Engineering, Faculty of Technology, Fırat University, Turkey, ORCID ID: http://orcid.org/0000-0001-6672-2119

1. INTRODUCTION

Interest in mobile technologies is increasing day by day, thanks to their portability, ease of use, and functionality [1]. According to statistics, while the number of mobile users worldwide was 7.1 billion in 2021, this number is expected to reach 7.49 billion in 2025 [2]. Considering that the world population exceeds 8 billion [3], this number seems to be quite high. Nowadays, smartphones are used for many transactions and mobile users are looking for mobile applications that suit their needs. At this point, mobile applications that suit the needs need to be developed and presented to users. Although some devices have pre-installed applications, users can choose new applications through app stores such as the Google Play store for Android, the Apple App Store for iOS, or third-party providers such as the Amazon Appstore [2]. When the number of mobile applications developed for smartphones is examined, it is seen that there are 3.55 million applications on Google Play, 1.6 million on the Apple App Store, and 476 thousand applications on the Amazon Store in the third quarter of 2022 [4]. In light of this data, it can be seen that millions of applications have been developed and the mobile platform for which the most applications have been developed is Android. Looking at these numbers and general statistics, it is understood that Android phone use is more common [5]. For this purpose, there are many development environments such as MIT App Inventor, Thunkable, Kodular, and Android Studio for those who want to develop applications that can run on the Android system.

MIT App Inventor, developed by Google and transferred to the MIT Mobile Learning Center, is a platform used to develop mobile applications with visual blocks without the need for programming knowledge [6]. Thunkable is an App Inventor-like platform where you can develop mobile applications without writing code [7]. Kodular is also a programming environment based on App Inventor [8]. This platform states that it allows you to easily develop Android applications with a block-based editor without the need for coding skills. Android Studio is the official Integrated

Development Environment (IDE) based on IntelliJ IDEA, used to develop applications for smartphones running Android. Since it is an official development environment, it is anticipated that it will provide an advantage in the integration of Android system innovations. In Android Studio IDE; It has a flexible Gradle-based structure, an enriched emulator, GitHub integration, and software support in Kotlin and Java [9].

It is difficult for developers to choose the appropriate platform among them. There are studies in the literature examining mobile application development environments that can be used by those who want to develop mobile applications when making this choice. Some researchers have also conducted experimental studies on this subject that evaluate mobile content using certain performance criteria. Yılmaz and Üstün comparatively examined MIT App Inventor, Thunkable, and Kodular, which are block-based mobile application development platforms, in two stages. In the first phase, they compared the general features of mobile application development platforms. In the second stage, the same game application was developed with each mobile application development platform, and the platforms were compared through the developed application [10].

When the determined platforms are evaluated in terms of the operating system on which the application is developed, the application developed with the Thunkable platform offers output for both iOS and Android operating systems. In this way, it is an advantage for software developers who want to develop applications to not create different software for each operating system. It can also be said that providing output for two operating systems is important for efficiency.

It has been observed that there is no emulator support on the Kodular platform. The emulator allows users to use their desired phones as virtual devices and test their applications on these devices [11]. It can be said that being able to test the developed applications with an emulator without installing them on the phone saves time and work. On the Kodular platform, users must install third-party software or have a phone to try the applications. It can be said that this situation is a disadvantage.

All of the designated platforms have introductory training and community support. Documents prepared in the introductory training sections on App Inventor and Thunkable platforms are supported with pictures, moving pictures, and videos. The fact that sample projects and projects made by users are shared with other users means that it will be useful for other users to see the problem-solving methods and adapt them to the solutions of their problems.

When the games developed in terms of the number of codes are examined, it is seen that the least number of code blocks were used on the App Inventor and Kodular platforms. Simplicity, which depends on features such as the number of codes and the number of functions in the technically developed software, is one of the most important objectives for the application to be considered good [12]. The fact that the minimum number of code blocks is used on the App Inventor and Kodular platforms can be interpreted as these platforms being suitable for simpler application development.

When the determined platforms are evaluated in terms of memory usage and storage space, it is understood that the application developed on the App Inventor platform has the lowest storage space usage, while the application developed on the Thunkable platform uses 7.78 times more storage space than App Inventor. In their study, Willocx et al. [13] stated that in evaluating mobile applications, the first thing to do is to measure the space occupied by the installed application on the device and that the area occupied by the application is especially important for low-quality devices with limited resources. Pekyürek et al. performed the same application in both MIT App Inventor and Android Studio examined the CPU and RAM loads and emphasized the importance of the memory level used by a developed mobile application [14]. The maximum memory usage of the application developed on the Thunkable platform is 3.9 times higher than the application developed on the App Inventor platform. Although it is considered a negligible difference for small-scale applications, it can be commented that it will pose a problem for programmers who want to develop more comprehensive applications in Thunkable. This appears to be the biggest disadvantage of the Thunkable platform [10].

In this study, information about MIT App Inventor, one of the Android application development platforms, is given and a brief introduction about the use of the platform is made. Additionally, an application that automatically calculates the motor power of a four-wheeled mobile robot has been implemented on the platform.

2. MIT App Inventor

2.1. MIT App Inventor Overview

MIT App Inventor was first provided by the Google company and is now maintained by the Massachusetts Institute of Technology (MIT) [15]. MIT App Inventor is a web-based and free-access development platform that can create and design fully functional Android applications and provides a graphical interface to users [16,17]. It uses a block-based programming language built on Google Blockly [18] and inspired by languages such as StarLogo TNG [19] and Scratch [20,21]. In the last decade, MIT App Inventor has been used for Android applications in various projects such as automation systems [22], smart switches [23], games and quizzes [24], smart home control [25-28], and education [29].

2.2. History of MIT App Inventor

Hal Abelson, who previously taught a course on mobile programming at MIT, came up with the idea for App Inventor in 2007. At the same time, in 2007, Google announced the Android operating system to the public [30]. Abelson and Mark Friedman from Google began developing an intermediate language between the block language and the Java APIs for Android, called Yet Another Intermediate Language (YAIL). The project aimed to help young students program for Android. Abelson and Friedman built YAIL from a block-based language based on OpenBlocks [31] and took the design from StarLogo TNG [32]. The Google version of the project was terminated at the end of 2011, but the educational technology was transferred to MIT so that the development and training aspects could continue [33]. Prof. Abelson joined Prof. Eric Klopfer from the Scheller Teacher Education Program laboratory and Prof. Mitch Resnick from the MIT Media Lab to form a group.

The MIT team also hosted workshops training teachers in App Inventor pedagogy, primarily in the northeastern United States. To encourage self-directed learning, they now focus on guided and open exploration of the materials rather than providing students with step-by-step instructions. Technical development at MIT is focused on the development of new components including robotics (LEGO™EV3), cloud-focused data storage (CloudDB), and visualization (Map). The App Inventor team has also developed IoT-related extensions so students can interact with physical hardware outside of their mobile devices and take advantage of the growing array of small computer motherboards such as Arduino, BBC micro:bit, and Raspberry Pi. To this day, the team continues its development work by creating complementary educational materials in parallel [30].

2.3. Introduction to MIT App Inventor

When the URL address in the source [34] is typed into the internet browser address bar, the screen in Figure 1 opens. Here you can get general information about App Inventor, access resources and documents, get information about various news and events, and share about applications by becoming a member of app communities.

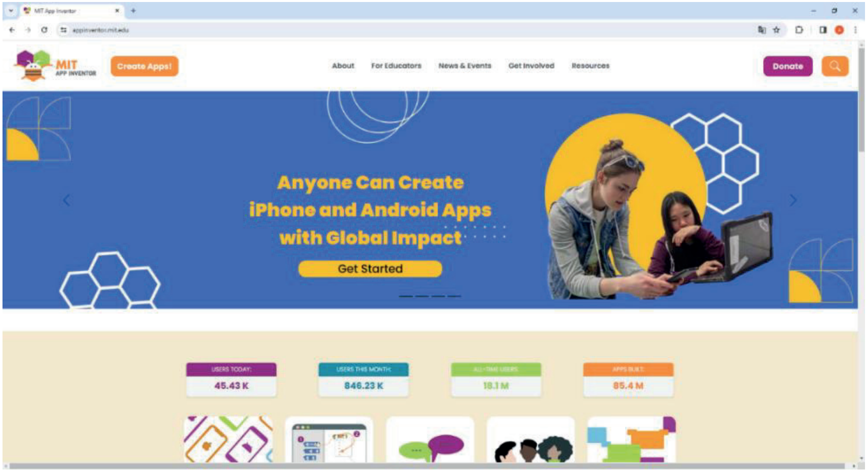


Figure 1. MIT App Inventor home screen

There is a button "Create Apps!" in the upper left corner of the screen. When the button is pressed, you are asked to log in from a Google account, as seen in Figure 2.

