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Magnetic Explosives Detection System (MEDS) based on wireless sensor network and machine learning

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Measurement

Magnetic Explosives Detection System (MEDS) based on wireless sensor network and machine learning.

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Abstract

This paper represents a new direction in detecting magnetic explosives by the use of a wireless sensor network adapted with machine learning. The Improvised Explosives Devices (IED) consider a series threat due to the easy manufacturing. However, the scientific directions heading towards the use of information technology in the development of explosives detection systems. In this paper, the type of explosives used is the magnetic explosives which are a type of IEDs that is used in targeting the vehicles. A Magnetic Explosives Detection System (MEDS) is a wireless sensor network system that uses a network of magnetic sensors to detect the magnetic field that emitted from magnetic effector and consider this magnetic field as a possible threat. The experiments of the system show its ability to detect the change in the magnetic field caused by the magnet stacked under the vehicle. The main use of the neural network algorithm in this paper is to determine the highest reading among a series of readings to determine where the threat exact position. Excellent results produced by the neural network algorithm in the MEDS to enable the system from learn and identify the required data type.

Keyword: Magnetic; Explosives; Wireless sensor network; Detection;

1. Introduction

The magnetic explosive is a part of the Improvised Explosive Devices (IED) which is a type of explosives that are used for special purposes [1]. Recently, IED's became the main tool for executing terrorist operations due to their portability and simple manufacturing [2]. Magnetic bombs are a type of explosives that use a magnet in order to enable the exploded material from sticking to a metallic objects. The magnet type used in the magnetic bomb is extremely powerful in order to prevent the explosives from being affected by the movement of the targeted object.

The main idea used in the detection of magnetic explosives is the physical attributes of the magnetic flux emitted from the magnet [3]. Magnetic Explosives (ME) use a powerful magnet and thus the magnetic flux of such a magnet changes the metallic material magnetic field. Magnetic flux is a physical power that its power affect the environment and especially metallic materials [4]. Therefore, terrorists use the ME in their operations due to its ability to target even the moving metallic objects as the magnet properties help to stick the ME to the target object metallic body.

The ME made of two main parts: the first part is the magnet as we previously saw. The second part is the exploded materials [5]. Exploded materials are chemical components with ability to produce a destructive effect when it is mixed to certain other chemicals [6]. A main exploded materials used in the ME are TNT and C4 [7]. ME is detonated remotely as the detonator remains at far distance from the ME with a wireless connection device used to connect to the ME device (typically a cellphone) in order to initiate the ME detonation [8]. The main sensor used in order to detect the magnetic flux is the magnetic sensor. Magnetic sensor is an electrical and electronic device that capable of converting the physical magnetic flux into an electrical signal that is digitized to serve multiple applications [9]. Magnetic field sensor involves multiple applications such as industrial, scientific, healthcare [10].

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2. Related work

This section represents the literature review to describe the relevant studies on explosives detection by the use of a sensor network.

Charles L... et al, (1999) [29]. The U.S Department of justice discussed different techniques for detecting explosives. Ion Mobile Spectrum (IMS) technology invented for the explosives detection by tracing explosives spectrum that released by the material and other environmental elements using a special-purpose hardware device that detects these features. This technology type is a fixed location and that mean there is no ability to this system to work on an environment that requires the system to be mobile.

Joshua Sundram and PhuaPohSim, (2007) [30]. Improvised a technology for detecting the IEDs using wireless sensor network. Using a set of sensors distributed over a large network would make the accuracy and the detection of magnetic explosives more efficient. They improved the network that contains multiple sensors to have better resolution in the detection of the IEDs. These sensors are distributed over a particular area (the targeted building) and monitor the passing vehicles. Furthermore, this improvised technique is a fixed-location technique and it is only applied to a building area.

The American department of defense directive 2000 19 E, (2006) [31]. The American DOD developed a technology for protecting their troops from the IED's that were targeted them heavily in Iraq and Afghanistan. This technology used to prevent the activation of the IED's that targeting the troops via an equipment in the Tanks that used to de-activate the signals that is sent by a sender device. This technology taken place in the military fields and reduced the casualties made by the IEDs. However, this technology is still for military use only and not for civilians. Additionally, it is an expensive and required an experts for technology implementation.

Mariusz Chmielewski, (2012) [32]. Sensor Amplified Perception for Explosives Recognition (SAPER) is a project created by a group of students in the military college in Warsaw, Poland. Students have invented an application that runs over a smartphone platform in order to make use of the features of built-in chipset sensors. This technology uses the magnetic sensor that built-in smartphone to detect the magnetic effects near 30 centimeters and send the information into a cloud-based central when a possible threat confirmed. However, this technology stays unclear.

Tamir Eshel, (2013) [33]. in his research on the modern technologies in detecting explosives by adding extra sensors to the smartphone to add an extra ability for sensing the environment for explosive materials. Research in this field has been at the naval research laboratory and developing advanced sensor technology for sensing the chemical composition of the explosives. This modern technology is expensive and requires a special type of sensor to implement such technology.

Srinivas Chakravarthy Thandu, (2014) [34]. A master thesis at Missouri University of science and technology discuss the effect of using accelerometer sensor for the explosives detection. The researcher discuss the effects and results of using an acceleration sensor for detecting an explosives and especially IED's. The experiments on this system use the accelerometer in the smartphone to measures the difference of the environmental reading when placing an explosives material nearby. This research based on using the accelerometer sensor rather than other sensors. However, the effect of using a magnetic sensor is more quality in detecting the magnetic explosives rather than the accelerometer sensor

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3. MEDS: The Theoretical Side

This section of the paper consists of five main tracks. The first track discuss the sensors within the MEDS from a detailed view. The second track discuss the wireless sensor network system and its details while the third track involves in explaining the general system structure with a detailed illustration. The fourth track of this section discuss the mathematical formulation and representation of the MEDS and fifth track discuss the algorithmic representation of the MEDS.

3.1 Magnetic sensor

MEDS is a WSN system that transmits data from sensors to the base-station for processing and analysis. MEDS extract the data from the environment using distributed sensors over a specific area range. Firstly, the search area specified at the MEDS in order to set the border limits for the system. There are many types of magnetic sensors that can be used to extract the magnetic field information as in [11] [12] [13]. MEDS system use a Micro-Electro-Mechanical Sensor (MEMS) sensors in the practical experiments. MEMS can be defined as a micro-size sensors work in different applications especially in industrial and scientific fields for the applications that requires a micro-size sensors [14].

The magnetic sensor used in the practical experiments of MEDS is three- dimension magnetic sensor. A three-dimension magnetic sensor obtain the data in 3d fashion, converting magnetic field information from the environment into three axis reading (X, Y and Z). Most of the MEMS sensors in modern applications are three-axis based sensors [15]. The magnetic sensor in MEDS affected by any magnetic field that emits from both magnets and metallic materials. Specifically, two types of magnetic field information can be extracted from the environment: the direct magnetic field and indirect magnetic field. The direct magnetic field is the magnetic field emits from a magnet itself where the reading appears more smoothly when extracting and digitizing the signal while the indirect magnetic field is the magnetic field that its information came from a metallic element that affected by a magnetic effector. Figure 1 shows a structural view of the magnetic sensor with internal parts [16].

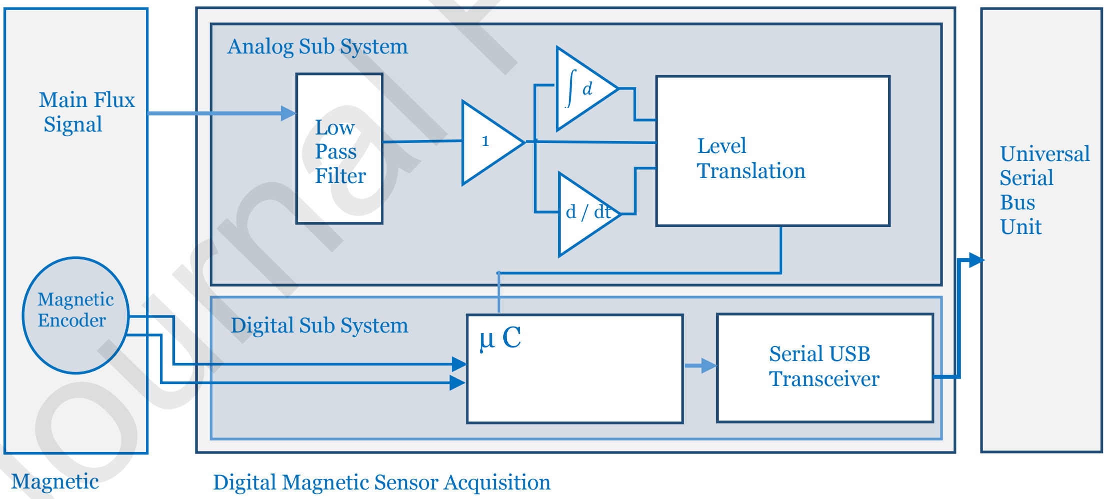

Figure 1. The internal structure of the magnetic sensor

When the magnetic signal enters the sensor range in its pure form it is converted to a digital signal by the use of logical circuit gates and micro-converter that work on digitizing the analog signal that came from the continues reading of the magnetic sensor. MEMS magnetic sensor operates the data in three different speeds: millisecond, second and 5 seconds depending on the type of application hence there are some applications that require critical and real-time reading. The connection between the magnetic sensor and the software applications made throughout the sensor framework as the sensor framework provides direct access to the magnetic sensor functionalities [17]. Furthermore, not only the magnetic sensor can be accessed through the sensor framework but all other types of sensors can be accessed throughout their framework.

