ISTANBUL TECHNICAL UNIVERSITY ★ INFORMATICS INSTITUTE

# DESIGN AND IMPLEMENTATION OF A GIS BASED, CLOUD SUBSTRUCTURED, HIGH SENSITIVE, NANOPHOTONIC EARLY FIRE DETECTION SYSTEM FOR FIRE RISK AREAS

**Ph.D. THESIS**

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**DECEMBER, 2019**

**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ BİLİŞİM ENSTİTÜSÜ**

# YANGIN RİSKİ TAŞIYAN AÇIK ALANLAR İÇİN CBS TABANLI, BULUT ALTYAPILI, YÜKSEK HASSASİYETLİ, NANOFOTONİK ERKEN YANGIN TESPİT SİSTEMİ TASARIMI VE UYGULAMASI

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**DECEMBER, 2019**

Yücel GÜLLÜCE, a Ph.D. student of ITU Informatics Institute student ID 706132004, successfully defended the thesis entitled “DESIGN AND IMPLEMENTATION OF A GIS BASED, CLOUD SUBSTRUCTURED, HIGH SENSITIVE, NANOPHOTONIC EARLY FIRE DETECTION SYSTEM FOR FIRE RISK AREAS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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**Date of Submission** : 21 October 2019
**Date of Defense** : 06 December 2019

***To my family and my spouse,***

## FOREWORD

One of the issues that is important in a possible fire is the rapid growth of fire. As fire grows, struggle with fire becomes more difficult and damage grows in direct proportion too. For this reason, early detection of fire and rapid response have an important place in fight against fire.In this study, a new generation Spatial Information System is put forward. This system is based on GIS and can detect the fire via special detectors sensitive to infrared rays and wireless sensor network circuits. Thanks to this system developed, fire in regions where fire danger is important can be detected very early and so that a significant advantage will be provided in terms of fighting against fire. In addition, spatial information about fire can also be transferred to mobile devices of concerning authorized people fastly. Using such technological and effective systems will contribute positively to the literature in terms of methodology and will also be a benchmarking for future fire detection systems. I am grateful to my precious advisor Prof. Dr. Rahmi Nurhan ÇELİK and my jury members Prof. Dr. N. Necla ULUĞTEKİN, Assoc. Prof. Dr. Burak AKPINAR, Prof. Dr. Melih BAŞARANER, Assoc. Prof. Dr. M. Tevfik ÖZLÜDEMİR for sharing their valued knowledge with me and for contribution to my thesis.

This research was supported by Scientific Research Projects Unit at Istanbul Technical University with 2 projects (Project ID: 3791 and Project ID: 37099). Moreover, base version of this project was awarded as 2nd finalist at “1st Turkey Technological Initiative Projects Competition” in Ataturk University Techno Park, Erzurum, Turkey in August 2011. In this study, it is aimed to implement and develop the awarded idea of this system.

October 2019 Yücel GÜLLÜCE

(Electrical-Electronics Engineer)

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**ABBREVIATIONS**

| | |
|---|---|
| **GIS** | : Geographic Information Systems |
| **MEA** | : Minimum Effective Area |
| **NI** | : National Instruments |
| **WSN** | : Wireless Sensor Network |
| **GCP** | : Google Cloud Platform |
| **DBOC** | : Detection by out of center |
| **DBTC** | : Detection by towards the center |
| **OEA** | : Optimum Effective Area |

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## DESIGN AND IMPLEMENTATION OF A GIS BASED, CLOUD SUBSTRUCTURED, HIGH SENSITIVE, NANOPHOTONIC EARLY FIRE DETECTION SYSTEM FOR FIRE RISK AREAS

### SUMMARY

Fire risk areas such as forests, shipyards and factories containing combustible or exlosive substances show similarities in terms of fire potential. These critical areas are needed to be appropriately managed, because they are very susceptible to fire outbreaks and consequences of such incidents could be in a disaster scale. Early fire detection, determination of 'source of fire' and 'spread speed of fire' have vital roles for firefighting in order to prevent it from becoming a disaster.

In this proposed system, special detectors with state-of-the-art multi-spectral infrared technology and mathematical modelling algorithms have been utilized to create a smart fire detection system by LabVIEW automation software that can detect fires from a very early stage. The geolocation and behavior of emerging fires in a forest are also estimated with maximum spatial resolution by superposition of the detection areas of multi-spectral infrared detectors. In this study, candidate fire regions are detected for feasibility first. Next, the most suitable detector type in fire detection is determined and used for expanding the fire control area, so as to have the highest positional accuracy in estimating the location of an emerged fire. Thereafter, mathematical models for the position of the detectors are created to have high spatial resolution in detecting the coordinates of forest fire by using libraries of Google Maps APIs in the cloud. The geolocation of the fire and behavior of fire inside the model are then simulated visually on the map portal thanks to an extraordinarily created standalone software called FireAnalyst. Wireless detectors collect fire alarm information from risky areas and send them to the fire operators' mobile devices via wireless network over internet (cloud). This interactive map also contains some useful GIS features, i.e. listing nearby fire stations to source of fire, drawing visual routes to these fire stations and estimation of approximate arrival time of fire engines to fire location according to real-time Google traffic information.

Compared to other fire detection systems used today, this study includes new generation features, such as real-time fire detection in seconds, detection of fire source by superposition, determination of propagation speed, direction of fire propagation and cloud-based real-time mobile alarm monitoring mechanism. Moreover, estimation of geolocation of emerged fire by superposition of detection areas of detectors is the main novelity.

The proposed system is implemented in "Faruk Yalcin Zoo & Botanical Park" – Darica, Turkey. Experimental results indicated that monitoring fire with FireAnalyst using selected multi-spectral infrared detectors positioned "towards the center geometry" outperformed other fire monitoring systems, providing a significantly

shortened fire detection timeframe and high spatial resolution (up to 4.5m) in detecting geolocation of fire in a minimum ~3599.56 $m^2$ forested area and adds with functionalities like as real-time fire behavior analysis.