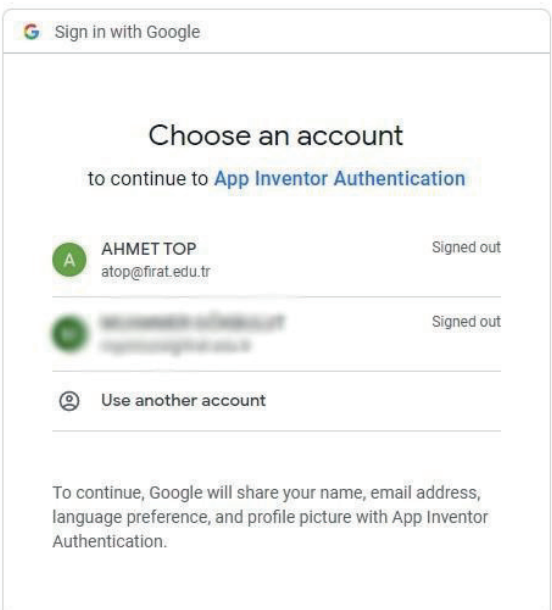


Figure 2. Login screen

After logging in from the account, the application design login screen in Figure 3 appears. The menus in the upper left corner of this screen are zoomed in and shown in the figure. These menus and their contents are explained below.

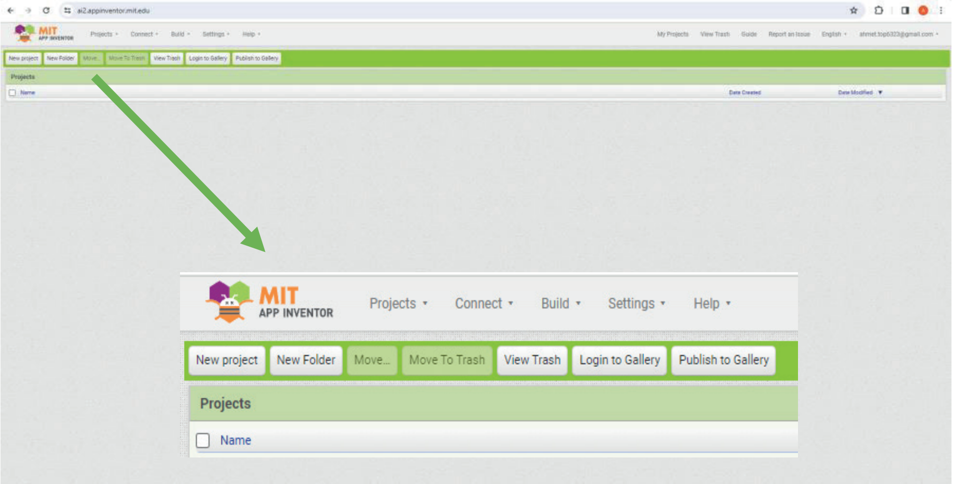


Figure 3. Project launch page

- Projects: It is used to see all your projects, to create a new project, and to transfer projects from your computer or storage to the app Inventor.
- Connect: Runs the project in the AI Companion application shown in Figure 4, in the emulator or on a device connected via USB.
- Build: For the developed application to be permanently installed on the smart device, it is compiled in .apk or .aab formats. When the application is compiled, a URL address is created and a QR code is generated. These are opened on the smart device and the application installation process is carried out directly.
- Settings: Project-related settings are made.
- Help: There is helpful content on the topics in the menu.

There are quick-access buttons at the bottom of these menus. These buttons and their functions are as follows.

- New project: Allows a new project to be opened. When the button is pressed, the screen in Figure 5 opens and you can give any name to the project here.
- New folder: Used to create a new file.
- Move: Moves projects to other files.
- Move to Trash: Performs the deletion of the selected project.
- View Trash: Shows the trash can.
- Login To Gallery: Performs the process of logging into the gallery.
- Publish to Gallery: Allows the project to be published in the gallery.

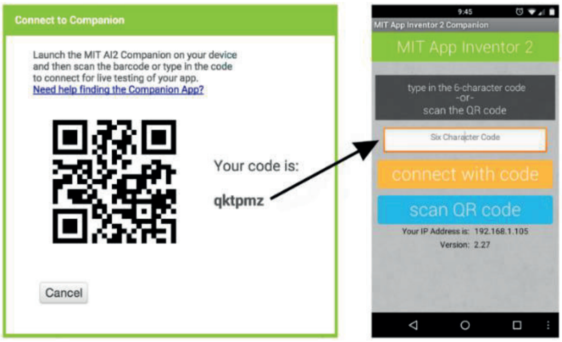


Figure 4. AI companion

When the "AI Companion" button in the Connect menu is pressed, it generates a code as seen on the left in Figure 4. The MIT App Inventor 2 Companion application is installed on the smart device and when this code is written on the screen on the right, the developed application is opened on the smart device. Changes made in the application can also be viewed directly on the smart device.

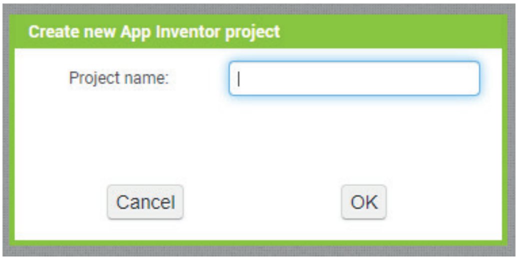


Figure 5. Project name input screen

The project preparation page that appears when a new project is opened consists of two parts. These are the design interface and the block editor. The design interface shown in Figure 6 is the part where screens and contents are created.

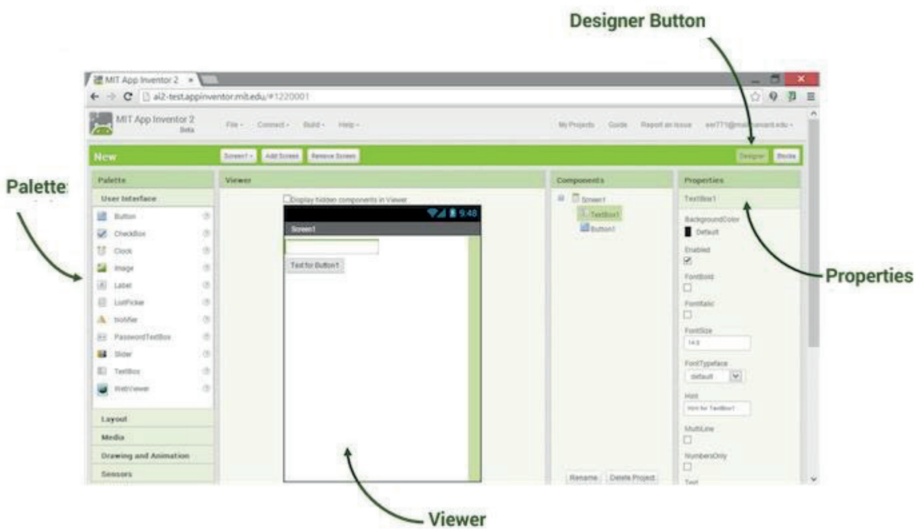


Figure 6. MIT App Inventor design interface

The sections in the design interface and the functions of these sections are given below [35]:

- Palette: This is the section where components are added to the Viewer area by drag and drop method.
- Designer: Used to open the design area.
- Properties: This is the section where component properties are edited.
- Viewer: This is the part that shows how to view the components.

The block editor, shown in Figure 7, is an environment where designers can visually organize the logic of their application with color-coded blocks that interlock like puzzle pieces to describe the program [36]. This allows users to create a specific or general program while avoiding many of the potential errors.

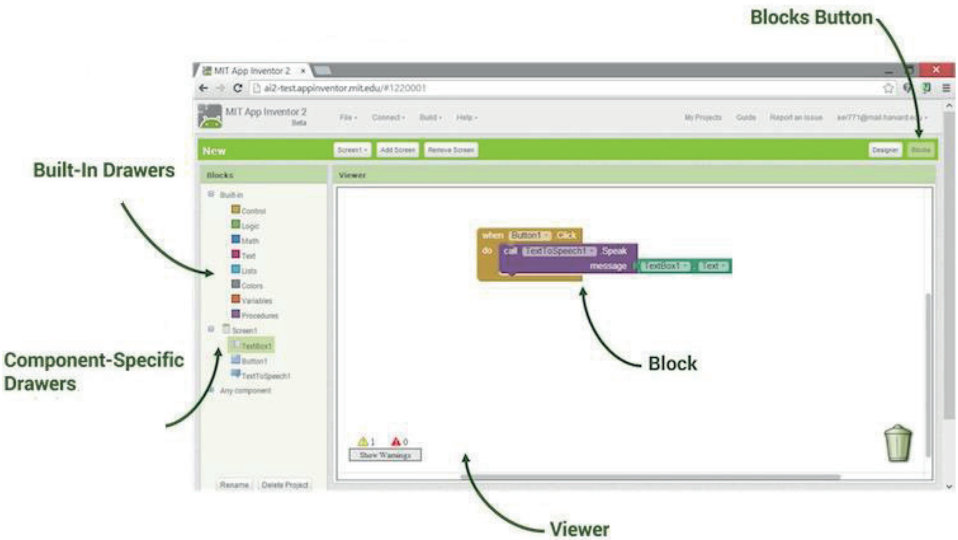


Figure 7. MIT App Inventor block editor

The sections and their functions in the block editor interface are as follows:

- Component-Specific Drawers: This is the section containing the code blocks that can be applied to the components on the design screen.
- Block-In Drawers: This is the section where general code blocks are located.
- BlocksButton: This is the button to open the block editor.
- Blocks Viewer: This is the area where code blocks can be dragged and dropped.
- Block: Code blocks used for software [14].