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3.2 Wireless sensor network (WSN)

WSN is a communication system used to join a group of the sensor at a specific range [18]. The main communication scheme used in the MEDS is the wireless communication scheme (Wi-Fi) where the range of the system is 35 meter in diameter. The Wi-Fi network is a communication technology used to connect the network peers wirelessly within 35 meters of diameter range [19]. WSN system in MEDS used to connect the magnetic sensors with the base station which act as the system server. The base station responsible for receiving the data from the sensors and process these data according to the threshold value of possible threats.

The WSN control of all MEDS functions as it transfers the signals from the system server to the connected sensors and vice versa. The sensors are used to receive the magnetic flux and turn it into a digital signal then sent data packets to the server via the WSN, which in turn sends and receives data in client-server methodology [20]. WSN follows the protocol IEEE 802.16 as this protocol organize the communications of a specific set of wireless networks including the WSN system [21]. Figure 2 shows an illustration of the WSN system in MEDS.

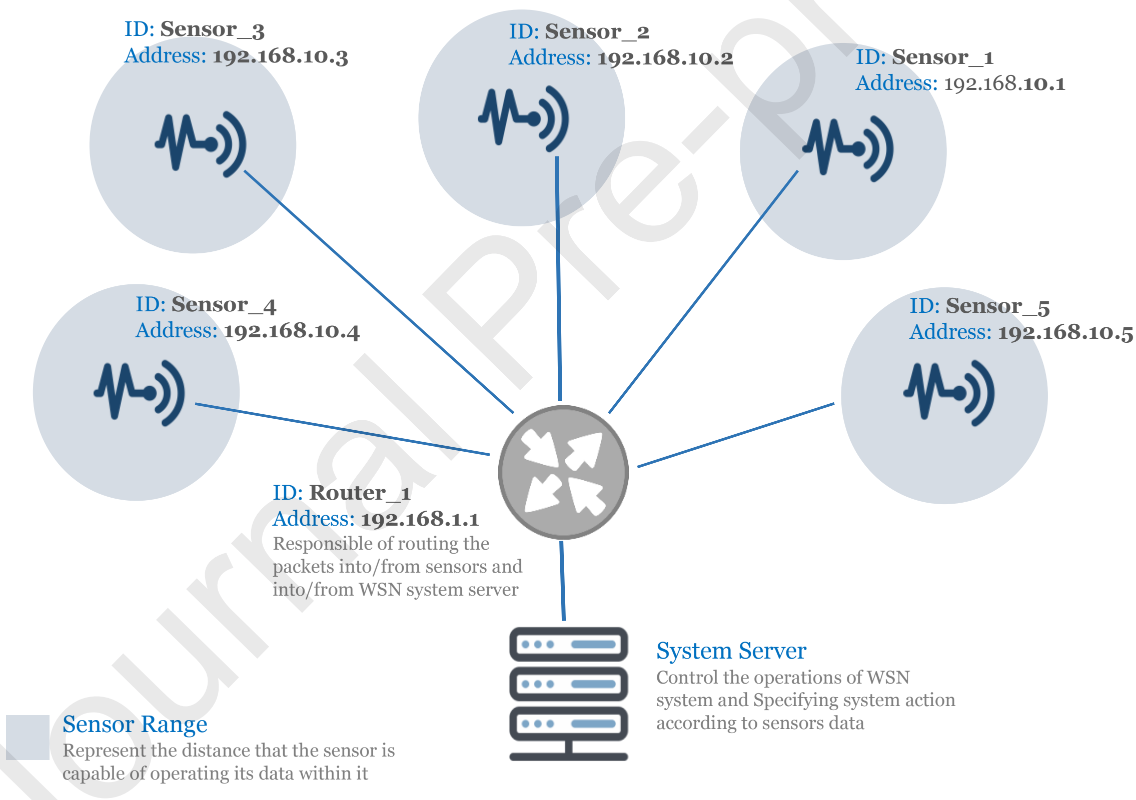

Figure 2. WSN structure in MEDS.

The interface between the system server and sensor nodes is the wireless router which acts as the main coordinator of the packets according to their IP address. The system server store the IP address of all the sensor nodes and forwards the packets alongside its IP address to the router in order to determine the packet destination. The system server contain the signal processing algorithms for the sensor nodes data, processing the signals and make a decision according to the sensor readings. The sensor reading follows TCP/IP communication protocol as a third-layer protocol [22] due to the need for reliable connection and integrity in data transmission.

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3.3 General system flowchart

Figure 3 represents the general MEDS flowchart and internal detailed structure

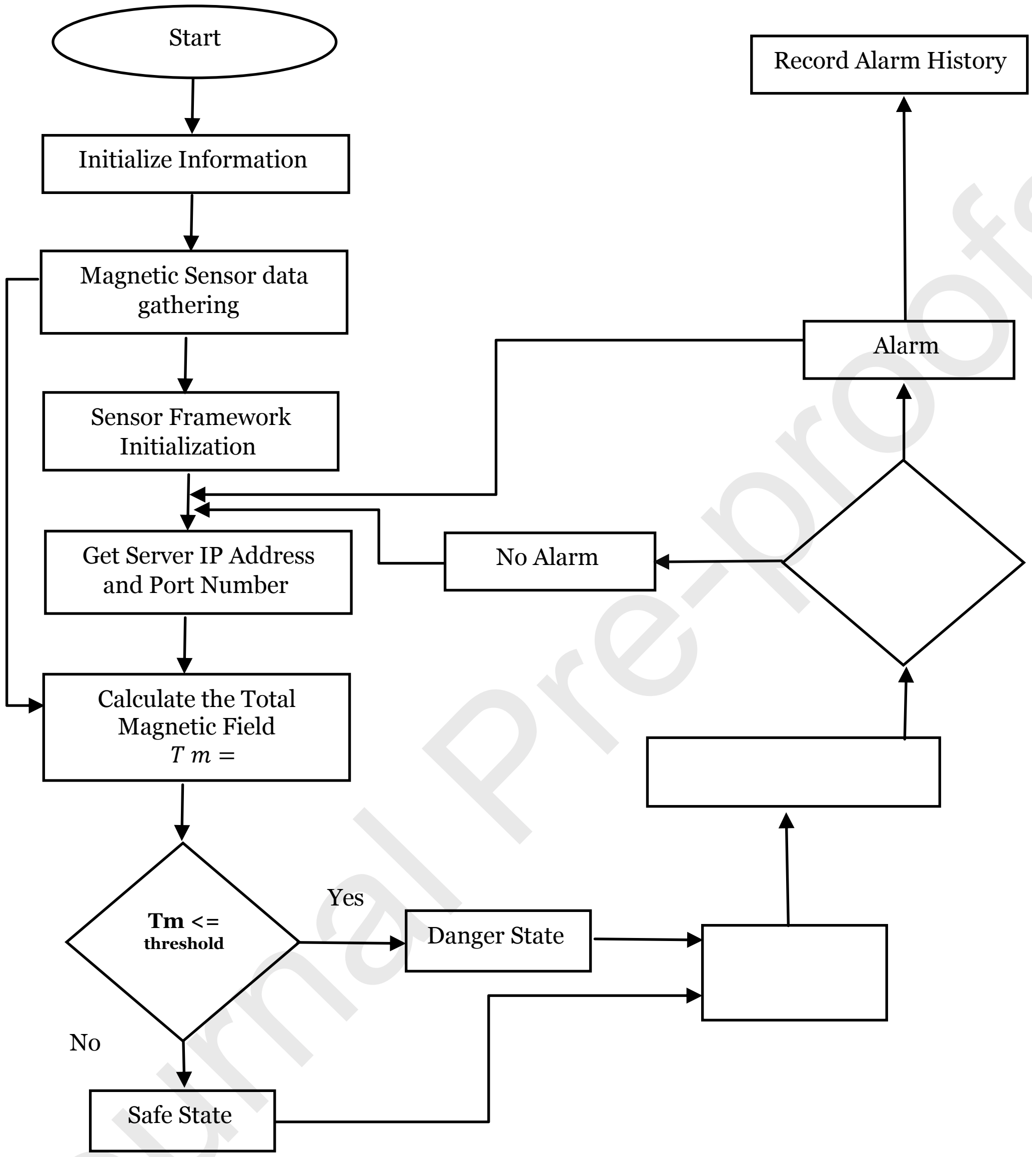

Figure 3. MEDS general flowchart.