# YANGIN RİSKİ TAŞIYAN AÇIK ALANLAR İÇİN CBS TABANLI, BULUT ALTYAPILI, YÜKSEK HASSASİYETLİ, NANOFOTONİK ERKEN YANGIN TESPİT SİSTEMİ TASARIMI VE UYGULAMASI

## ÖZET

Ormanlar, tersaneler, yanıcı veya patlayıcı madde içeren fabrikalar gibi yangın tehlikesi bulunan bölgeler yangın potansiyeli bakımından benzerlik göstermektedirler. Bu tür yangın olaylarının sonuçları afet ölçeğinde olabilmektedir. Bu yüzden yangının erken tespiti, kaynağı ve yayılım hızının belirlenmesi, yangınların felaket olmasını önlemek için hayati öneme sahiptir. Türkiye tarihinde orman, kuş cenneti, tersane gibi yangın riski taşıyan açık alanlarda birçok yangın felaketi yaşanmış ve maddi manevi kayıplar yaşanmıştır. Örneğin, Uluslararası Ramsar Sözleşmesi ile koruma altında bulunan Mersin'in Silifke ilçesindeki Göksu Deltası'nda bir çok bitki ve hayvan türü yaşamaktadır, ancak 22 Ocak 2017 tarihinde bilinmeyen bir nedenle bu deltada bir yangın meydana gelmiştir. İhbar üzerine bölgeye itfaiye ekipleri sevk edilsede arazi şartlarının uygun olmaması nedeniyle yangına hemen müdahale edilememiş (8 saat) ve sonuç olarak yangın kısa zamanda önemli ölçüde doğal hayata zarar vermiştir. Bundan dolayı yangında saniyeler çok önemlidir, bu tür geciken müdahaleler felakete sebebiyet verebilmektedir.

Endüstriyel yangınlar da başta can kaybı olmak üzere şirketlere ve hükümetlere her yıl milyarlarca dolara mal olmaktadır. Çoğu felaket kötü tesis inşaatından, tasarımından veya ihmalden kaynaklanır. 2018 yılındaki afet olaylarının % 42'si, endüstri fabrikaları veya depolardaki büyük yangınlar veya patlamalar dahil olmak üzere insan yapımı felaketlerdir. Ulusal Yangın Koruma Birliği'nden çıkan en son yangın istatistiklerine göre her yıl sınai ve üretim tesislerinde ortalama 37.000 yangın meydana gelmektedir. Bu olaylar 18 sivil ölümüne, 279 sivil yaralanmasına ve 1 milyar dolar doğrudan maddi hasara yol açmaktadır. Genellikle yöneticiler ve çalışanlar kendilerini her gün işte çevreleyen risklerin farkında değildir. Endüstriyel yangınların ve patlamaların en yaygın nedenlerinin başında yanıcı maddeler, sıcak iş, hatalı ekipman ve makineler gelmektedir.

Genellikle gözden kaçan ve çok ölümcül olan yanıcı maddeler, gıda üretiminde, ağaç işçiliğinde, kimyasal imalatta, metal işçiliğinde, eczacılıkta ve hemen hemen tüm diğer endüstrilerinde yangının başlıca nedenlerinden biridir. Bunun nedeni, gıdalar, boyalar, kimyasal maddeler ve metaller dahil olmak üzere hemen hemen her şeyin - daha büyük parçalarda yangın riski olmayan malzemeler bile - toz halinde yanıcı olma potansiyeline sahip olmasıdır. Yanıcı toz yangınları ve patlamalarındaki ana bileşen, tozun kendisinin varlığıdır. Tipik bir olayda, küçük bir yangın, yanıcı maddelerin tutuşma kaynağı ile temas etmesinden kaynaklanır. Bu bir toz patlaması olabilir, ancak toz olması gerekmiyor, diğer herhangi bir patlama türü olabilir.

Ancak, bu küçük patlamalar sorun teşkil etmeyip asıl sorun sonrasında meydana gelen olaylardır. Bölgede toz varsa, birincil patlama bu tozun hava almasına neden olacaktır. Daha sonra, toz bulutu kendiliğinden tutuşabilir ve birincil patlamanın boyutu ve ciddiyetinin misli olabilen ikincil bir patlamaya neden olabilir. Yeterli miktarda toz birikmişse, bu ikincil patlamaların tüm tesisi yıkma potansiyeli vardır ve bu da büyük hasarlara ve ölümlere neden olabilir.

Örneğin, Amerika'da bir imalatçı, bir toz toplayıcıyı çalıştırırken yaralanmalara sebebiyet verdiği için 150.000 dolar para cezasına çarptırılmıştır. Olaydan sorumlu müfettişler sebep olarak çalışanları bilinçli olarak riske maruz bıraktıklarını ve şirketin toz toplama sisteminde meydana gelen dördüncü yangın olduğunu belirtmişlerdir.