3. Design of Motor Torque Calculation Application For Robots

3.1. Motor Torque Calculation

One of the most important issues when choosing a motor for mobile robots is determining the weight of the robot and calculating the load torque on the wheels. The maximum slope (degree) that the robot can climb during movement and the movement acceleration (m/s^2) value while advancing on this slope must also be determined by the designer. According to these criteria, the torque values that the motors to be used in the robot should have been calculated as follows, considering the situation in Figure 8.

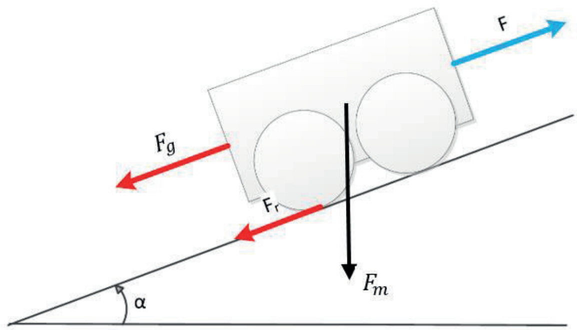


Figure 8. Forces acting on the robot

where F_m is the force generated by the weight of the robot, F_g is the resultant of the force generated by this weight acting in the movement plane, F_r is the friction force and F is the force that must be applied for the robot to move.

The Society for Automotive Engineers (SAE) reported that, in their tests in SAE J1269 and SAE J2452 standards for the rolling friction coefficients of wheels, this friction coefficient for the newest passenger wheels was between 0.007 and 0.014 [37]. Considering this report, an average value can be determined by the designer. The friction force acting on all wheels is calculated as in Equation 1.

$$F_r = \mu_r mgCos(\alpha) \tag{1}$$

In this formula, m is the mass of the robot, g is the gravitational acceleration (9.81m/s^2), α is the tilt angle, and μ_r is the rolling friction coefficient. The total weight is calculated by taking into account all weights that may affect the robot, such as the robot's chassis, motors, wheels, sensors, and electronic circuits, and the mass in kg is taken into account. In addition to the friction force, the vehicle's weight creates a direct force F_m due to gravitational acceleration. The effect of this force on robot movement is as in Equation 2.

$$F_g = mgSin(\alpha) \tag{2}$$

These two forces are in the opposite direction to the F force that must be applied to the robot to move, as seen in Figure 8. Therefore, as seen in Equation 3, to calculate the net force, the net force is found when the sum of the force resulting from the mass and the friction force is subtracted from the applied force. This force is also equal to ma according to the formula of Newton's second law of motion.

$$\mathrm{F_{net}} = \mathrm{F} - \left(\mathrm{F_r} + \mathrm{F_g}\right) = \mathrm{ma} \tag{3}$$

Since the mass of the robot and the acceleration determined as the design criterion are known, the total force (F) that must be applied to the vehicle is obtained as in Equation 4.

$$\mathrm{F} = \left(\mathrm{F_r} + \mathrm{F_g}\right) + \mathrm{ma} \tag{4}$$

When the forces, weight, and acceleration in the above calculations are put into the equation, the force that needs to be applied to the robot is calculated. Assuming that the wheels do not slide on the ground and that the conditions are ideal and that the robot will be designed with n wheels, the force on each wheel (F_t) is calculated in Newton units according to Equation 5.

$$\mathrm{F_t} = \frac{\mathrm{F}}{\mathrm{n}} \tag{5}$$

If the radius (r) of the wheels on the robot is known, the net load torque (T_{net}) per wheel is calculated with Equation 6.

$$\mathrm{T_{net}} = \mathrm{r.F_t} \tag{6}$$

Due to the possibility of inaccuracy in the calculated and predicted values, a 10% tolerance is added to this value, and the net load torque per wheel is recalculated. Since 1Nm = 10.197 kg-cm [38], the load torque is converted into a kg-cm unit with equation 7. If desired, these calculations can be repeated for a smooth road by giving zero value to the slope angle [39].

$$T_{net-kgcm} = T_{net}10.197 \quad (7)$$

3.2. Android Application Design

Application design consists of two parts. The first of these is the interface that will be seen on the Android device screen shown in Figure 9. The second part is the block code writing editor in Figure 10, which will perform the functions of the button, text editor, and labels in the interface. In the image at the top of the interface, a representative robot is placed on an inclined surface and the forces acting on the robot are shown. At the bottom of the image, text editors and tags are placed for the designer to fill in information about the robot and design parameters.

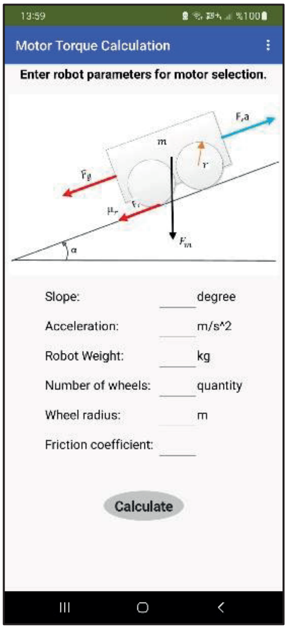


Figure 9. Android application design interface

After all the values are entered, when the "calculate" button at the bottom is pressed, operations will be carried out in the background according to the motor calculations mentioned in section 3.1. At the same time, the values resulting from the calculation will be written next to the forces in the visual on the screen. Meanwhile, the values entered by the designer will disappear from the screen and the calculated torque value will be written on the screen with a DC motor visual. There will be a representative image at the bottom according to the number of motorized wheels specified by the designer.

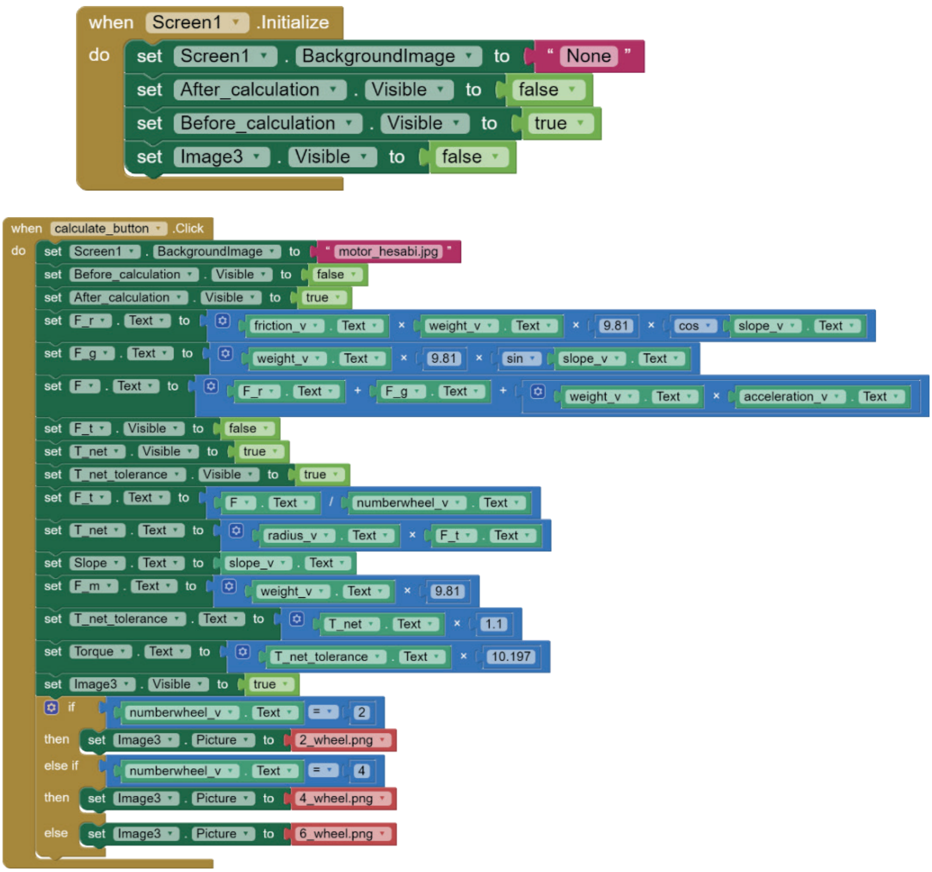
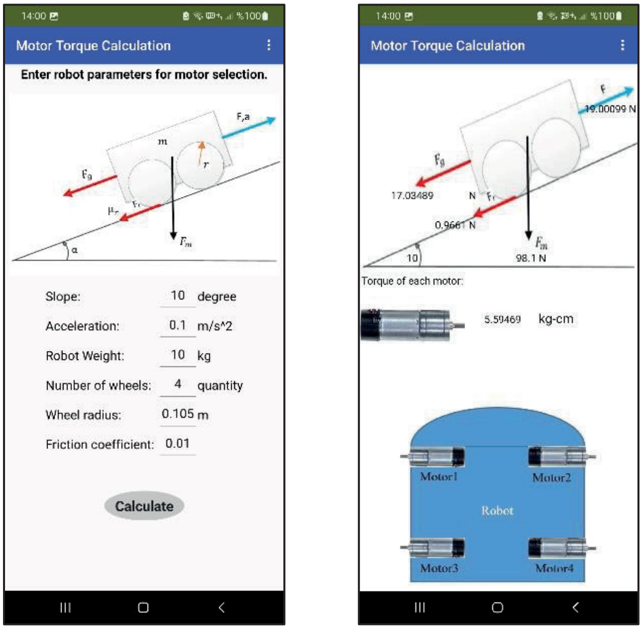


Figure 10. Coding created in Block editor

For example, it was taken into account that the robot could climb a 10^0 slope with an acceleration of 0.1 m/s^2 , and the rolling slip coefficient was accepted as 0.01. Anticipating that this robot would weigh 10 kg, it was designed to be driven by four motors, each with a diameter of 21 cm, and these values were entered into the interface as seen in Figure 11 (a). The motor torques calculated for these values are given in Figure 11 (b).