The system starts by initializing the main information. The main system information includes IP addresses, port numbers, connection availability, algorithm state, network state, and sensor availability. The system server start gathering the data from the sensors throughout their framework. Afterwards, the system server initialize the framework information, setting up the connection information for the sensors through the related sensor framework. The sensor framework is mainly a programming library that can be used to manage most of the sensor operations. After getting the packets from the sensors, the calculation of the magnetic field readings and data analysis starts as the algorithms inside the system server activated. The MEDS algorithms work to obtain the probability of a threat according to an adjustable threshold. When the magnetic reading is above that threshold, a checking process is activated. Otherwise, the reading is ignored if it is below the threshold of the system. Thresholds settings are adjusted according to the system objectives. Magnetic sensor process in MEDS control of the assign of the system threshold to a specific value according to the average readings gained from the magnetic sensor readings.

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3.4 Mathematical Representation

This section contain the mathematical representation modal of the magnetic sensor in the MEDS. The main aim of the magnetic sensor is to detect the magnetic field alongside its intensity. According to the Bio-Savart principle [23], the intensity of a magnetic field can be calculated as in eq.1:

$$d\mathrm{B} = \frac{\mu_{0_{IdI} \times r}}{4\pi r^3} \qquad (1)$$

Where r is the vector from the current point to a specific point and IdI is the current element while B is obtained by the eq.2:

$$\mathrm{B} = \nabla \times \left[\frac{\mu_0}{4\pi} \int \frac{IdI}{r}\right] = \nabla \times \boldsymbol{A} \qquad (2)$$

where

$$\boldsymbol{A} = \frac{\mu_0}{4\pi} \int \frac{IdI}{r}$$

A represent the potential vector of the magnetic field. At a given point $p(x, y, z)$, the calculation of the three-axis magnetic induction represented in eq.3:

$$\begin{cases} BX = f[p(x,y,z).Ty(-90^o)].Ty(90^o) \\ BY = f[p(x,y,z).Tx(-90^o)].Tx(90^o) \\ BZ = f[p(x,y,z)] \end{cases} \qquad (3)$$

Where $Tx()$ and $Ty()$ are the angular rotation around the X axis and Y axis. Figure 4 shows an illustration of the 3d magnetic induction calculation.

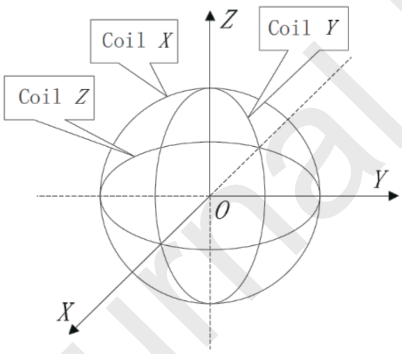

Figure 4: 3-axis magnetic induction calculation

The intensity of the magnetic flux can be determined in 3-axis with orientation (a, b, c) by eq.4 [24] which merge both eq.1, eq.2, and eq.3:

$$\begin{cases} B\acute{X} = BX.Tx(-a).Ty(-b).Tz(-c) = f[p(x,y,z).Ty(-90^o)].Ty(90^o).Tx(-a).Ty(-b).Tz(-c) \\ B\acute{Y} = BY.Tx(-a).Ty(-b).Tz(-c) = f[p(x,y,z).Tx(-90^o)].Tx(90^o).Tx(-a).Ty(-b).Tz(-c) \\ B\acute{Z} = BZ.Tx(-a).Ty(-b).Tz(-c) = f[p(x,y,z)]\,.Tx(-a).Ty(-b).Tz(-c) \end{cases} \qquad (4)$$

After intensity is determined, negative values will results from the reading in eq.4 due to the rotation process. To prevent the negative values from affecting the sensor reading and have more accurate results the absolute magnetic readings are determined by the eq.5:

$$\begin{cases} |BX| = |B\acute{X}| = \sqrt{{B\acute{X}_x}^2 + {B\acute{X}_y}^2 + {B\acute{X}_z}^2} \\ |BY| = |B\acute{Y}| = \sqrt{B\acute{Y}^2{}_X + B\acute{Y}^2{}_Y + B\acute{Y}^2{}_Z} \\ |BZ| = |B\acute{Z}| = \sqrt{B\acute{Z}^2{}_X + B\acute{Z}^2{}_X + B\acute{Z}^2{}_X} \end{cases} \qquad (5)$$

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3.5 System Algorithm

Algorithm 1 represents the first algorithmic representation of the MEDS. The number of sensors n initialized at the beginning of the system activation. As we previously discussed, the sensors can be accessed through their framework. The system algorithm start the initialization of the sensor framework f for each sensor node as an iteration performed to process all nodes. Framework initialization includes the sensor IP address IP_B and the sensor port number P_B. Afterwards, the system algorithm examines the connectivity of the sensor units and reserve those who are not active in a special type array $ideal[]$ for the restricting of in-active sensor units and maintain the active unit in another array $Active[]$.

ALGORITHM 1: first MEDS algorithm

Input: $IP_S, IP_B, P_S, P_b, f, B_x, B_y, B_z, \mathbf{f(x)}, Int_S, n, So$
Output: $Msg_N, pckg_{N,S}, \ddot{Int}_S, B_{total}$

Start
$\dot{f} = \sum_{i=1}^{n} initilize(f, IP_S, P_s)$
for i = 0 to n
  $Connection_s{}^i = check_{connection}(IP_{S,i})$
  if$(Connection_s{}^i \,!= true)$
    $ideal[Connection_s{}^i]$
  else
    $Active[Connection_s{}^i]$
end for
while $(N\,! = end\_of(Active[]))$
  do
  $Connection_s{}^N = open\_server\_port(IP_B, P_b)$
  $|BX| = |B\acute{X}| = \sqrt{B\acute{X}_x{}^2 + B\acute{X}_y{}^2 + B\acute{X}_z{}^2}$
  $|BY| = |B\acute{Y}| = \sqrt{B\acute{Y}^2{}_X + B\acute{Y}^2{}_Y + B\acute{Y}^2{}_Z}$
  $|BZ| = |B\acute{Z}| = \sqrt{B\acute{Z}^2{}_X + B\acute{Z}^2{}_X + B\acute{Z}^2{}_X}$
  $B_{total} = \sqrt{|BX^2| + |BY^2| + |BZ^2|}$
  $\ddot{Int}_S = compute\_intensity(Int_S)$
  $pckg_{N,S} = encapsulating(B_{total}, \ddot{Int}_S, IP_B, P_s, IP_B, P_b)$
  $Msg_N = forward\_msg(pckg_{N,S}, So, TCP/IP)$

endWhile
End

The system algorithm start the data gathering process as the connectivity checking accomplished successfully and the connection between the base station and the sensor nodes are maintained. The data gathering process depends mainly on the active nodes array $Active[]$ as it contains the currently active nodes of the MEDS. The connection between the sensor node and the base station performed by opening the connection port from the server-side in order to enable the sensor unit from sending the data package. After the sensor unit calculate the total magnetic field B_{total} and its intensity $\ddot{Int}_S$, the communication process within the algorithm work on encapsulating the data into one package and send it to the server unit via sockets So. The socket work on regulating the process of package forwarding through the TCP/IP protocol.

After the packet is received by the server unit, the MEDS activate the second part of the algorithm which involves in the data analysis process. Algorithm 2 represents the second part of the MEDS algorithm on the server-side.

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ALGORITHM 2: second MEDS algorithm

Input: $E_f, B_{best}, A_{state}, Msg_N, pckg_{N,S}, \ddot{Int}_S, B_{total}, T, P$
Output: $E_{state}, P_{state}, A_{state}$

```
Start
Initialize(T)
Initialize(P)
while (N != end_of(Active[]))
    do
        M = recieve_msg(Msg_N, So, TCP/IP)
        pckġ_{N,S} = decapsulating(B_total, Int_S, IP_B, P_s, IP_B, P_b)
        Ḃ_total = pckġ_{N,S}. B_total
        Inṫ_S = pckġ_{N,S}.Inẗ_S
        A_state = Validating(Ḃ_total, Inṫ_S)
        if(A_state ≥ T)
            for(i = 0 to p)
                if(A_state.P ≥ P)
                    P_state= Neural_Network (A_state)
                else
                    P_state="BY_PASS"
            end for
        else
            E_state, ="FALSE"
        end if
        if (P_state=="ALARM")
            pckg_{N,S} = encapsulating(P_state, Inẗ_S, IP_B, P_s, IP_B, P_b)
            Msg_N = forward_msg(pckg_{N,S}, So, TCP/IP)
endWhile
End
```

The main validation process in MEDS taken place at the server-side algorithm where the data is processed by the validation function $Validating()$. The output from algorithm 1 enters algorithm 2 as input and the output of the algorithm 2 extracted as the system output. The first process in algorithm 2 is the initialization of both system threshold T and reading time P. The active sensor array $Active[]$ tested to find the packages that came from these sensor nodes.