Sıcak iş, tüm endüstrilerde endüstriyel yangınların önde gelen nedenlerinden biridir. Sıcak işin kullanım alanı yaygın olarak kaynak ve torç kesme ile eşit olsa da, yanma, ısıtma ve lehimleme gibi yangına sebep olan birçok faaliyette kullanılır. Bunun nedeni, 1000° F'den yüksek sıcaklıklara ulaşan kıvılcımların ve erimiş malzemenin, 35 fitten daha kolay hareket etmesidir. Sıcak işlerin sonucu olan birkaç örnek felaket mevcuttur. 2014 yılında, Kaliforniya'daki bir iskele yangını, bir depo katının kısmen çökmesine neden olduğu zaman 100 milyon dolardan fazla zarar vermiştir. 2012 yılında ise sıcak iş yapan üç işçi, metal bir ham petrol tankını sökerken hayatlarını kaybetmişlerdir. İşten çıkan kıvılcımlar, tankın içindeki buharları ateşleyerek yakındaki odunlara yayılan yangına neden olmuştur. Benzer şekilde, 2010 yılında da bir işçi 10.000 galon bulamaç tankında kaynak yaparken bir patlamada yaralanmıştır. Önceki olaya benzer şekilde, kaynaktaki kıvılcımlar, tankın içindeki buharları ateşlemiştir. Sıcak iş, aynı zamanda yanıcı toz yangınlarında büyük bir etkendir, çünkü işten çıkan kıvılcımlar, çevredeki tozları tutuşabilmektedir. Kuzey Carolina'daki bir kazada, kıvılcımlar çalıştıkları silodaki odun tozunu tutuşturduğunda üç taşeron firma ciddi şekilde yanmıştır.

Alev alabilen sıvılar ve gazlar, çoğu zaman kimyasal tesislerde ortaya çıkan yangına eğilimlidirler. 2010'da Middletown'daki enerji santrali patlaması, altı kişiyi mezar olmuş olup olayda 50'den fazla kişi yaralanmıştır.

Hatalı ekipman ve makineler de endüstriyel yangınların ana nedenleridir. Isıtma ve sıcak iş ekipmanları, özellikle uygun şekilde kurulmamış, işletilmeyen ve bakımı yapılmayan fırınlar, tipik olarak buradaki en büyük sorunlardır. Ek olarak, herhangi bir mekanik ekipmandaki hareketli parçalar arasındaki sürtünme yangın tehlikesi oluşturabilmektedir. Bu risk, yağlama dahil önerilen temizlik ve bakım prosedürlerini izleyerek pratik olarak sıfıra indirgenebilir. Görünüşteki masum ekipmanların bile doğru koşullar altında bir tehlike oluşturabilmektedir. Çoğu durumda, en az yangın riski olarak düşünülebilecek ekipman, en büyük sorun olarak ortaya çıkabilmektedir. Bunun nedeni, şirketlerin riski tanımaması ve bu nedenle gerekli önlemleri almamasıdır.

Son yirmi yılda meydana gelen en ölümcül 6 endüstriyel felaket daha var. Bu 6 farklı felaket dünyanın 6 farklı ülkesinde meydana gelmiş olup kaza, ihmal veya yetersizlikten kaynaklanan büyük hasar, yaralanma ve can kaybına neden olmuştur. Örneğin, Kunshan, Jiangsu-Çin'deki bir otomotiv fabrikasında çalışan işçiler, 2 Ağustos 2014'te korkunç bir toz patlamasıyla karşı karşıya kaldı. Fabrika, Zhongrong Metal Production Company'ye aitti ve General Motors dahil olmak üzere birçok Amerikan şirketine otomobil parçaları üretmekteydi. Bu patlamada 146 işçi ölüp 114 kişi yaralanmıştır.

2010 yılında Tazreen Moda fabrikası, Dakka-Bangladeş'de açıldığında 1.500'den fazla işçi çalıştırmaktaydı. Fabrika, çeşitli global perakendeciler için tişörtler, ceketler ve diğer giyim eşyaları üretmekteydi. Açıldıktan 2 yıl sonra, fabrikanın 17 saatten fazla yanmasına neden olan korkunç yangın meydana gelmiştir. Yangın, sekiz katlı binanın zemin katında başlamış ve çalışanları yukarı katlarda tutsak hale getirmiştir. Fabrika, Bangladeş'te yangın veya endüstriyel kazalara karşı minimum güvenceyle çalışan yaklaşık 4.000 benzer tesisten biridir. Bu yangın en az 111 kişiye mezar olup hastaneye yüzlerce işçi göndermiştir.
Diğer bir örnek ise Pakistan Fabrikaları yangınlarıdır. Pakistan'ın en büyük sanayi kazası, 11 Eylül 2012'de Karaçi'de bir tekstil fabrikasında meydana gelmiştir. Çubuklu pencereler ve kilitli çıkışlar dört katlı binada kapana kısılmış 300'den fazla işçinin ölümüne neden olmuştur.
Seest Fireworks Afeti ise 3 Kasım 2004'te meydana gelmiştir. Johnsens Fyrværkerifabrik havai fişek fabrikasında çalışan iki personel, havai fişekleri içeren bir kutuyu yanlışlıkla düşürerek havai fişeklerin ateşlenmesine neden olmuştur. İtfaiyeciler olay yerine geldiğinde, yangın çok yoğundu ve söndürmede çok zorlanmıştır. Havai fişek kabı depoda 280 ton havai fişeğin patlamasına sebep olmuştur. Bu felaket de bir itfaiyeci ölmüş olup kurtarma ekibinden 7'si yaralanmıştır. Çevrede 355 ev hasar görmüş ve 176'sı yaşanamaz hale gelmiştir. Hasarın maliyeti 100 milyon Euro olarak tahmin edilmiştir.
Bu çalışmada yangın riski taşıyan alanlar için kablosuz sensör ağları ile entegre olan, kızılötesi ışınlara yüksek hassasiyetli nanofotonik detektörler kullanarak olası yangını başlangıç aşamasında algılayabilen, CBS tabanlı erken yangın tespit sistemi önerilmiştir. Geliştirilen sistem, detektörlerin algılama alanlarının superpozisyon yöntemi ile ateş kaynağını yaklaşık 4 metrelik mekansal çözünürlüğe kadar saniyeler içinde bulabilmektedir. Kablosuz detektörler, riskli bölgelerde ortaya çıkan yangın alarm bilgisini alır ve internet (bulut) aracılığıyla bir kablosuz ağ üzerinden yangın operatörlerine iletilir. Yangının tüm davranışları FireAnalyst adlı interaktif bir görsel harita üzerinde izlenebilir. Ayrıca FireAnalyst, en yakın itfaiye istasyonlarını yangın kaynağına göre listelemesi, bu istasyonlara görsel rotalar çizmesi ve gerçek zamanlı Google trafik bilgilerine göre itfaiye arabalarının yangın yerlerine ulaşma zamanını tahmin etmesi gibi bazı yararlı CBS özellikleri içerir. Günümüzde kullanılan diğer yangın tespit sistemlerine kıyasla bu çalışma yangının saniyeler içinde algılanışı, kaynak konumun süperpozisyon yöntemiyle tespiti, yayılma hızının saptanması, yangının yayılma yönü ve bulut altyapılı-gerçek zamanlı mobil alarm izleme mekanizması gibi yeni nesil özellikleri barındırır. Poligon geometrisinin süperpozisyonu ile yangının enlem ve boylam değerlerinin tahmin yöntemi, ilgili çalışmalara göre dünyada ilk kez gerçekleştirilmiştir.Önerilen sistem "Faruk Yalçın Hayvanat Bahçesi ve Botanik Parkı, Darıca, Türkiye'de" uygulanmıştır. Deneysel sonuçlar, FireAnalyst ve "içe dönük" geometri tipi kullanılarak konumlandırılan çok spektrumlu kızılötesi dedektörler ile yangın izlemesinin, diğer yangın izleme sistemlerine göre daha efektif olduğunu göstermiştir. Sistemin gerçek zamanlı yangın davranış analizi (yangın yayılma hızı, yayılma yönü) gibi işlevleri barındırmasıyla beraber, yangının coğrafi konumunun tespit edilmesinde yangın algılama süresini önemli ölçüde kısaltarak minimum 3599.56 m2 ormanlık alanda yüksek mekansal çözünürlük (~4.5 m'ye kadar) sağladığını göstermiştir.