(a) (b)

Figure 11. Sample application -1 (a) entering the parameters, (b) calculating the results

The same calculation was made considering another mobile robot weighing 5 kg and having 6 wheels with a diameter of 20 cm, so that it could move with an acceleration of 0.1 m/s^2 on an uninclined road, the values were entered into the interface in Figure 12 (a) and the results have been obtained in Figure 12 (b). The torque value calculated as 5.594 kg-cm for the previous robot was calculated as 0.185 kg-cm for each motor of the second robot.

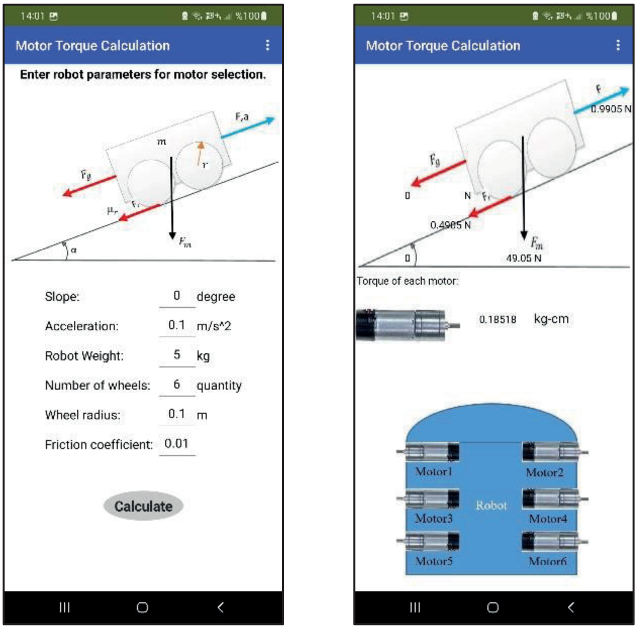


Figure 12. Sample application-2 (a) entering the parameters, (b) calculating the results

REFERENCES

[1] Akyol, G. (2014). Mobil uygulama arayüzlerinin incelenmesi üzerine bir çalışma. *ISITES2014, Karabuk.*

[2] Statista. (2024a, Ocak). Forecast number of mobile users worldwide from 2020 to 2025 https://www.statista.com/statistics/218984/number-of-global-mobile-users-since-2010/

[3] Tuik. (2024, Ocak). Dünya Nüfus Günü, 2023. https://data.tuik.gov.tr/Bulten/Index?p=Dunya-Nufus-Gunu-2023-49688

[4] Statista. (2024b, Ocak). Number of apps available in leading app stores as of 3rd quarter 2022, https://www.statista.com/statistics/276623/number-of-apps-available-in-leading-app-stores/

[5] Statista. (2024c, Ocak). Share of Android vs iOS users worldwide as of June 2023, by generation https://www.statista.com/forecasts/1406595/android-vs-ios-users-worldwide-by-generation

[6] Özdinç, F. (2015). Mobil programlama eğitiminde yeni yaklaşımlar: App Inventor örneği. *Akademik Bilişim Konferansı–17, Eskişehir.*

[7] Bales, S. (2018). Build Android apps without Coding: Get started with Android apps using Thunkable-MIT app Inventor.

[8] João, P., Nuno, D., Fábio, S. F., & Ana, P. (2019). A cross-analysis of block-based and visual programming apps with computer science student-teachers. Education Sciences, 9(3), 181.

[9] Google Developers. (2020, Nisan). *Meet Android Studio.* https://developer.android.Com/studio/ intro adresinden elde edildi.

[10] YILMAZ, Ö., & ÜSTÜN, A. B. (2021). App Inventor ve alternatif blok tabanlı mobil uygulama geliştirme platformlarının karşılaştırmalı incelenmesi. Disiplinlerarası Eğitim Araştırmaları Dergisi, 5(9), 1-11.

[11] DANDIL, E., Öztürk, İ., Ziya, E. K. Ş. İ., & ÇAKIROĞLU, M. (2015). Mobil Cihazlar İçin İlk Yardım Paketi Uygulaması. *Academic Platform-Journal of Engineering and Science*, *3*(1), 16-20.

[12] Alakuş, T. B., Daş, R., & Türkoğlu, İ. (2017, September). Yazilim geliştirme süreçlerinin analizi: Zorluklar, tasarim prensipleri ve tekniksel yaklaşimlar. In 2017 International Artificial Intelligence and Data Processing Symposium (IDAP) (pp. 1-10). IEEE.

[13] Willocx, M., Vossaert, J., & Naessens, V. (2015, June). A quantitative assessment of performance in mobile app development tools. In 2015 IEEE international conference on mobile services (pp. 454-461). IEEE.

[14] PEKYÜREK, M. F., SAĞLAM, Z., & USTUN, A. B. (2020). MIT App Inventor ve Android Studio kullanılarak tasarlanmış mobil uygulamanın performans karşılaştırması. Bilgi ve İletişim Teknolojileri Dergisi, 2(2), 161-181.

[15] Hong, S., & Hwang, Y. (2020). design and implementation for iort-based remote control robot using block-based programming. *Issues in Information Systems*, *21*(4), 317-330.

[16] Pokress, S. C., & Veiga, J. J. D. (2013). MIT App Inventor: Enabling personal mobile computing. *arXiv preprint arXiv:1310.2830*.

[17] Colter, A. J. (2016). *Evaluating and improving the usability of MIT App Inventor* , Doctoral dissertation, Massachusetts Institute of Technology.

[18] Fraser, N. (2013). Blockly: A visual programming editor. https://code. google. com/p/blockly, *42*.

[19] Begel, A., & Klopfer, E. (2007). Starlogo TNG: An introduction to game development. *Journal of E-Learning*, *53*(2007), 146.

[20] Resnick, M., Maloney, J., Monroy-Hernández, A., Rusk, N., Eastmond, E., Brennan, K., ... & Kafai, Y. (2009). Scratch: programming for all. *Communications of the ACM*, *52*(11), 60-67.

[21] Maloney, J., Resnick, M., Rusk, N., Silverman, B., & Eastmond, E. (2010). The scratch programming language and environment. *ACM Transactions on Computing Education (TOCE)*, *10*(4), 1-15.

[22] De Moura Oliveira, P. B. (2015, March). Teaching automation and control with App Inventor applications. In *2015 IEEE Global Engineering Education Conference (EDUCON),* (pp. 879-884). IEEE.

[23] Howedi, A., & Jwaid, A. (2016, December). Design and implementation prototype of a smart house system at low cost and multi-functional. In *2016 Future Technologies Conference (FTC)* (pp. 876-884). IEEE.

[24] Asghar, M. Z., Sana, I., Nasir, K., Iqbal, H., Kundi, F. M., & Ismail, S. (2016). Quizzes: Quiz application development using Android-based MIT APP Inventor platform. *International Journal of Advanced Computer Science and Aplications*, *7*(5).

[25] Sullivan, D., Chen, W., & Pandya, A. (2017, June). Design of remote control of home appliances via Bluetooth and Android smart phones. In *2017 IEEE International Conference on Consumer Electronics-Taiwan (ICCE-TW)* (pp. 371-372). IEEE.

[26] Kannapiran, S., & Chakrapani, A. (2017). A novel home automation system using Bluetooth and Arduino. *international journal of advances in computer and electronics engineering*, *2*(2), 41-44.

[27] Prayogo, S. S., Saptariani, T., & Salahuddin, N. S. (2015, October). Rancang Aplikasi Android Pengendali Mobil dan Kamera Menggunakan APP inventor, *Seminar Nasional Aplikasi Teknologi Informasi (SNATI)* (Vol. 1, No. 1).

[28] Adiono, T., Anindya, S. F., Fuada, S., Afifah, K., & Purwanda, I. G. (2019). Efficient Android software development using mit app inventor 2 for bluetooth-based smart home. *Wireless Personal Communications*, *105*(1), 233-256

[29] Asghar, M. Z., Sana, I., Nasir, K., Iqbal, H., Kundi, F. M., & Ismail, S. (2016). Quizzes: Quiz application development using Android-based MIT APP Inventor platform. *International Journal of Advanced Computer Science and Aplications*, https://doi.org/10.14569/IJACSA.2016. 070 508

[30] Patton, E. W., Tissenbaum, M., & Harunani, F. (2019). MIT app inventor: Objectives, design, and development. *Computational thinking education*, 31-49.

[31] Roque, R. V. (2007). *OpenBlocks: an extendable framework for graphical block programming systems* (Doctoral dissertation, Massachusetts Institute of Technology).