The validation function takes the total magnetic sensor reading B_{total} and the related intensity $\ddot{Int}_S$ in order to be analyzed according to the system requirements. The validation function returns a pure reading from the process of combining both magnetic sensor reading and its intensity, producing a numerical form that is processed in the next algorithm steps. The time iteration process received packages according to their period of activity. Firstly, the magnetic reading examined according to the threshold. If the magnetic reading is larger or equal the threshold value then it is considered as a probability state P_{state}. If not, it is considered as an error state E_{state} that determines a false alarm reading.

The determination of the P_{state} depending on the period of activity in the process of gathering magnetic reading. The magnetic reading package received in every 5 seconds from the sensor. Meanwhile, the server unit algorithm checks the old packet and the current packet that came from the same sensor unit. If the reading of the magnetic field sensor changed then a bypassing state indicated. Otherwise, the system will check the stability of the reading, if it is stable in the both of the incoming packages then it is a possibility for the magnetic object settled in and could be a magnetic explosive. When an alarm state indicated, the algorithm starts a forward process at the same sensor unit and encapsulating the packet using the same TCP/IP protocol. The message Msg_N contains the state of the reading validation and thus an alarmed voice rising in both of server unit and sensor network unit.

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4. MEDS: The Practical Side

The practical side of the MEDS consists of three main tracks. The first track in this section discuss the software internal structure with all related details. The second track discuss the requirements and related specifications for system implement on real-world. The third track discuss the implementation of neural network algorithm within the MEDS.

4.1 Software Structure

Figure 5 illustrates the main software structure in the sensor unit within the new MEDS.

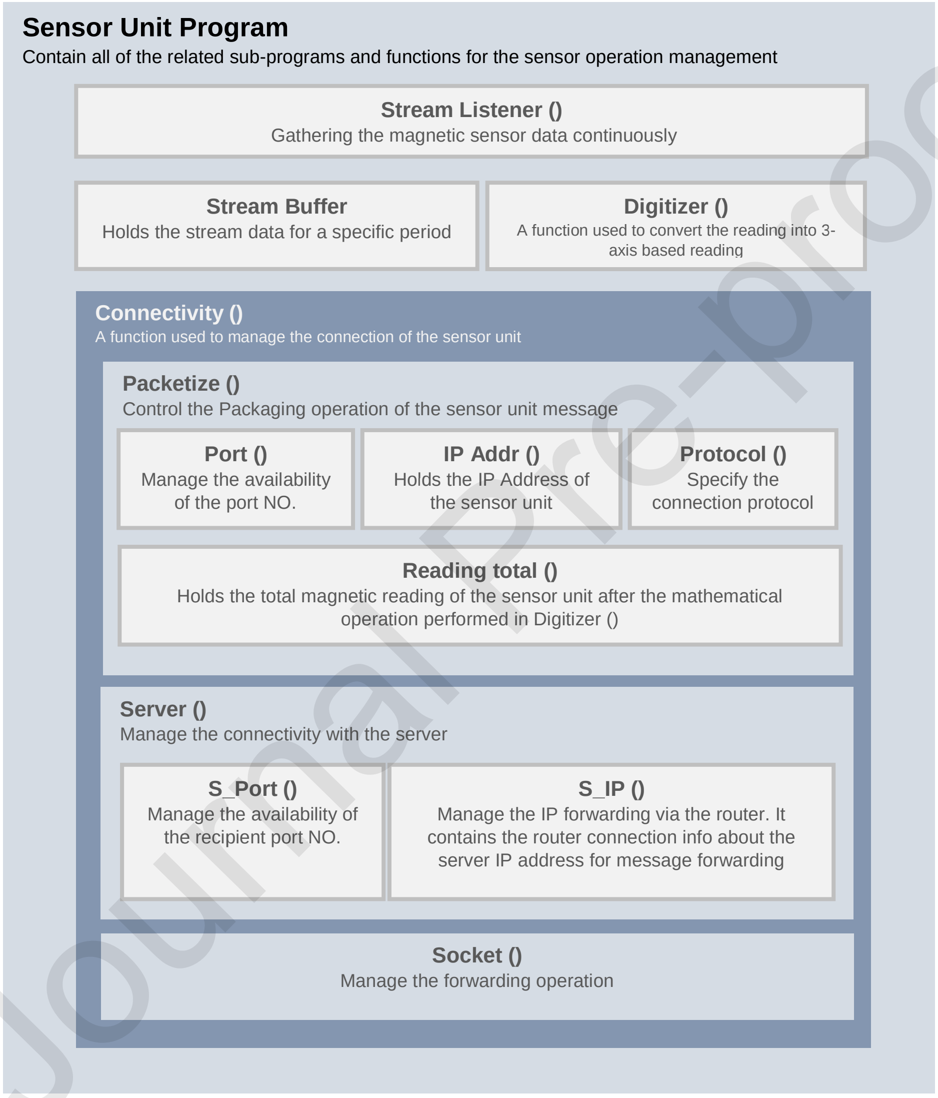

Figure 5: Main software structure of the MEDS sensor unit

As illustrated in figure 3, the sensor unit program contains all the functionality that is operated by the sensor unit. Sensor unit program consists of three main functions. The first function is the stream listener function that is used to sense the magnetic field in the environment as this function operates in a continuous fashion over time. The stream listener function store the result for each time period in a stream buffer that works as intermediate storage for the other functions. The digitizer function work to compute the total magnetic field value by determine the 3-axis reading of the current magnetic field. The largest function in the sensor unit program is the connectivity function which takes advantage of overall connections of the sensor unit as it controls the message forwarding and message packetizing

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Figure 6 illustrates the main structure of the server program within the MEDS.