# 1. INTRODUCTION

## 1.1 Purpose of Thesis

A forest could be defined as large area of land covered with trees or other woody vegetation. It contains lots of trees and also live animals. Emergence of a fire in these kind of areas may result a disaster. Other example to important fire risk area can be given as shipyard areas. They are special regions that comprise of workshops which are usually installed on seafront where ship building and hot works carried out, i.e., repair, metal sheet cutting, welding, rasp and some other. They can contain dangerous, explosive cargoes / materials. So that, these kind of work areas also have crucial fire potential. A regulation of Premiership of Turkish Republic (1975) states that since fire risk is excessive in these kind of areas, fire Intervention should be well coordinated with fire departments. Governmental and private related bodies including army and navy should coordinate extinguishing fire in port areas because of its scale of danger. According to related regulation, ports and shipyards constitute high risk in terms of safety of life, property and environment. Because of this fact, many governmental and private organizations must work in coordination. On 15th February of 1997, TPAO tanker catastrophe in Tuzla/Turkey proved how shipyard and port regions are dangerous in terms of safety (Erdem, 1997). In such regions, water line for firefighting should cover the whole area. There should also be fire extinguishers in miscellaneous points and standard indoor fire alarm systems. Safety of Life at Sea (SOLAS) convention (1974) aimed to protect safety of life and property at sea. It dictates fire prevention standards and firefighting methods for ships. Despite the fact that there are similarities in terms of firefighting methods, there is no specific international standard, rule or regulation regarding fire prevention and detection. Sensors for fire areas are selected based on location, purpose that will be used. They are connected to a control panel that located in a work place where can be observed at a fixed place.

In this study, it is aimed to propose an extraordinary fire detection system which utilizes nanophotonic fire detectors for spatial resolution and timing purposes, that is, the geolocation of the fire and behavior of fire are simulated visually on the map portal thanks to an extraordinarily created standalone software called FireAnalyst.

### 1.2 Literature Review

This study consists of 2 parts which are Wireless Sensor Network (WSN) usage and GIS based fire detection with flame detectors. Nowadays, there are lots of applications that utilize wireless sensor networks in many different areas including military, medical, detection of natural disasters, environmental monitoring, intelligent buildings (Sevin et al.,2013). Xihuai et al. (2000) applied fuzzy interference system based on a neural network with genetic algorithm learning method and concluded that usage of more than one sensor provides less false alarm and more information about nature of fire. Lioret et al. (2009) established a multi-sensor and IP video camera system which contains heat, flame and smoke sensors. In case of fire in any observed area, the activated node sends information to the central server. Then, the server issues a command to IP video camera of related area. Thus, fire detection could be made precisely. Erciyes et al. (2011) set up a system based on wireless nodes on TOSSIM simulator by establishing spanning tree and localization protocols. Simulator results proved that the system works effectively, but could not detect fire at initial stage which is out of aim of this study. Garcia et al. (2008) established a simulation platform, named as Equipment Destined for Orientation and Security (EIDOS). They proposed to detect forest fire and fire location by setting up wireless multi-sensor network, using wireless PDA's for firefighters and deploying UAVs (unmanned aerial vehicles). By taking information of geographical specialties, humidity pattern, sensor network, vegetation models and mobile devices, they established a simulator platform. The result of the study suggested that the system could be effective for not only fire detection but also spread speed and direction.

The other component of this study which is fire detection with flame detectors has also drawn a great deal of attention in recent years due to a wide range of civil and military applications. Literature reviews show many projects about flame detection. Flame detectors are used in fire monitoring and burner combustion monitoring equipment because even weak UltraViolet (UV) light can be detected reliably (Sun et al., 2014).

In recent years, ZnO are regarded as one of the most promising candidates for UV flame detectors. Nevertheless, the technology of ZnO-based materials and photodetectors was not yet mature and there should be more research efforts to address the challenges which are the fabrication of p-type ZnO-based materials. Liu et al. (2010) claimed in their ZnO-Based Ultraviolet Photodetectors research that ZnO-based photodetectors, especially for ZnO-based photoconductors usually had a slow response speed due to the adsorption and dis-adsorption of oxygen molecular near the surface of semiconductors. Since ZnO-based photodetectors have not fast response speed, multi-IR sensors are preferred in this study.