[32] Begel, A., & Klopfer, E. (2007). Starlogo TNG: An introduction to game development. *Journal of E-Learning*, *53*(2007), 146.

[33] Kincaid, J. (2011). Google gives Android App Inventor a new home at MIT Media Lab. Techcrunch., from https://techcrunch.com/2011/08/16/google-gives-android-appinventor-a-new-home-at-mit-media-lab/.

[34] MIT App Inventor main screen, https://appinventor.mit.edu/

[35] Massachusetts Institute of Technology. (2020). Designer and blocks editor. https://appinventor.mit.edu/explore/designer-blocks

[36] Patton, E. W., Tissenbaum, M., & Harunani, F. (2019). MIT app inventor: Objectives, design, and development. In *Computational thinking education* (pp. 31-49). Springer, Singapore.

[37] Transportation Research Board, (2006), Tires and Passenger Vehicle Fuel Economy: Informing Consumers, Improving Performance, *Special Report 286*, *Transportation Research Board*, Washington, DC, USA.

[38] Unit conversion, https://www.unitconverters.net/torque/newton-meter-to-kilogram-force-centimeter.htm

[39] Arslan S., Haziran 2011,*Dört Tekerlekten Tahrik Edilen Yanal Kayma İle Yönlendirilen Bir Mobil Robotun Tasarımı ve Dayanıklı Hareket Kontrolü*, İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi

CHAPTER 4

GROUNDBREAKING TECHNOLOGY IN SMART GRIDS: ADVANCED MEASUREMENT INFRASTRUCTURE- NEW DIMENSIONS IN MEASUREMENT

Mehmet GÜÇYETMEZ[1]

1 Asst. Prof. Dr., Sivas University of Science and Technology
ORCID: 0000-0003-2191-8665
mehmetgcy@sivas.edu.tr

INTRODUCTION

This study discusses advanced measurement infrastructure (AMI), one of the most vital smart grid (SG) components. In this context, information about SG is first given, and then AMI and its current structure are summarized. Sensing, communication, and data security are the most essential components in AMIs, and the system works based on these components. Finally, some suggestions have been made regarding smart meters (SMs) and the AMI. These recommendations can be summarized as follows: With the development of the SM structure, AMIs should also keep up with this development, and the relevant software should be adapted to the changes; SMs and AMIs should become more sensitive to human behavior and have more sensor structures.

SMART METERS

In an age where technology continues redefining how we live, work, and interact, the term "smart" is becoming very popular and increasingly common, adorning everything from phones to homes (Goddard, Kemp, & Lane, 1997). One of the areas where these developments are effective is SMs. So what exactly is an SM, and how does it transform how we consume and understand our energy use?

An SM is a sophisticated device that discerns power consumption with much greater granularity than a conventional meter. It then transmits the gathered data to the grid for load monitoring and billing purposes (Yan et al., 2013). Unlike their analog predecessors, SMs have advanced sensors and communication modules that enable two-way communication between the service provider and the consumer. Thus, in these meters, controlling the energy at all times and detecting the reflection of environmental changes on energy use are at the forefront.

One of the main features distinguishing SMs from others is their numerous capabilities, which can be added compared to traditional meters. The most prominent of these is that SMs provide real-time data on energy consumption. Service personnel must read traditional meters manually, often leading to delayed and sometimes inaccurate billing. SMs provide numerous advantages to consumers, such as the ability to approximate their bills using the compiled data, enabling them to efficiently regulate their energy usage and consequently lower their electricity expenses (Zheng et al., 2013). In addition, the ability of the meter to direct or control the consumer is another crucial and distinctive advantage that requires the use of SMs.

The emergence of SMs also marks a significant shift in consumer awareness and empowerment. Thanks to real-time data accessible through mobile applications or online portals, users can monitor energy consumption patterns and make informed decisions to optimize usage (Islam et al., 2016).

This transparency encourages energy-saving practices, allowing individuals to identify and correct wasteful habits that contributing to higher bills and an increased carbon footprint (Yan et al., 2013).

In this period, when economic difficulties, climate change, and global warming are accelerating, this guiding feature of SMs will provide significant positive contributions to consumers in economic and environmental terms.

Additionally, SMs pave the way for dynamic pricing models in which energy prices fundamentally fluctuate. This encourages consumers to adjust their energy usage during peak hours on demand, increasing efficiency and reducing the grid's load. SMs are essentially devices that contribute to personal savings and the overall stability and sustainability of the energy infrastructure (EPDK, 2015).

Privacy concerns often come up when discussing the implementation of smart technology. However, SMs are designed with robust security measures to protect user data. Encryption, communication, and detection are among the most essential features of SMs. Encryption protocols and secure communication channels address data privacy concerns by ensuring that sensitive information remains private (Abdalzaher, Fouda, & Ibrahem, 2022).

The environmental benefits of SMs go far beyond personal use. The data collected from these devices allows service providers to analyze usage patterns on a larger scale, facilitating the development of more efficient energy distribution systems. The SM is a vital distribution system component in this respect. This data-driven approach reduces energy waste and greenhouse gas emissions, aligning with global efforts to combat climate change (Zheng et al., 2013). As we continue to advance in the ever-evolving technology landscape, the SM stands as a beacon of innovation in energy management. Its ability to empower consumers, increase efficiency, and contribute to a more sustainable future positions it as a critical player in the ongoing transition to an innovative and connected world (Aubel &Poll, 2019). The SM provides fast and effective data processing thanks to the electronic kit containing an approximately 1 GHz system on a chip (SoC) with a microcontroller and some flash memory (Akpolat & Dursun, 2017). The SM consists of hardware structures such as the step-down transformer, microprocessor core, real-time clock, memory unit, and an LCD, as shown in Figure 1 (Weranga et al., 2014).

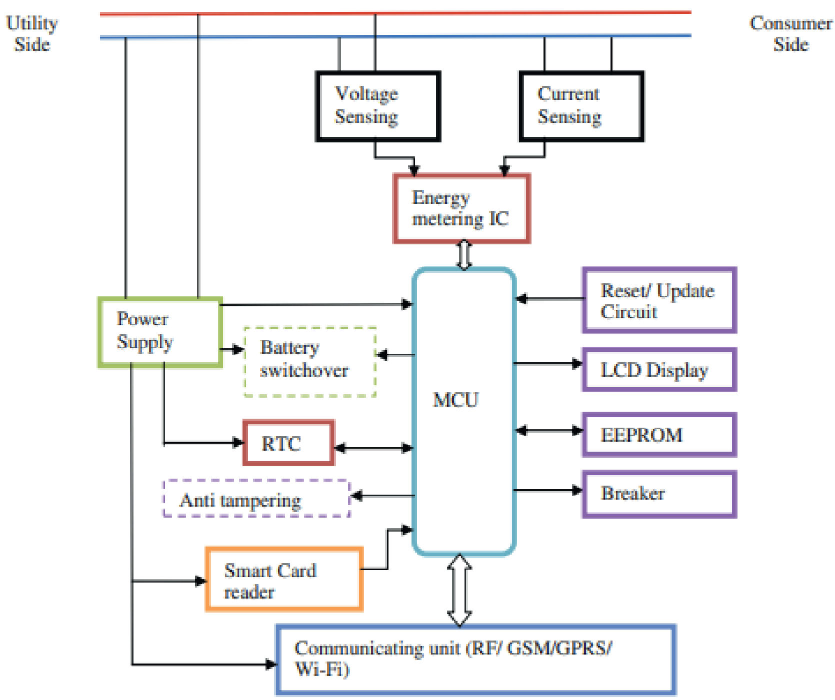


Figure 1 *A modern SM hardware (Weranga et al., 2014).*

As a result, SMs are not just a digital alternative to traditional meters; they represent a paradigm shift in how we perceive and manage our energy consumption. SMs, which harness the power of real-time data and encourage conscious energy use, are emerging as a cornerstone to a more sustainable and efficient energy environment. Adopting this transformative technology is not just a step forward but a step towards a future where energy management is more innovative, greener, and connected.

Advanced Measurement Infrastructure (AMI)

The challenges arising in the energy market of the 21st century lead to inevitable changes in electricity systems. The energy sector faces challenges such as introducing Distributed Energy Resources (DER), more effective control schemes for complex systems, improving power quality, and traditional and centralized energy production methods associated with environmental concerns, consumer information protection, and system security. The economics of power systems are also important, from maintenance costs to equipment renewal and network expansion. Europe and North America have moved to smart grids (SG) to address these challenges by modernizing their energy production and distribution systems (Mohassel et al., 2014).

While the origins of electrical grids trace back to the late 1800s, the 1960s marked a pivotal era often referred to as the zenith of electrical grids, and this period witnessed substantial enhancements in the distribution network's reach and capacity to carry loads. The reliability and standard of the distributed power achieved commendable levels. Moreover, notable advancements occurred in centralized energy production's technical and economic spheres, encompassing fossil fuels, hydroelectricity, and nuclear power plants. Along with these developments, the increasing need for energy at the end of the 20th century brought many developments. Today, the traditional electricity grid is transitioning significantly towards SGs, called smart or microgrids (Berger & Iniewski, 2012).

AMI is an infrastructure enabling two-way communication and data exchange between service providers and end users, which is pivotal in modernizing traditional power distribution systems. AMI, a critical element of the smart power grid, increases energy efficiency, ensures grid reliability, and facilitates the integration of renewable energy sources (Abdullah et al., 2023).