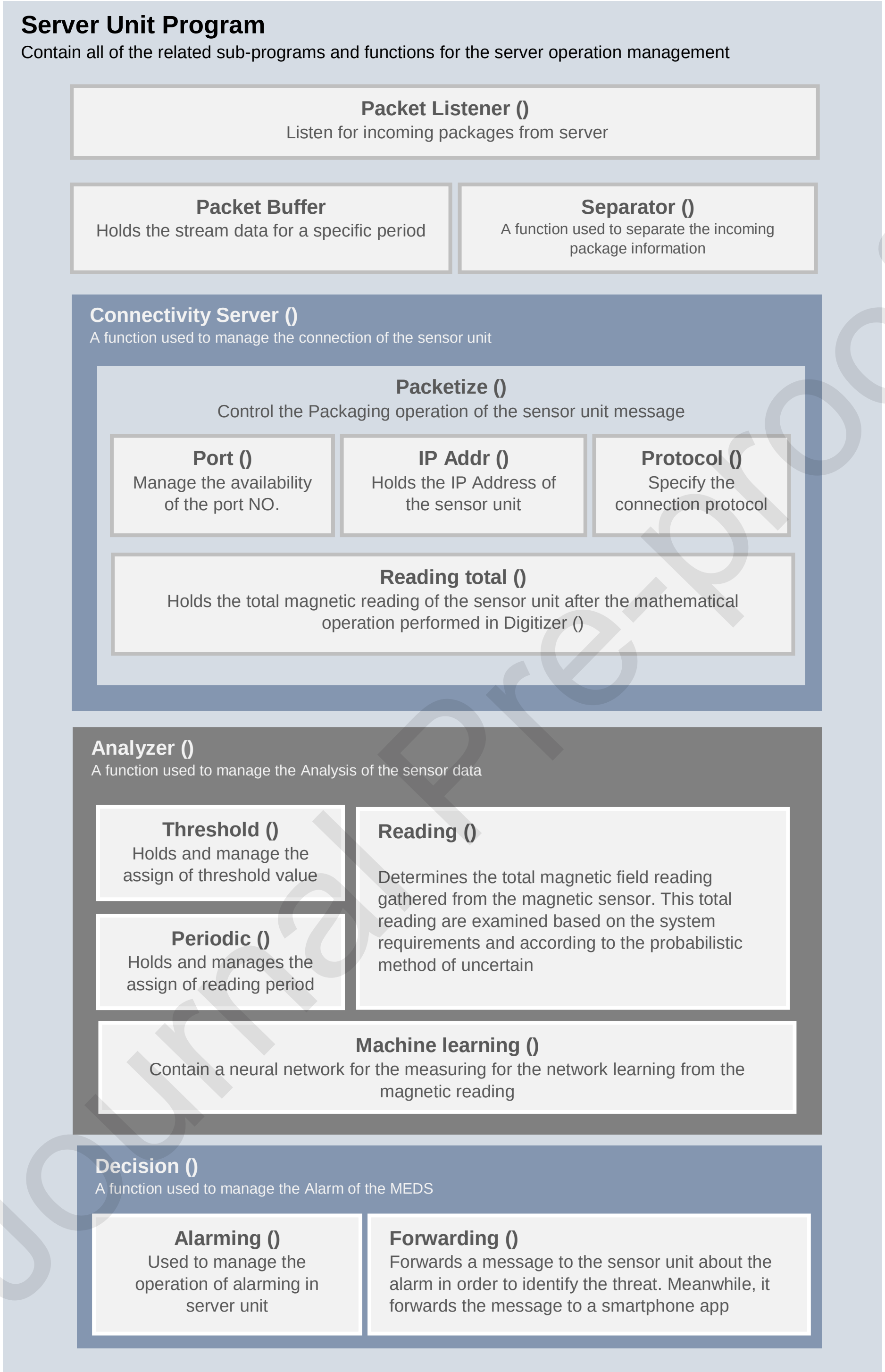

Figure 6: Main software structure of MEDS server unit

The server unit program is more complex then sensor unit program as it is responsible for analyzing the incoming sensor data and make a decision. The server program contains six main functions. Packet listener function responsible for handling the incoming packets while the packet buffer work on storing the packet for each period of time. The separator function work to separate the packets info's as each packet need to be processed. The connectivity server controls the operation of server connectivity with

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the sensor nodes as it contains the same information and procedures of the connectivity function within the sensor unit program.

The analyzer function works as the main data analysis function hence it receive the magnetic reading from the connectivity function and processes the reading according to the internal methods. Firstly, the analyzer function check the threshold method for the system condition. If the threshold condition is met then the periodic method examine the period of the magnetic reading in order to analyze the reading stability. Additionally, the analyzer function forwards processed conditional reading to the machine learning method. The neural network method used in MEDS programming to enable machine learning in the MEDS.

The last function is the decision function. Decision function responsible for determining the alarm state and message forwarding in case of an alarm. When a threat state is determined, the decision function start an alarm state function that works on raising the alarm on the server unit. Meanwhile, an alarming message is forwarded into the sensor units telling them about the coordination of the alarm in order to raise an alarm at the sensor unit itself. At the same time, the decision-making function process the alarm state and forwards it to the special type app installed on a smartphone.

4.2 System Requirements

In order to implement MEDS in real-world, there are multiple requirements need to be available. Table 1 shows the hardware requirements of the MEDS with its related descriptions

Table 1: the hardware requirements for the MEDS

Name	Description	Role in MEDS
Honeywell HMC 1053	A micro-electromechanical sensor used to detect the magnetic field from the environment. This type of magnetic field is highly sensitive to low magnetic field intensity [24]	Act as the sensor nodes for gathering magnetic field data from the environment and forward this information to the server
Extrinsic MAG 3110	A micro-electromechanical sensor used to detect 3-axis magnetic field data as this type of sensors used in robotics and smartphones [25]	Act as the sensor nodes for gathering magnetic field data from the environment and forward this information to the server
Android Smartphone	An android based smartphone for the detection of the magnetic field and receiving an alarm signal from the system server. A special type app installed in the smartphone in order to integrate with the system	Act as a portable sensor node and additional system receptor for the alarm process
Wi-Fi Router	Wi-Fi router used for the communication between the sensor nodes and the system base station (system server). The chosen Wi-Fi router is due to its ability to provide a coverage area up to 35 meter in diameter [26]	Act as the main communication link for the system communication
Windows PC	The windows PC machine installed and act as the main system server that contains the system algorithms and operations. Windows PC is connected to the sensor nodes via a Wi-Fi router	Act as the main system server for holding, processing, and forwarding data from/into sensors and from/into the smartphone
Arduino board	Electronic circuits grouped in the single board to enable direct communication between the software and the hardware sensor units. Arduino is an open source technology that can be customized and programmed according to the required objectives [27]	Used to connect the software of the MEDS to the sensor units in the system in order to manage the data gathering and transfer

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4.3 Machine learning: Implementation of the neural network

The server-side application in MEDS contains the machine learning method that works to predict the next reading positions and intensity. The main aim of adding machine learning to the MEDS is to enable the system from identifying the current safety state and predict the future state of the magnetic readings. The machine learning algorithm used in this paper is the neural network algorithm. A neural network is a general artificial intelligence algorithm that solves complex problems and enables the machine/system from learning throughout the trial and error [25].

The neural network algorithm consists of four main parts. The first part is to the backward propagation of the data. The backward propagation of the data means that the output of the data returns to effect on the next input. Eq.6 shows the details of output propagation of the neural network.

$$O_j = \varphi(net_j) = \varphi\left(\sum_{k=1}^{N} w_{ij}\, O_k\right) \qquad (6)$$

Where is the input of the network φ and O_k is the output of the previous iteration. The N represent the number of iteration in the neural network system while k is the counter for such an operation. The second part is about the chosen of the appropriate activation function. The activation function in the neural network responsible for drawing the shape of the outputted data as it is the main coordinator of the neural network data propagation [26]. The chosen of the activation function depends on the objective of the system hence each one of the activation function produces a different effect. Eq.7 shows the details of activation functions in the neural network algorithm.

$$f(x) = \begin{cases} identical: \ f(x) = x \quad r(\infty, -\infty) \\ binary\ step: f(x) \begin{cases} 0: x < 0 \\ 1: x \geq 0 \end{cases} \quad r(0,1) \\ logistic: f(x) = \sigma(x) = \dfrac{1}{1+e^{-x}} \quad r(0,1) \\ square\ non-linear: f(x) = \begin{cases} 1: x = 2.0 \\ x - \frac{x^2}{4}: 0 \leq x \leq 2.0 \\ x + \frac{x^2}{4}: 0 \leq x \leq 2.0 \\ -1: x = -2.0 \end{cases} \quad r(-1,1) \\ Soft\ Exponential: f(\propto, x) = \begin{cases} \dfrac{-\ln(1 - \propto (x + \propto))}{\propto} : \propto < 0 \\ x : \propto = 0 \\ \dfrac{e^{\propto x} - 1}{\propto} + \propto : \propto < 0 \end{cases} \\ Parameteric\ rectified\ linear\ unite: f(\propto, x) = \begin{cases} \propto x : x < 0 \\ x : x \geq 0 \end{cases} \end{cases} \qquad (7)$$

The third part of the neural network algorithm is the error function. The error function responsible for computing the error value that results from the neural propagation process [27]. The main aim of using the error function is to determine the correctness in the neural network operation in order to adjust the required settings. Furthermore, all of the systems that use the neural computing system work on reducing the error value as possible. The error value represents the difference between the current output and the desired output. Eq.8 shows the details of the error function in the neural network algorithm.

$$E_f = \frac{1}{2}(t - y)^2 \qquad (8)$$

Where t represent the desired output of the training sample and y is the actual layer output. The neural network algorithm may contain more than one hidden layer. The hidden layer is a computation layer that works to derive the outputted signal in the appropriate direction.

The final part of the neural network algorithm is weight training. The weight training is the place where the neural network results can be adjusted. The weights are arrays of values that implement the user desired directions in the outputted signal [28]. The weight training process performed to enable the change in the layer output where each neuron in the neural network contains a weight value. There are

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two main parts that the neural network output can be adjusted, the first part is the weights while the second part is the activation function. The weight training performed depending on the training rate, which is another important factor in the learning operation as the weight values generation depends on the training rate as the main factor of generating the new weights. The output of the new weights is updated to the neural computing method in order to adapt the system with the new weights and get the desirable results. Eq.9 shows the details of weight training in the neural network algorithm.

$$\Delta w_{ij} = \sum_{i=1}^{N} -\eta \frac{\partial E}{\partial w_{ij}} \qquad (9)$$

Where η represent the training rate, E is the error rate, w_{ij} is the previous weight value, N is the neuron count in the layers and i is the counter of the update process. In order to enable the neural network from processing the sensor data, the original neural network algorithm should be adjusted and adapted with the parameters of the MEDS. Algorithm 3 represents the neural network algorithm in MEDS with its details.