Pyro-electric Infrared (PIR) sensor usage is one of the preferred methods for detecting open flames. Erden et al. (2012) experimented with a differential PIR sensor, which produced a time-varying signal and which was only sensitive to sudden temperature variations within its viewing range. The study suggested that the system could be used even in spacious rooms for uncontrolled fire flame detection. However, the method in this study could not provide a feasible solution for outdoor scenarios because there would always be sudden temperature variations at play in the equation due to the effects of the sun and the wind.

Another alternative method for fire detection is vision-based monitoring. Although vision-based fire detection approaches have many disadvantages, they do provide benefits such as a fast response time. In one instance, a group of scholars designed a new fire detector that used two cameras which one acquired color video signals and the other infrared video signal. When the fire detector ran, it captured video and processed the images to find the location of the fire quickly (Chen, 2016). Another vision-based fire detection method was used for an early-warning fire-monitoring system. The software detected moving regions and segmented focusing on the colors of non-fire affected and fire areas, which it then classified as fire regions and non-fire regions using its preprogrammed algorithms (Truong, 2012).

Owrutsky et al. (2005) studied video image detection in fire detection cases. They concluded that video image detection system which is designed for early warning system to detect fire or smoke is inadequate. They suggested that long wavelength video detection system as an addition to this system can make more sensitive and precise fire detection.

Wu et al. (2019) presented an intelligent fire detection system by video cameras for preventing fire hazards from going out of control in chemical factories and other high-fire-risk industries. Their study contained motion detection, region classification and fire detection. Firstly, moving objects were detected by a background subtraction method through cameras and when fire appeared in any camera, the approach could detect it and output the coordinates of the fire region. Since the scholars explained that their approach could meet the needs of real-time fire detection on the precision and the speed, detecting the coordinates from a camera image in a small area such as a factory would not be so effective for fire detection. Moreover, the proposed system suffers the same major disadvantages as the video method preceding it.

Although proposed vision-based techniques appeared to effectively detect fire, they could represent a good solution for indoor use where there is no visual obstacle such as trees in the video capturing process.

Monedero et al. (2019) presented Wildfire Analyst (WFA) software that was designed to be used by the wildland fire prevention community to effectively estimate fire behavior and its potential changes over time in an incident. The software used well-known mathematical models built by the scientific community for different purposes and user input, such as weather data, fuel type, topography and fuel moisture. Although this study provided helpful information to firefighting teams, it could not detect real-time geolocation of fire because the software did not use any other real-time sources, such as fire sensor, video source or satellite imagery. It just estimated the fire behavior according to saved mathematical models of fire, instant local weather conditions, and user inputs.

Over the last decade, Geographical Information Systems (GIS) have been used in extensive range of forestry applications. Eugenio (2016) proposed and evaluated different methodologies to determine the most effective locations to install fire detection towers using topography, risk areas, conservation units and heat spots through GIS techniques. Likewise, another fire detection tower project was designed to test the performance of three optical sensor systems (EYEfi, FireWatch, and ForestWatch) installed on towers in comparison to those of manned observation towers to determine the difference on their performance in forest fire detection (Mathews, 2010; Alkhatib, 2014). Though fire detection towers were widely being used in the world, it had been observed that the towers equipped with the optical sensors were slower and less reliable than those of trained human tower observers in effective fire detection.

Another fire detection approach being used is satellite-based detection that uses satellite imagery gathered from two main satellites. The advanced very high resolution radiometer (AVHRR) was launched in 1998 and the moderate resolution imaging spectroradiometer (MODIS) was launched in 1999 (Alkhatib, 2014). Ganesh et al. (2013) stated the problems associated with those systems were that they had a long scanning cycle, that is, they could not detect the emerging fire in short while. Moreover, there were additional drawbacks to consider as well like cloud and meteorological interference between the satellite and the monitored area.

According to related studies, there is no system that can detect and analyze the fire real-time with high spatial resolution in fire risk areas. In this study's proposed method, an extraordinary fire detection system, FireAnalyst, is presented (Gulluce et al., 2019). The proposed system is implemented in Faruk Yalcin Zoo & Botanical Park in Darica, Turkey (Figure 1.4c).

FireAnalyst provides accurate estimations for the geolocation and behavior of fire in fire risk areas rapidly by using state-of-the-art multi-IR flame detectors and reliable GIS-based mathematical modelling methods (Gulluce et al., 2014). FireAnalyst has a user-friendly graphical user interface (GUI) and is a standalone monitoring program (.exe) that is created via LabVIEW. It can visualize the calculated geolocation of fire on map (Figure 1.1c). The system can detect the fire with a spatial resolution of up to 4.5 meters. It can also estimate some real-time fire behaviors, such as fire speed and fire direction (Figure 1.1b).

**Figure 1.1 :** FireAnalyst Map Portal: (a) State of fire, (b) Fire behavior outputs, (c) Simulation of real-time estimated geolocation of fire.

### 1.3 Methods

In this study, methodological steps in Figure 1.2 are followed to reach the proposed solution.