The successful implementation of several subsystems is necessary to achieve an SG. The robust setup and functionality of each subsystem affect the overall SG performance, as the output of each layer acts as a foundation for the next layer. Figure 2 illustrates this relationship and summarizes the role of each subsystem in developing and deploying the electrical grid (Strategy NMG, 2008).

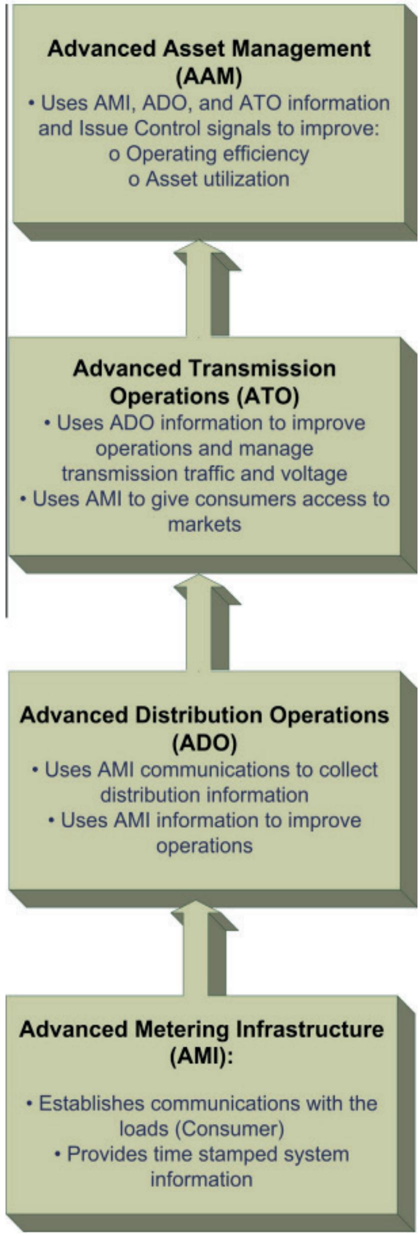


Figure 2 *Overview of the SG subsystem array (Strategy NMG, 2008).*

AMI represents not a solitary technology but a meticulously structured framework amalgamating various technologies to fulfill its objectives. This framework encompasses smart meters (SMs), communication networks spanning various tiers of the infrastructure hierarchy, Meter Data Management Systems (MDMS), and facilitating tools enabling the seamless integration of gathered data into software application platforms and interfaces. As delineated in Figure 3, consumers are furnished with sophisticated solid-state electronic measurement devices adept at capturing time-based data. These meters can transmit accumulated data through prevalent fixed networks such as Broadband over Power Line (BPL), Power Line Communication, Fixed Radio Frequency, and public networks like landline, mobile, and paging.

The AMI host system receives measured consumption data, and then the data is sent to an MDMS that manages data storage and analysis and provides the information in a format that is helpful to the utility provider. AMI allows two-way communication; Therefore, it is also possible to provide communication or command or price signals from the grid to the meter or load controllers (Mohassel et al., 2014).

AMI Advantages

There are numerous benefits associated with the utilization of AMI. From the utility standpoint, leveraging historical data gleaned from smart meters (SMs) enables the detection and mitigation of illicit electricity consumption. The Smart Grid (SG) can be remotely monitored and managed through AMI, thereby enhancing maintenance practices, demand management strategies, and overall planning efficacy. Moreover, a robust SG facilitated by AMI contributes to outage prevention and cost savings for power companies. AMI obviates the need for manual monthly meter readings, expedites electrical system monitoring, fosters more judicious utilization of power resources, furnishes real-time data pivotal for load balancing endeavors, thus mitigating the occurrence of power outages (e.g., blackouts), facilitates dynamic pricing mechanisms based on demand fluctuations (e.g., adjusting electricity costs accordingly), circumvents the necessity for substantial capital investment in constructing new power plants or retrofitting existing ones, and aids in revenue optimization utilizing existing resources.

AMI offers consumers several advantages, including enhanced precision in electricity billing, heightened control over power quality, and heightened awareness. Empowered with more significant insights, consumers can optimize their consumption patterns, thereby reducing household energy requirements and subsequently lowering their utility bills. Consequently, end-users benefit from improved electricity service quality, flexible billing frameworks, comprehensive energy bill data, detailed feedback on energy usage, insights into consumption behaviors, and heightened energy awareness, fostering rational energy utilization and enabling interoperability (Martins et al., 2019; CioWiki, 2023).

AMI Problems and Disadvantages

While specific challenges with AMI pertain to consumer privacy and confidentiality, others revolve around unauthorized device access, leading to cybersecurity concerns. On the consumer front, safeguarding data necessitates robust data management practices, including anonymization. End-users may encounter difficulties verifying the accuracy of new meters, while concerns arise regarding the maintenance of data accuracy and potential additional fees for installation. Utility providers must ensure data accuracy and guard against physical or cyber-attacks on meters. This entails implementing various cybersecurity measures encompassing confidentiality, integrity, and authentication of exchanged data to thwart cyber threats such as eavesdropping, traffic analysis, and malware. However, constraints in processing power hinder the full implementation of cybersecurity measures in some smart meter (SM) and Smart Grid (SG) systems.

Moreover, transitioning to new technologies and processes entails higher personnel training, equipment development, and production costs. Overcoming public resistance and fostering customer acceptance of new meters pose additional challenges. Furthermore, committing to long-term investments in new meter technology and associated software raises financial concerns. Technical hurdles emerge in managing and storing vast quantities of meter data, while ensuring the security and confidentiality of such data remains an ongoing challenge (Martins et al., 2019).

Subsystems of AMI

The SG has advanced metering infrastructure (AMI), of which SMs are a key component. Advanced metering infrastructure is an integrated, fixed-network system that measures, stores, analyzes, and presents electricity, gas, and water consumption in real-time, establishing two-way communication between service providers and customers (Popović, Ž. & Čačković, V., 2014). Advanced metering infrastructure offers many advantages to improve energy efficiency, billing, demand management, fault detection, remote control, and customer engagement.

AMI is a complex structure consisting of many subsystems. These subsystems are SMs, communication networks, data management systems, application software, and security systems. The general scheme of AMI is shown in Figure 3 (Céspedes et al., 2017).

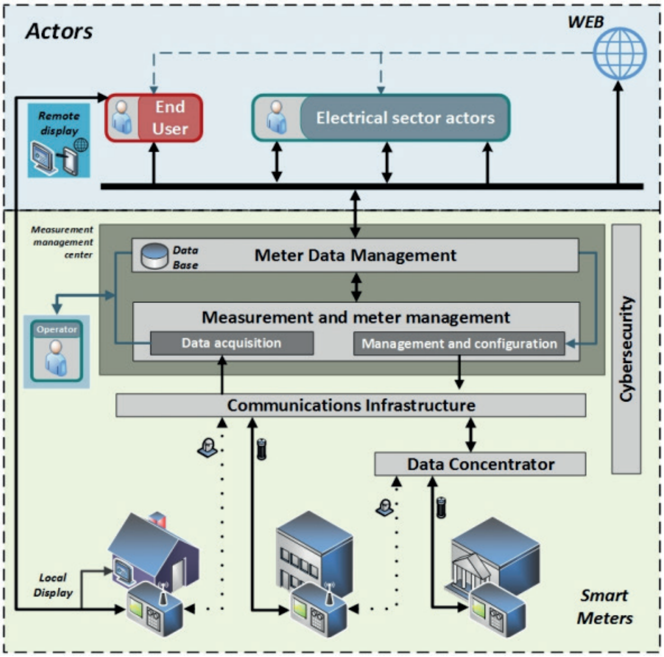


Figure 3 *General schematic representation of the AMI (Céspedes et al., 2017)*

1) SMs

SMs are the most essential components of advanced metering infrastructure (Ko, E. & Jeong, G. S., 2023). SMs, unlike traditional meters, are digital electronic devices that measure energy consumption on an hourly or more frequent basis, transmit data remotely, can be adjusted according to received commands, and can communicate with other devices. SMs can measure electricity, gas, and water consumption. Some features provided by SMs are:

• It can detect and report malfunction, interruption, leakage, and theft.

• It can measure and report parameters such as energy quality, voltage, current, frequency, and power factor.

• It can be connected, interrupted, restarted, updated, and configured remotely.

• It can be applied to time-based, dynamic, multiple tariffs and invoices.

• It can be adapted to demand response, distributed generation, and electric vehicle charging applications.

• It allows customers to monitor and manage energy consumption.

SMs can connect communication networks using protocols, frequencies, modulations, and encryptions. Communication technologies of SMs can be broadly classified as wired or wireless, point-to-point or networked, centralized or distributed (Zheng et al., 2013). When choosing communication technologies for SMs, factors such as geographical location, network structure, data rate, security, cost, reliability, and scalability should be considered. An example of an SM is shown in Figure 4, and data according to the model is given in Table 1.