ALGORITHM 3: neural network in MEDS

Input: $N, h, w_{ij}[], f(x), \partial, \eta, S_{id}, server.state, th$
Output: $Mag, B_{best}, Error_{rate}$

Start
$Initialize(N)$
$Initialize(h)$
$Initialize(w_{ij}[])$
$Initialize(f(x))$
$Initialize(\partial)$
$Initialize(\eta)$
while ($server.state$!= "**deactive**")
do

$$O_j = \varphi\left(\sum_{k=1}^{N} w_{ij}\, O_k\right)$$

$\dot{Mag} = f(O_j)$

$$Error_{rate} = \frac{1}{2}\left(d - O_j\right)^2$$

if($Error_{rate} \leq th$)
{
  $desicion(\dot{Mag}, S_{id})$;
  $B_{best} = O_j$
}
Else
{

$$\Delta w_{ij} = \sum_{i=1}^{h} -\eta \frac{\partial Error_{rate}}{\partial w_{ij}}$$

  $update(\eta)$

  $update(w_{ij}[])$
}
endWhile
End

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The neural network algorithm within MEDS start by initializing the main parameters where N is the number of iteration, h is the number of hidden layers, $w_{ij}[]$ is the weight array, $f(x)$ is the activation function, ∂ is an adjustable control variable and η is the learning rate. After the parameters initialized, the algorithms start by checking the main condition which is the server state$server.state$. The server state variable is an object-oriented variable that contains the state of the server wither it is active or deactivated. The data propagation start by the computing of the layer output according to the iterations and stored in O_j . The magnetic field reading determined by the activation function while the output propagation performed. The error rate $Error_{rate}$ examined to determine the error rate of the current iteration and compare with the targeted values (desired values). If the error rate is less or equal to the threshold variable th then the algorithm indicates that it is the best position for the current state. Otherwise, the algorithm continues to update the weights Δw_{ij} and learning rate η to produce the required output results.

As discussed previously, the neural network algorithm method placed in the server-side application. Under the $analyzer()$ function in figure 4, the neural network activated to receive a series of magnetic sensor reading in order to be processed and finding the best reading among a series of readings. For the MEDS, we seek for the higher magnetic field reading in order to be processed as a threat possibility. The programming of the neural network algorithm is made by the use of C# in order to integrate with the server-side application.

The type of neural network used in the MEDS is the feed-forward backpropagation and the network designed to give feedback at each output process. Two arrays have been defined inside neural network modal. The first array is for holding the input data as the input data is the magnetic field information from the magnetic sensor and the second array is for holding the target data information. Target data is the threshold value where the magnetic field data is examined and compared with it to determine the safety status of the current state. The two arrays synchronized together while inside the neural network as the first array act as the system initial input and the second array represent the desired target output. The first process is propagating the input array into the layers and apply the training, adaptation and the transfer function.

The training function responsible for train the network as the network are feed-backed by the output of the previous process. The adaptation function responsible for adapting the weights of the network as the weights are the control parameters that allow the network to be adjusted. The transfer function main objective is to organize the transfer operation of the neuron signal as the neuron signal transferred from layer to another through the transfer function. The neural network consisting of two layers to train the MEDS data as more layers means more complicated programming but in turn, it gives a deep learning process that can deal with big data in any future extension for the system. Figure 7 shows the neural network structure for the training of MEDS data.

The path from which the input taken placed until it is processed as output is named as “Credit Assignment Path” (**CAP**) [35]. The details of CAP calculation illustrated under figure 7 as the computing of the signal CAP depending on the neural network type.

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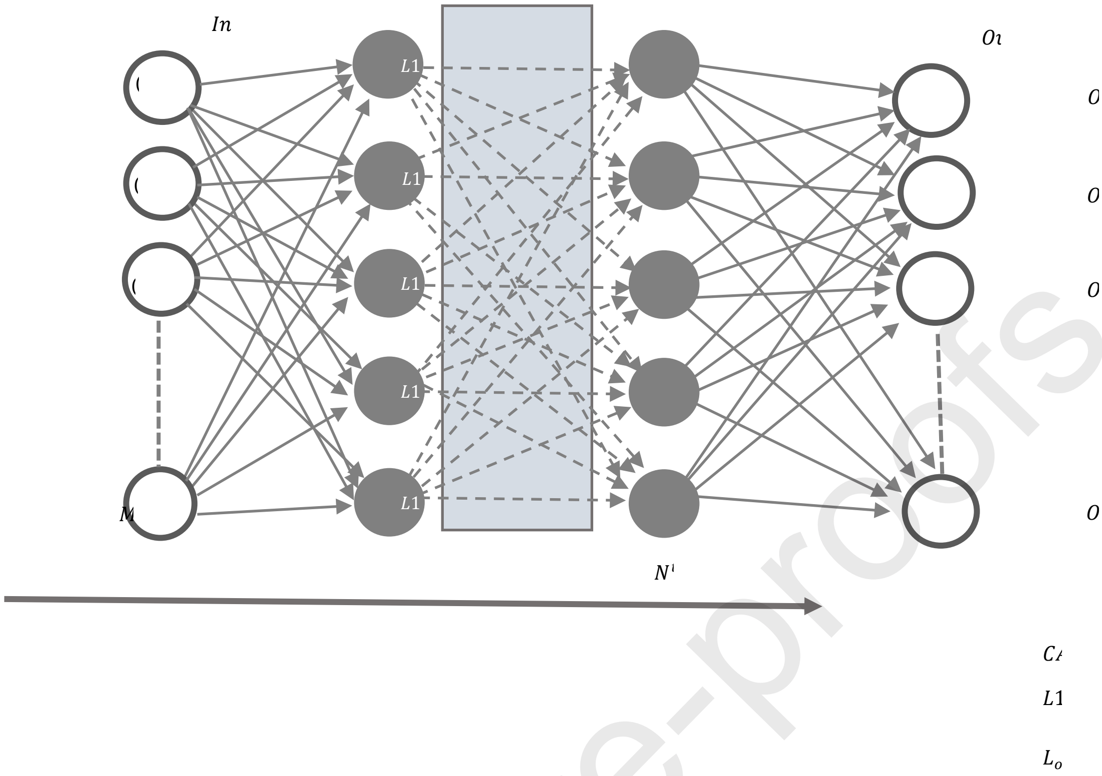

Figure 7: The structure of the neural network in MEDS as it contains two hidden layers for processing the input signals.

5. MEDS: Implementation and Results

This part of the paper represent the experiments and results of real world MEDS implementation. This section falls into two main classes: the first class is illustrate the real-world implantation of the MEDS and its details. The second class involve in illustrating the results of the intelligent mode in the MEDS where the intelligent mode enable the neural network algorithm.

5.1 Real-world experiments

The testing is the most important part of the process of system production. The test methods take three forms: the first form is the online mode where all nodes are connected together and the system is fully connected to the server through the Wi-Fi network. The second experiment take place when the sensor and server only connected. The third experiment are when the offline mode where smartphone app act as a server and client for offline situations.

After the activation of the magnetic field sensor the initial magnetic field in free space and without any metallic or magnetic effector between 30 to 40 µT. Figure 8 shows the modal of the experiment and sensor placement. The experiment uses two magnetic sensors distributed over the vehicle body. Sensors are placed under the vehicle to monitor the magnetic field state.

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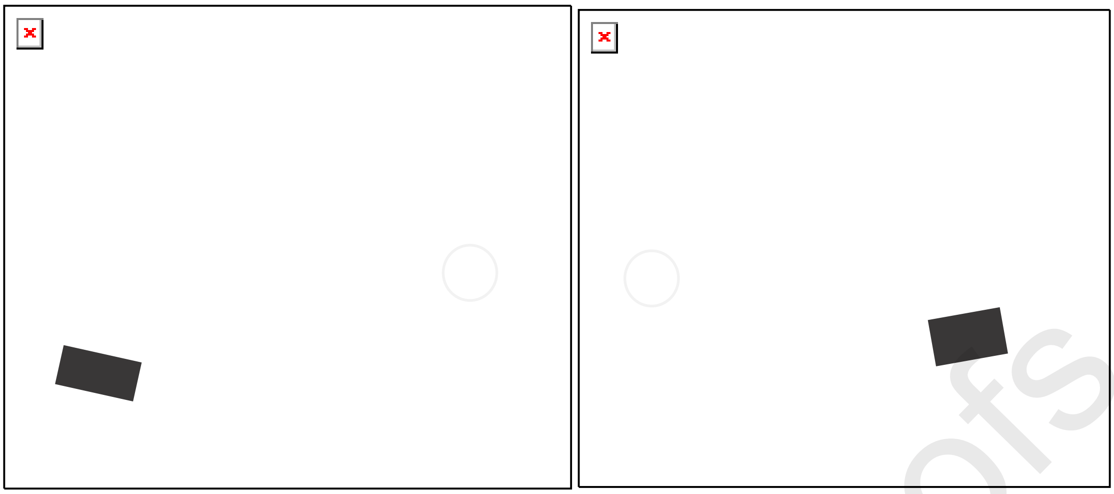

Figure 8: MEDS sensor placement under the vehicle. The white circle shows the exact location of the magnetic sensor were two sensors units placed at the left and right side of the vehicle.