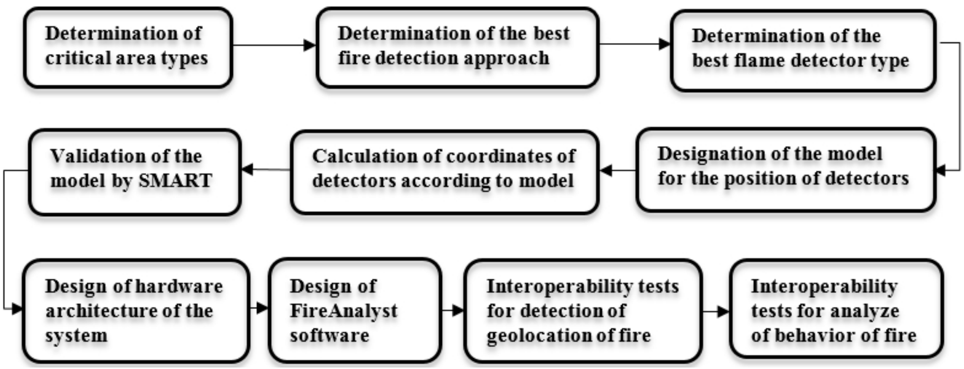


**Figure 1.2 :** Methodological steps of study.

The proposed system consists of state-of-the-art Multi-IR detectors, WSN and a personal computer to run FireAnalytics software for monitoring. Figure 1.3 shows the architecture of the implemented system with 4 detectors.

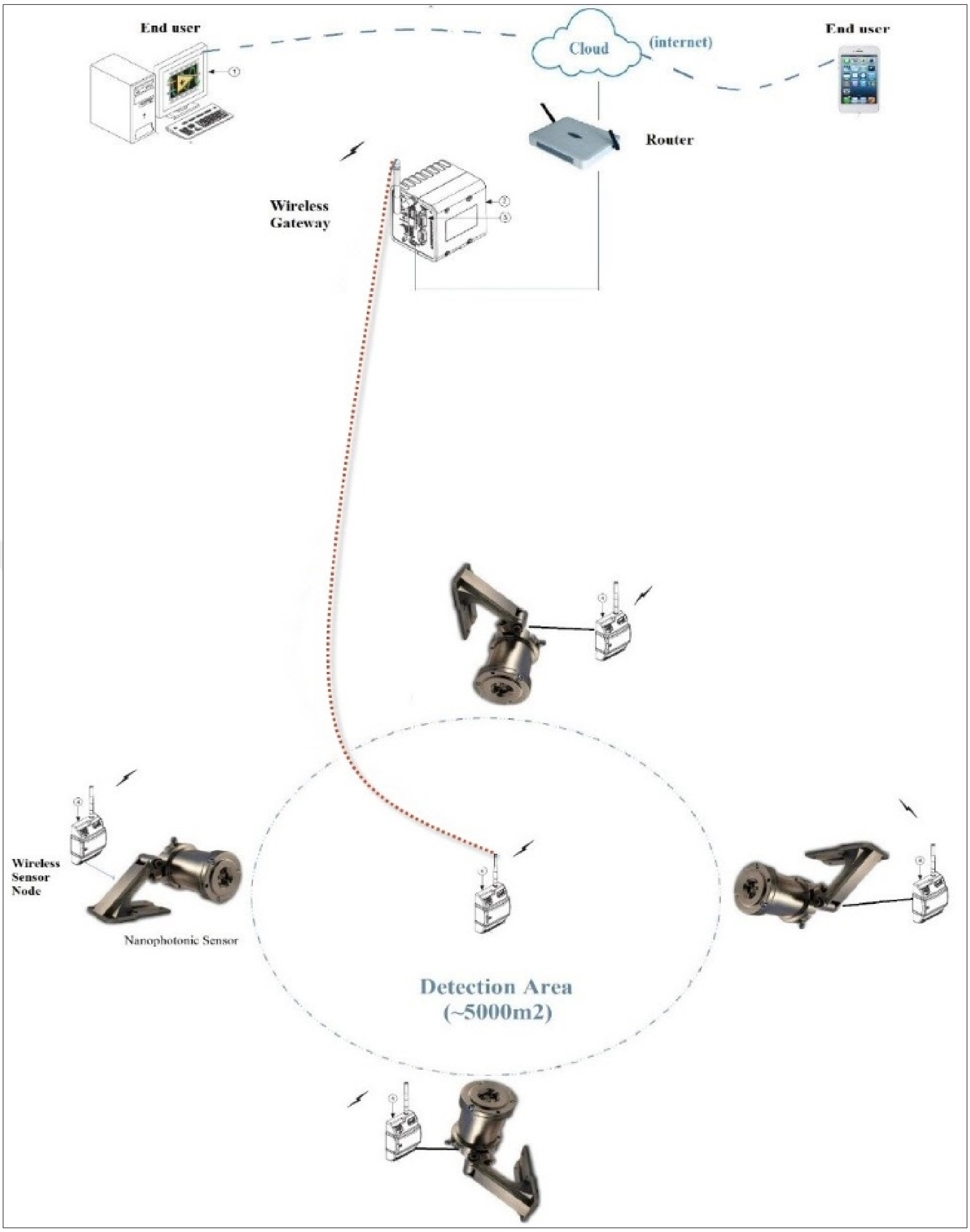



**Figure 1.3 :** Architecture of the Fire Detection System.

When a fire is detected by a detector or a few detectors, alarm signals are created to be taken by sensor nodes placed near each detector.These signals are sent to central gateway by wireless sensor nodes in order to interpret the location and behaviour of fire by LabVIEW Automation&Measurement software, then created spatial information are broadcasted through internet, so that mobile devices and computers can fetch spatial data easily on all over the world. Thus, no GPS device or sim card is be needed.

The total cloud based system consists of 6 components which are

- PC or Mobile device for fire operator (end user)
- WSN Real-Time Programmable Gateway
- WSN Nodes
- Router device
- Nanophotonic flame dedectors
- Internet connection (for cloud monitoring).

The aim of WSN gateway is to be a bridge between wireless nodes and internet. WSN gateway, routers, and nodes work together to form a mesh network.

FireAnalyst is a standalone monitoring portal that post-processes the data on time-dependent logical states of multi-IR detectors recorded using a WSN in order to visualize the estimated geolocation of fire on map (Figure 1.1c).