Figure 4 *SM Model (Fronius, 2024)*

Table 1 *SM General Data (Fronius, 2024)*

Rated voltage	230-240 V
Maximum current	1×63 A
Phase and neutral conductor connection cross-section	1-16 mm^2
Current converter and communication gate connection section	0,05-4 mm^2
Self-consumption	1,5 W
Starting current	40 mA
Accuracy class	1
Effective energy accuracy	Class B (EN50470)
Reactive energy accuracy	Class 2 (EN/IEC 62053-23)
Overload (short)	30 x Imax / 10ms
Assembly	Internal mounting (DIN rail)
Enclosure	2 Modules DIN 43880
Degree of protection	IP 51 (Front), IP 20 (Terminals)
Screen	Six-digit LCD
Working area	-25±55°C
Interface to inverter	Modbus RTU (RS485)

2) Communication Networks

Communication networks are subsystems forming the backbone of AMI (Cai et al., 2014). AMI creates a communication network between grid systems and SMs, enabling two-way communication to transmit data and control signals. Communication networks collect, store, process, and send data from SMs to where it needs to be transmitted. In addition, they transmit commands from the AMI bedside system or other application software to SMs (Kumar V., Kumar R., & Pandey, 2021).

AMI uses three levels of communication: home area network (HAN), neighborhood area network (NAN), and wide area network (WAN). HAN is responsible for providing connectivity to the NAN and communication between all smart devices in the home (Molokomme, Chabalala, & Bokoro, 2020). NAN carries information between SMs and a data concentrator. WAN consists of data collectors, grid substations, etc. It is responsible for the bidirectional transportation of incoming information to network control centers (Kabalci, 2016). WAN, power line communication (PLC), fiber optic, WiMax and Satellite, NAN; PLC, Zigbee, WiMax and GSM, HAN; It can use different communication protocols and infrastructures such as Zigbee, WiFi, ZWave, GSM and PLC (Kabalci, 2016).

2.1. Wide Area Network (WAN):

A WAN is typically set up as a backhaul network with instances geographically dispersed. WANs help communicate between electricity markets and power providers in SGs, as shown in Figure 5. WAN links the service control center (UCC) and the home network (HAN) to enable communication between various SG networks. Additionally, WAN connects these servers via UCC to communicate. 5G could be an excellent technology for WAN applications and services. Cognitive radio networks (CRNs) can also adapt to improve the spectral efficiency of the network by dynamically accessing idle spectrum bands (Bouabdellah et al., 2019).

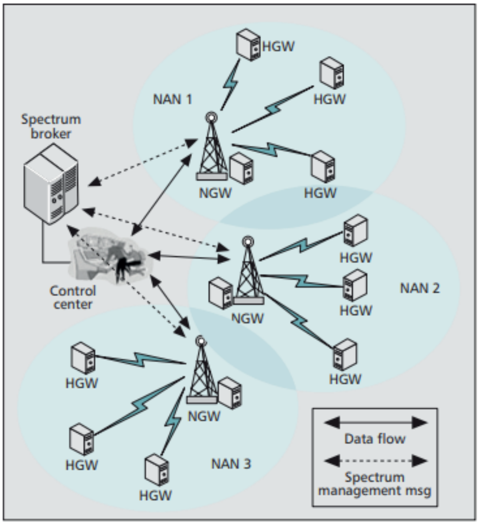


Figure 5 *Wide area network (WAN) architecture (Yu et al., 2011)*

2.2. Neighborhood Area Network (NAN):

NAN is the second layer of the NAN, SG communication architecture, and receives measurement and service data from many HANs and sends it to data collectors that connect the NAN to the upper layer, the WAN layer (Yu et al., 2011). It also works as a bridge to communicate HAN and WAN in SGs; that is, it transmits the power consumption data of every smart electrical device in the HAN in real-time. NANs connect HANs and establish connections between HANs and WANs, as shown in Figure 6. NANs act as intermediate nodes by sending information from SMs to the UCC. Communication technologies used in this layer vary depending on VR applications. Therefore, wireless and wired communication technologies are suitable solutions for the various QoS needs of NAN applications. Optical fiber and 5G are excellent technologies for NAN applications as they can support real-time latency-sensitive applications. Moreover, establishing a suitable information structure between SMs, sensors, and utility data centers is still a complex problem. Therefore, NAN gateways must be deployed to transfer information from heterogeneous IoT smart devices to the WAN (Gungor & Sahin, 2012).

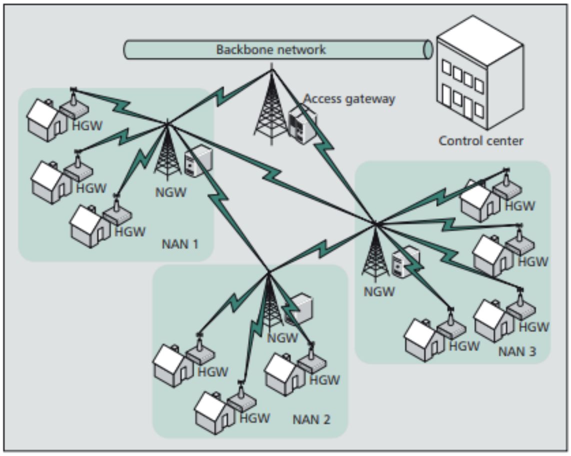


Figure 6 *A central NAN topology for SG communication (Meng et al., 2014)*

2.3. Home Area Network (HAN):

The SG provides a valuable function in controlling the energy consumption of homes. Home energy management covers the various devices in the home, from lights, appliances, heaters, air conditioners, local generating units (such as solar panels), and electric vehicles, as shown in Figure 7. Home energy management systems (HEMS) have been designed and implemented to enable energy consumption, storage, and production of these devices. Communication is established between these devices through a home area network (Budka, Deshpande, & Thottan, 2014). The customer's facility area network can be divided into three categories depending on the environment: HAN, business area network (BAN), and industrial area network (IAN) (Eder-Neuhauser, et al., 2016). The characteristics of these areas depend on various factors such as climate and economic conditions. The daily habits of networked consumers and climate changes determine load demand on HAN. During winter and peak times, load demand is expected to be higher than during summer and off-peak times. In BAN, the load demand depends on the economy and is less affected by climate change. Therefore, HAN acts as a communication bridge between smart devices and SMs. The main task of SMs in HAN is to collect energy consumption data and monitor the network status in real-time. The traditional communication structure is insufficient to manage the large amount of data coming from SMs. AMI has been implemented in HAN to meet QoS needs (Molokomme et al., 2020).

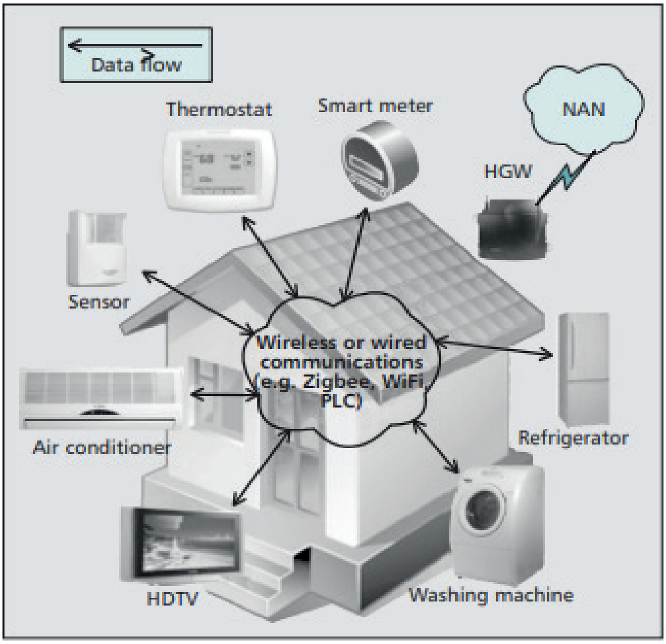


Figure 7 *Home Area Network Architecture (Eder-Neuhauser, Zseby, & Fabini, 2016)*

3. Meter Data Management System (MDMS):

The data management system is the central data repository of the AMI (Popović & Čačković, 2014). The data management system receives, stores, processes, analyzes, and presents data from communication networks. The data management system interfaces the AMI bedside system and other application software. The data management system provides many functions to improve AMI's performance, quality, and security. MDMS securely manages new requests and data sizes. It also fulfills needs regarding delivery times and service hours. Another aim of the MDMS project is to increase customer satisfaction. This is achieved through better customer service. When a customer calls to complain, customer service can access customers' meter data and handle the problem more effectively. The best way for customers to benefit from the MDMS project's advantages may be through online service (Mäkelä, 2011).

The data management system is one of the AMI's most critical and complex subsystems (Cai et al., 2014). The data management system must process large amounts of diverse, fast, and constantly flowing data. The data management system requires sufficient hardware, software, and human resources to ensure data security, confidentiality, integrity, and availability. The network structures mentioned above and the general architecture of the meter data management system are shown in Figure 8 (Popović & Čačković, 2014).