The smartphone node placed inside the vehicle so as to provide extra coverage into the system and test its connection ability with the server application. Figure 6 shows the placement of the smartphone inside the vehicle. When placing the smartphone inside the vehicle, it is important to make sure that the app in the smartphone is connected to the router of the MEDS and have a connection with the server side application. The server-side application contains an analytical interface that holds information about the currently connected devices. When the connection performed between the sensor nodes, smartphone, and the server side application the system then start obtaining the data from the environment and enable the analyzing process in the server application.

For applying a magnetic effect on the vehicle, we use the same magnet that is used in the magnetic explosives and placed under the vehicle. The system registers the full movement of the magnetic field from the moment it enters the magnetic sensor range to the moment of the magnet sticks to the vehicle metal. Figure 9 and figure 10 shows the magnet placement under the vehicle. The registered readings represented in table 2.

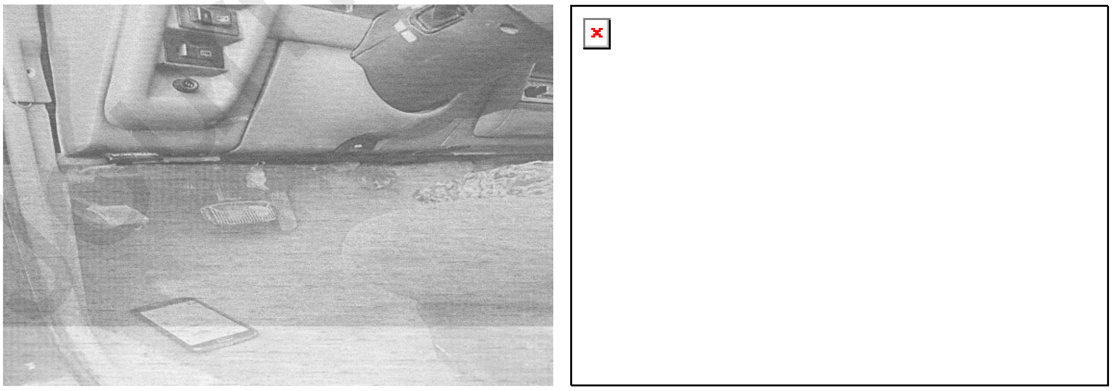

Figure 9: MEDS smartphone placement inside the vehicle.

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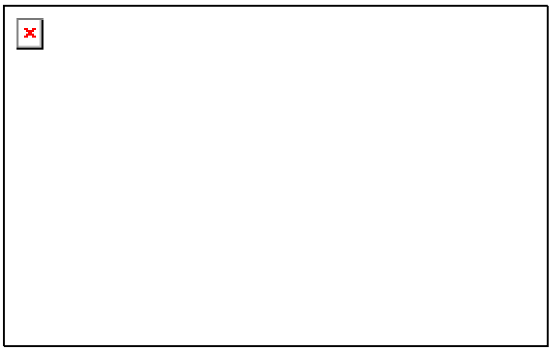

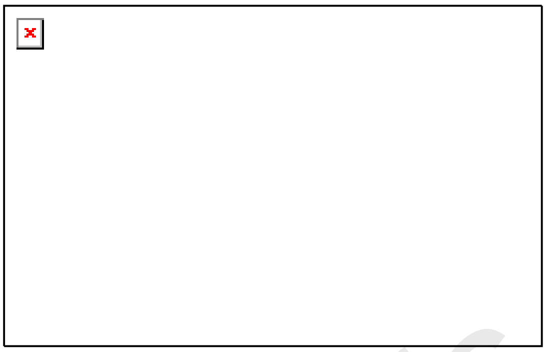

Figure 10: the magnetic effector under the vehicle. The experiments use two magnet types to measure the possible difference in readings.

Table 2: the magnetic readings from sensor units of the MEDS.

Distance from vehicle body	Left sensor	Right sensor	Smartphone
100 cm	40.3 µT	42.2 µT	34.5 µT
95 cm	41.2 µT	42.2 µT	35.6 µT
90 cm	43.7 µT	41.2 µT	37.6 µT
85 cm	44.2 µT	43.2 µT	40.1 µT
80 cm	49.5 µT	49.1 µT	49.3 µT
75 cm	52.0 µT	50.2 µT	48.2 µT
70 cm	55.2 µT	60.3 µT	50.1 µT
65 cm	59.3 µT	62.2 µT	51.3 µT
60 cm	65.5 µT	62.1 µT	55.2 µT
55 cm	71.2 µT	69.1 µT	59.3 µT
50 cm	71.3 µT	71.3 µT	60.1 µT
45 cm	79.9 µT	73.2 µT	62.3 µT
40 cm	82.3 µT	95.4 µT	66.7 µT
35 cm	107.2 µT	140.5 µT	72.2 µT
30 cm	220.8 µT	190.4 µT	80.3 µT
25 cm	360.2 µT	260.3 µT	82.2 µT
20 cm	390.9 µT	280.8 µT	84.3 µT
15 cm	420.2 µT	403.2 µT	120.7 µT
10 cm	550.3 µT	501.2 µT	260.8 µT
5 cm	800.4 µT	610.3 µT	420.9 µT
0 cm	1004.5 µT	800.2 µT	607.2 µT

Figure 11 shows a graphical representation of the extracted results.

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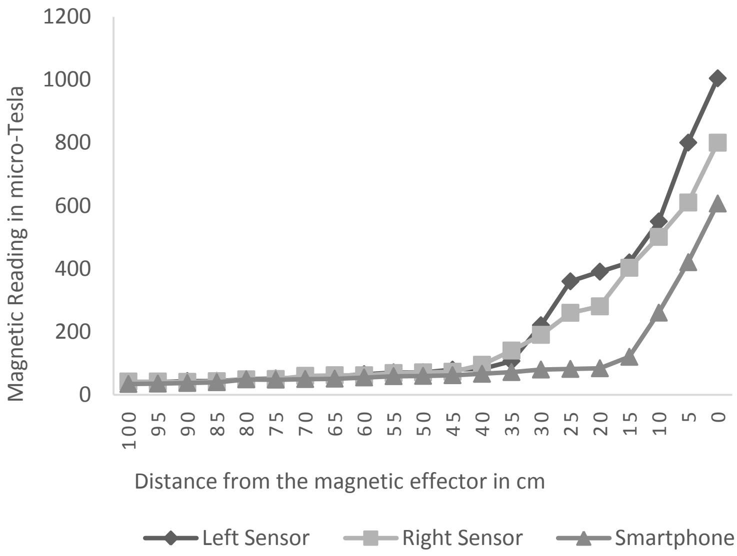

Figure 11: the graphical representation of the results gained from the sensor units of the MEDS.

5.2 Machine learning mode experiments

After getting the results from the magnetic sensors distributed under and inside the vehicle it's the time for enabling the machine learning mode in order to enable predictability within MEDS to view the next expected positions of the magnetic reading. The system registered data in the previous section altered many times with different positions. Multiple experiments were made to provide the neural network with the dataset of the registered reading. Figure 12 shows the details of the multiple experiments that act as the dataset for the neural network method.

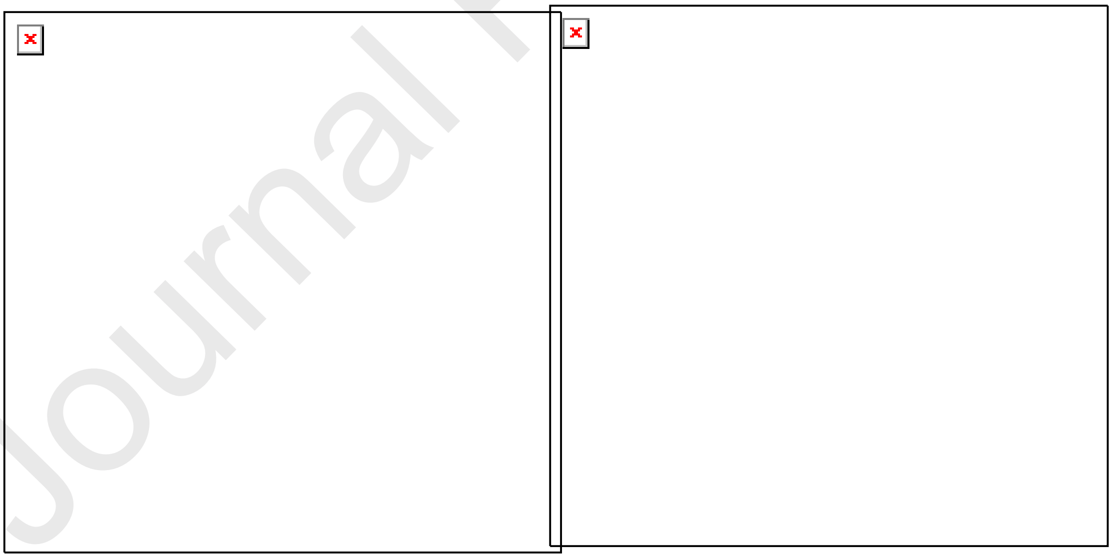

Figure 12: (A) represents the magnetic reading where the effector placed in the left side sensor. Note that the left sensor has a greater sensitivity from the right side. (B) Represent the experiment where the magnetic effector placed directly under the driver seat. Note that the left sensor and smartphone have greater sensitivity than the right sensor.