During formation of any flame, UV and IR rays occur together at once (Bogue, 2013). Since UV or IR rays can be detected rapidly, sensing flames provides rapid-fire detection for this system. Moreover, the detectors used in this study (Figure 1.4a) can detect these IR rays up to a distance of 60 meters, which is by far the longest range in comparison to competing types of fire detectors. Therefore, maximum detection range in forested areas can be provided. According to trials in this study, multi-IR sensors have an approximately 45° cone of vision (horizontal) with the highest sensitivity lying along the central axis. The graph given in Figure 1.4b visually represents the cone-shaped field of vision of a Multi-IR detector.

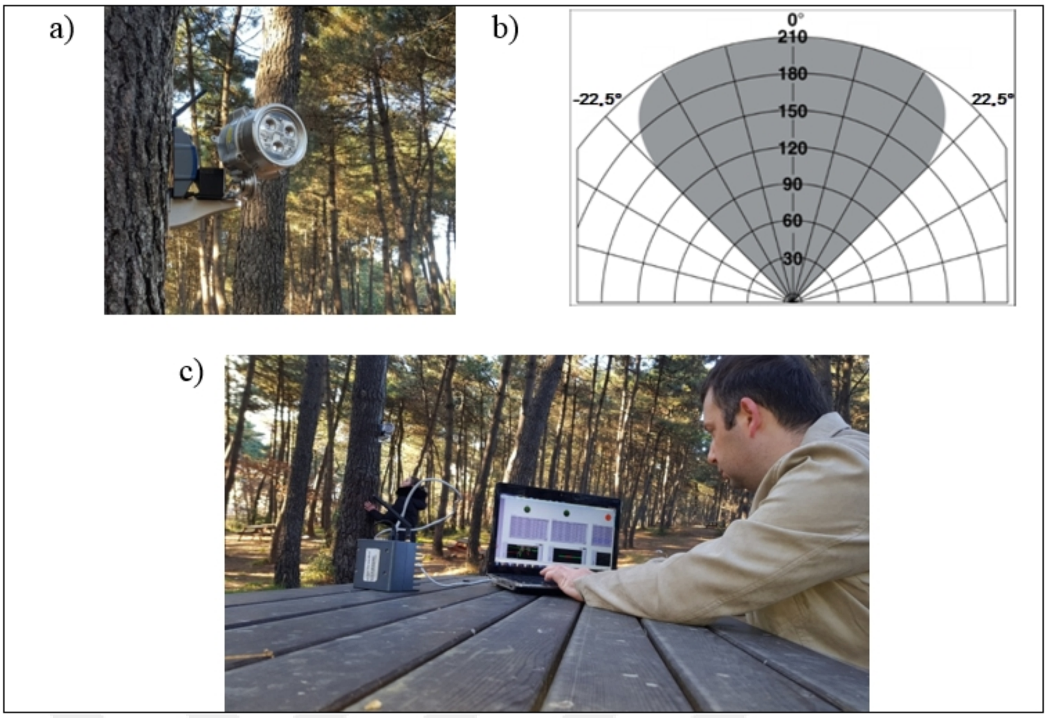



**Figure 1.4 :** System implementation: (a) Multi-IR detector and transmitter, (b) Cone of vision of detectors (ft vs. degree), (c) Implementation of monitoring system.

The shape of the detection area is a cone as illustrated in Figure 1.4b. So that an optimum 2D model is created for the maximum area of coverage increasing the geolocation of a fire, that is, when detectors are installed in various areas, then the detection areas of detectors are ‘superposed’ (Figure 1.5a), and new overlapping areas are formed which are smaller (Figure 1.5b). As a result, smaller detection areas provide a more accurate fire geolocation.

GIS are designed to handle, store, and retrieve spatially referenced data explicitly. In addition to basic Euclidean or straight-line distances, they are also capable of more complex forms of analysis. For instance, the Earth is three-dimensional and a distance between two points on a sphere is not a straight line, but a great circle (a type of geodesic). As such, geometric functions on a sphere necessitates using spherical geometry to calculate distance such as “Haversine formula” (Gardiner et al, 2011; Chopde, 2013). GIS use those spherical geometries for calculating distances between two points. Moreover, they can also take slope and/or elevation into account in the context of physical geography. Likewise, the coordinates of a point at a certain distance and at a certain angle can also be calculated via GIS.

In this study, Google Cloud Platform is used as GIS solution. This platform contains a set of real-time APIs and SDKs in the cloud for web clients, that is, FireAnalyst uses some libraries of “Google Maps JavaScript API” such as Map(), Marker(), geometry(), LatLng() and Polygon(). For instance, geometry library provides utility functions for the computation of geometric data and for constructing polygons on the map that the gelocation of fire is contained. The proposed system uses a namespace of geometry library, called spherical, to compute angles, distances and areas from latitudes and longitudes. Likewise, to calculate the coordinates of all remaining detectors and corner points of new polygons on mathematical model, a function, called "ComputeOffset", is used. This function enables FireAnalyst to compute scalar values from spherical coordinates (longitudes & latitudes). For instance, the coordinates of the 1st detector is fixed and known (40.785213, 29.369822). The distance between the 3rd detector and the 1st detector is 78.79 meters and there is 135° angle between them (Figure 1.5d). Therefore, the coordinates of the 3rd detector can be calculated in FireAnalyst.