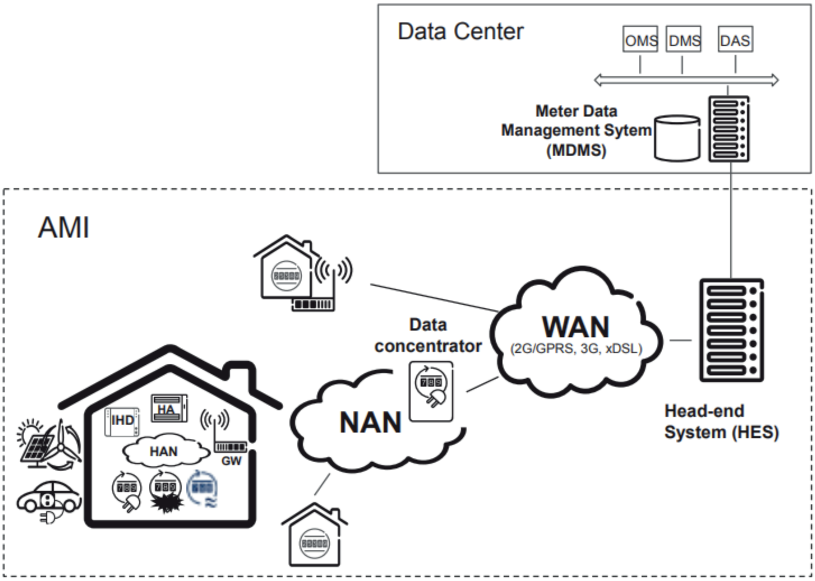


Figure 8 *AMI overall communication network architecture (Popović & Čačković, 2014)*

Conclusion

AMI is a system with critical measurement functions for developing SGs. However, the AMI can still be considered cumbersome. The most important reason is that the detection level in SGs is still not very advanced. Integrating many sensor types and technologies into SGs continues, directly affecting the development of the AMI.

On the other hand, human behavior is highly variable and dramatically impacts the consumption and efficiency of electrical energy. For future studies, developing an AMI for SGs that handles human behavior with artificial intelligence methods and contains more sensors is necessary.

REFERENCES

Abdalzaher, M. S., Fouda, M. M., & Ibrahem, M. I. (2022, October 1). Data Privacy Preservation and Security in Smart Metering Systems. *Energies*. MDPI. doi:10.3390/en15197419

Abdullah, A. A., El-den, B. M., Abo-Al-Ez, K. M., & Hassan, T. M. (2023). Security Management for an Advanced Metering Infrastructure (AMI) System of Smart Electrical Grids. *Applied Sciences*, *13*(15), 8990.

Akpolat, A. N., Dursun, E., Akpolat, A. N., & Dursun, E. (2017). *Advanced Metering Infrastructure (AMI): Smart Meters and New Technologies*. Retrieved from https://www.researchgate.net/publication/332111353

Berger, L. Torsten., & Iniewski, K. (2012). Smart grid: applications, communications, and security, 464. Retrieved from https://books.google.com/books/about/Smart_Grid_Applications_Communications_a.html?hl=tr&id=vZaADwAAQBAJ

Bouabdellah, M., El Bouanani, F., Sofotasios, P. C., Muhaidat, S., Da Costa, D. B., Mezher, K., … Karagiannidis, G. K. (2019). Cooperative Energy Harvesting Cognitive Radio Networks with Spectrum Sharing and Security Constraints. *IEEE Access*, *7*, 173329–173343. doi:10.1109/ACCESS.2019.2955205

Budka, K. C., Deshpande, J. G., & Thottan, M. (2014). Computer Communications and Networks. Communication networks for smart grids: Making smart grid real. *London, UK: Springer Verlag*, *10*, 978-1.

Cai, D., Xie, T., Huang, Q., & Li, J. (2014, July). Short-term solar photovoltaic irradiation predicting using a nonlinear prediction method. In *2014 IEEE PES General Meeting| Conference & Exposition* (pp. 1-5). IEEE.

Céspedes, R., Rosero, J., Montaño, W., & Reyes, J. F. (2017, September). Methodology for defining the functionality of advanced measurement infraestructure in colombia. In 2017 IEEE PES Innovative Smart Grid Technologies Conference-Latin America (ISGT Latin America) (pp. 1-6). IEEE.

CioWiki (2023), 'Advanced Metering Infrastructure (AMI) - CIO Wiki'. Accessed: Feb. 14, 2024. [Online]. Available: https://cio-wiki.org/wiki/Advanced_Metering_Infrastructure_%28AMI%29

Eder-Neuhauser, P., Zseby, T., & Fabini, J. (2016). Resilience and Security: A Qualitative Survey of Urban Smart Grid Architectures. *IEEE Access*, *4*, 839–848. doi:10.1109/ACCESS.2016.2531279

EPDK (2015). Proje Adı: Akıllı Sayaç Sistemleri Fayda-Maliyet Analizi Metodolojisinin Geliştirilmesi, ADM ve GDZ EDAŞ Bölgesi İçin Yaygınlaştırma Yol Haritasının Çıkarılması. doi:10.05.02.01-477

Fronius Smart Meter TS 65A-3. (n.d.). Retrieved 9 February 2024, from https://www.fronius.com/tr-tr/turkey/guenes-enerjisi/kurulumcular-ve-partnerler/teknik-veri/t%C3%BCm-%C3%BCr%C3%BCnler/sistem-denetimi/donan%C4%B1m/fronius-smart-meter/fronius-smart-meter-ts-65a-3

Goddard, N. D. R., Kemp, R. M. J., & Lane, R. (1997). *An Overview of Smart Technology*. PACKAGING TECHNOLOGY AND SCIENCE* (Vol. 10).

Gungor, V. C., & Sahin, D. (2012). Cognitive radio networks for smart grid applications: A promising technology to overcome spectrum inefficiency. *IEEE Vehicular Technology Magazine*, *7*(2), 41–46. doi:10.1109/MVT.2012.2190183

Islam, K. T., Islam, A. J., Pidim, S. R., Haque, A., Khan, M. T. H., & Morsalin, S. (2016, December). A smart metering system for wireless power measurement with mobile application. In *2016 9th International Conference on Electrical and Computer Engineering (ICECE)* (pp. 131-134). IEEE.

Kabalci, Y. (2016, May 1). A survey on smart metering and smart grid communication. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2015.12.114

Ko, E., & Jeong, G. S. (2023, November). Analysis of Standards for Electricity Advanced Metering Infrastructure in the Housing Sector. In 2023 IEEE Green Energy and Smart Systems Conference (IGESSC) (pp. 1-6). IEEE.

Kumar, V., Kumar, R., & Pandey, S. K. (2021). LKM-AMI: a lightweight key management scheme for secure two way communications between smart meters and HAN devices of AMI system in smart grid. *Peer-to-Peer Networking and Applications*, *14*(1), 82-100.

Mäkelä, P. E. K. K. A. (2011). New Business and Process Development Opportunities Utilizing Meter Data Management System. *Tampere. Diplomityö. Tampereen Teknillinen Yliopisto*.

Martins, J. F., Pronto, A. G., Delgado-Gomes, V., & Sanduleac, M. (2019a). Smart Meters and Advanced Metering Infrastructure. In *Pathways to a Smarter Power System* (pp. 89–114). Elsevier. doi:10.1016/B978-0-08-102592-5.00004-1

Meng, W., Ma, R., & Chen, H. H. (2014). Smart grid neighborhood area networks: a survey. IEEE Network, 28(1), 24-32.

Mohassel, R. R., Fung, A., Mohammadi, F., & Raahemifar, K. (2014, June). Application of advanced metering infrastructure in smart grids. In *22nd Mediterranean Conference on Control and Automation* (pp. 822-828). IEEE.

Molokomme, D. N., Chabalala, C. S., & Bokoro, P. N. (2020, June 1). A review of cognitive radio smart grid communication infrastructure systems. *Energies*. MDPI AG. doi:10.3390/en13123245

Strategy, N. M. G. (2008). Advanced metering infrastructure. *US Department of Energy Office of Electricity and Energy Reliability*.

Popović, Ž., & Čačković, V. (2014, May). Advanced metering infrastructure in the context of smart grids. In 2014 IEEE International Energy Conference (ENERGYCON) (pp. 1509-1514). IEEE.

Rashed Mohassel, R., Fung, A., Mohammadi, F., & Raahemifar, K. (2014). A survey on Advanced Metering Infrastructure. *International Journal of Electrical Power and Energy Systems*, *63*, 473–484. doi:10.1016/j.ijepes.2014.06.025

Van Aubel, P., & Poll, E. (2019, July 1). Smart metering in the Netherlands: What, how, and why. *International Journal of Electrical Power and Energy Systems*. Elsevier Ltd. doi:10.1016/j.ijepes.2019.01.001

Weranga, K. S. K., Sisil, ·, & Chandima, K. D. P. (n.d.). *SPRINGER BRIEFS IN APPLIED SCIENCES AND TECHNOLOGY Smart Metering Design and Applications*. Retrieved from http://www.springer.com/series/8884

Yan, Y., Qian, Y., Sharif, H., & Tipper, D. (2013). A survey on smart grid communication infrastructures: Motivations, requirements and challenges. *IEEE Communications Surveys and Tutorials*. doi:10.1109/SURV.2012.021312.00034

Yu, R., Zhang, Y., Gjessing, S., Yuen, C., Xie, S., & Guizani, M. (2011). Cognitive radio based hierarchical communications infrastructure for smart grid. *IEEE network*, *25*(5), 6-14.

Zheng, J., Gao, D. W., & Lin, L. (2013). *Smart meters in smart grid: An overview*. In *IEEE Green Technologies Conference* (pp. 57–64). doi:10.1109/GreenTech.2013.17