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After applying the machine learning mode, results of the iterations of the neural network and the data details can be represented in figure 13. In order to plot the data resultant from the neural network method we use the Matlab in order to generate the graphical representation of the data.

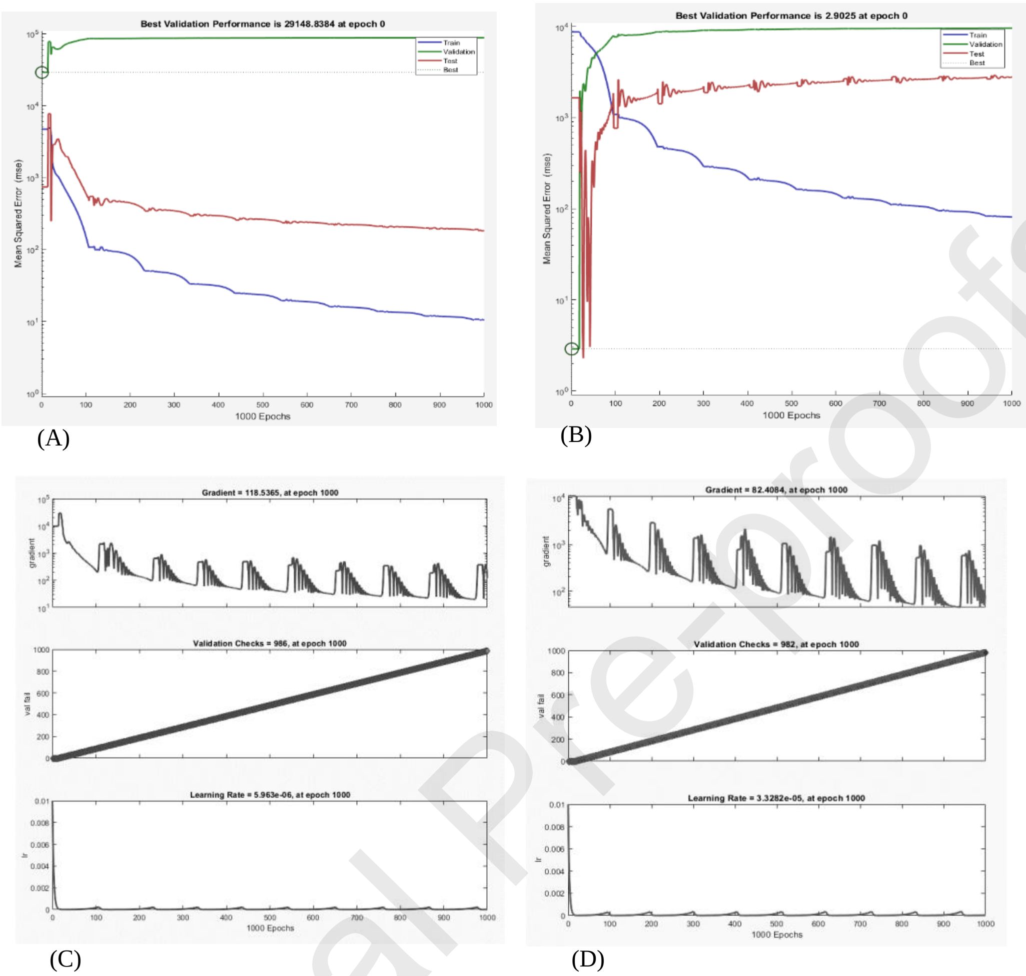

Figure 13: (A) represents the testing, validation and best position recognition of the machine learning method for the magnetic readings with 1000 iteration. (B) a second experiment that represents the testing, validation and best position recognition of the machine learning method for the magnetic readings. (C) and (D) represent the training of the network during the implementation of the neural network method

The implementation of the neural network algorithm gives excellent results in predicting the best positions with higher magnetic reading. The neural network parameters at the implementation time can be seen in table 3.

Table 2: the magnetic readings from sensor units of the MEDS.

Control Parameter	Description	Value
Learning rate	Specify the rate that the network learns according to its value	0.01
Number of iterations	Defines the number of iteration performed by the network	1000, 100000
Weights	Defines the customization of the neural network output	[0, 1]
Learning increment	Defines the incremental value of the learning rate	0.03
Activation function	Defines the output of the layer	Logistic
Target data	Defines the target which the neural network seeks for	[2000, 2300]

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6. Conclusion and future challenges

MEDS is a wireless communication system that use the concept of distributed sensors to cover a certain area. The main objective from the MEDS is to detect the threat of magnetic sensor remotely to prevent the damage caused by the explosives through the pre-detection. The paper structured into three main parts.

The first part discusses the theoretical aspects with the mathematical representation, algorithm structure and system structure. The second part involves exploring the practical experiments and the details of the software. First, the internal structure of the software alongside with the internal methods and functions are discussed, secondly, the theoretical, mathematical and algorithmic structure of the machine learning. The algorithm that is used in order to enable machine learning to the MEDS is the neural network algorithm is discussed. For integration purposes, the neural network algorithm programming made by the same programming language that used to build the server-application. A special type of smartphone app was built to enable the system user from identifying the threat by receiving the signal from the system server.

The practical experiments that were made to express the validity of the MEDS show excellent performance when there is a magnetic effector. The main objective of building MEDS is to protect the civilians and military vehicles from such a threat. The experiments made by using an SUV vehicle to monitor the system behavior when placing a magnetic effector. The magnetic effector used in the experiments was the same type of magnetic effector that is used by the magnetic IED. After the installation and implementation of the MEDS, the results of the magnetic reading were registered and analyzed in the server-side application.

Two modes of experiments have been applied. The first mode of experiments was made by normal execution of the system and receiving the magnetic field signals from the sensors. The first experiment was made by placing the magnetic effector under the left side of the vehicle. The magnetic reading in the left sensor ranged from 40 to 1004 µT while the right sensor readings ranged from 42 to 800 µT. the smartphone app reading ranged from 34 and 607 µT. multiple experiments have been made to validate the sensor work. When placing the magnetic effector on the right side of the vehicle, the right sensor has the greatest sensitivity among the rest of the sensor nodes. The right sensor readings ranged from 40 to 1120 µT.

The machine learning mode (neural network method) activated in the system to enable machine learning to the system software by enabling the server-side application from analyzing the sensor readings and predict the next positions of the magnetic effector placement and the best readings gained from the magnetic sensors. The neural network method programmed to enable the server application from identifying the higher magnetic reading among a series of magnetic readings. The experiments show that the neural network method increases the MEDS ability to finds higher reading with a minimum time compared with serial processing.

As a continuation for the development of this research field, there are multiple topics that can be focused in order to develop and enhance the system ability in many directions. These topics are:

1. Communications: a major enhancement can be applied to the MEDS by adding extra technology for connecting between the network peers. Wider range network will enable the MEDS from having greater coverage area (across a city when using Wi-Max).
2. Sensor technology: using more advanced sensor technology would enable greater performance on the production of enhanced readings. Rather than using one sensor, advanced sensor technology could develop a greater sensitivity sensor that works instead of multiple sensors. An extra ability can add to the system by adding the chemical sensors to enable the system from detecting the vapors of the components of the chemical explosive and by result this would produce more quality in the process if detecting explosives and not only magnetic explosives but can be explosives at any type.

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3. The use of advanced artificial intelligence: the most important part in analyzing and processing of the data in the MEDS is the neural network algorithm that works to choose the best reading among several readings. Furthermore, an enhancement to the system can be done by integrating the advanced artificial intelligence algorithms such as evolutionary computing, swarm intelligence, reinforcement learning and probabilistic methods of uncertain. Such a topic will enable a greater optimization and decision making of the explosives detection system

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Highlights

Research title: Magnetic Explosives Detection System (MEDS) based on wireless sensor network and machine learning

The research highlights are:

1- Using the magnetic sensors in detecting the magnetic IED
2- Using the concept of WSN in connecting the magnetic sensors with the server side.
3- Discuss the theoretical part of developing the new detection system
4- Discuss the practical side of the detection system.
5- Testing, validating and analyzing the results from the new detection system.

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