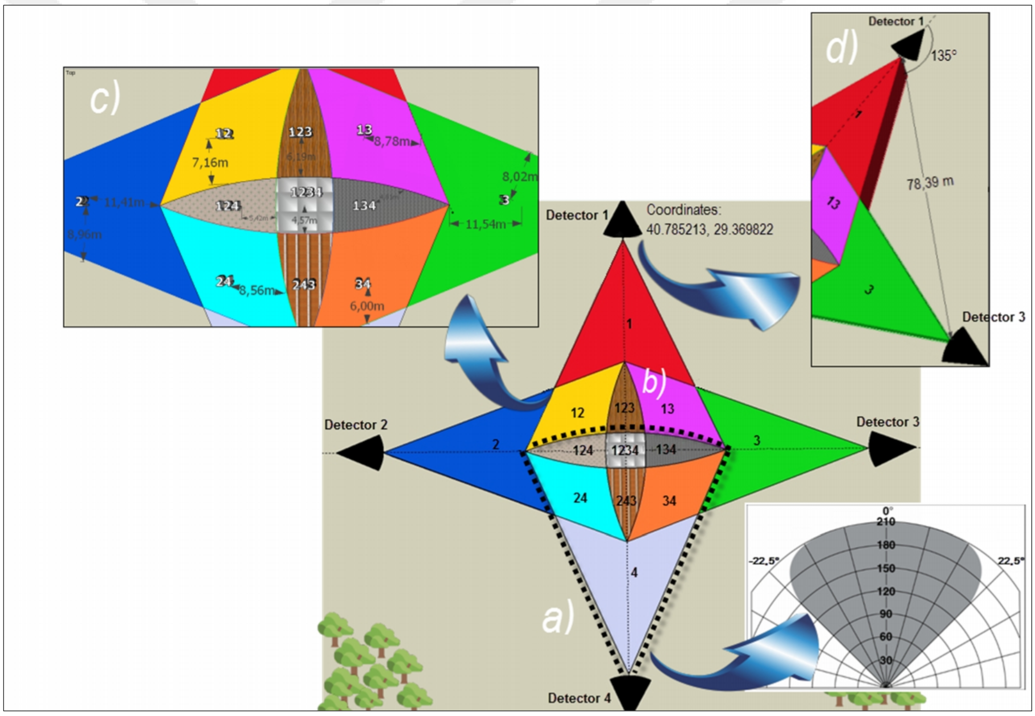



**Figure 1.5 :** Superposition of detection areas of 4 Multi-IR detectors and superposed regions: (a) Detection area of 4th detector; (b) a new and smaller superposed region labelled as 13; (c) Distances from midpoints to borders; (d) Spherical geometry parameters for auto-calculation of coordinates of the other detectors.

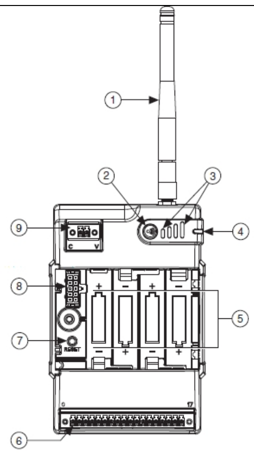
All in all, the coordinates of all intersection points, that is used to visualize the mathematical model, and coordinates of all detectors, no matter how much detector is used, can be calculated automatically. Each area (formed by superposition of the detection areas) is numbered with the number of detectors that creates an intersection. For instance, the area with number ‘134’ means that when a fire is detected by 1st ,3rd  and 4th detectors, it can thus be triangulated on the map that the location of fire has to be inside the '134' area (Figure 5.4a). Hence, it provides increased accuracy for locating fire to within 4.5 meters. Figure 1.5c shows the distances calculated by the SketchUp tool (Trimble Inc., 2019) from the midpoint of each area to their borders. When the fire becomes larger than these distances, it starts becoming detectable in other neighboring regions. SketchUp graphic files are also provided as supplementary information (at https://drive.google.com/open?id=1AZR4s7i42obukZA3NBfPR30870S32HGV).

## 2. WIRELESS SENSOR NETWORK ARCHITECTURE

Wireless measurement systems are useful for power and network infrastructure challenges. They are cost effective and flexible compared to traditional wired measurement systems. A WSN consists of three main components: nodes, gateways, and software. The spatially distributed measurement nodes interface with sensors to monitor their environment. The acquired data is wirelessly transmited to the gateway, which can be connected to a computer in order to process, analyze collected data using an automation software.

### 2.1 WSN Nodes

A WSN node is a low-power, wireless device that works with other WSN nodes and gateways to form a wireless sensor network.
The WSN system in this study consists of one WSN gateway and 4 WSN nodes to receive and analyze sensor data.



1. Antenna
2. Wireless connect button
3. Signal status leds
4. User led
5. Battery slots
6. I/O connector
7. Reset button
8. Pro2 port
9. External power input (for solar energy)

**Figure 2.1 :** Wireless sensor node interface , adapted from National Instruments Corp. (2013).

Wireless sensor nodes that are used in this project consist of 9 parts as given in Figure 2.1. Sensor is powered via battery or external power such as solar power. By pressing wireless connect button, the sensor tries to connect to the gateway.

### 2.1.1 Node characteristics

According to technical datasheet of National Instruments Corp. (2013), WSN nodes has radio mode of IEEE 802.15.4 with a data rate of 250 Kbps. The communication range is measured during the tests as about 200 meters. Each node needs about 6V which equals to 4 AA batteries. The nodes can be connected to an external power such as solar power in case of unreachable places, i.e. forests and high mountains. If both battery and external power are connected, device works from the external power input. in case of loss of external power, power source automatically switches to battery power. Since the purpose of this study is for fire risk areas, there is no need for an external power, because the batteries inside last up to 3 years according to sample interval of detection mechanism. Table 2.1 shows the battery life, according to the detection frequency setting.

**Table 2.1 :** Battery life statistics up to sample interval, adapted form National Instruments Corp., (2013).

| Power statistics | 60 second sample interval | 1 second sample interval |
|---|---|---|
| Battery life | Up to 3 years | Up to 1 month |

There are 17 pinout of each nodes. In this study, only analog I/Os and sensor power pinout are used. The layout of pinouts are given in Figure 2.2.

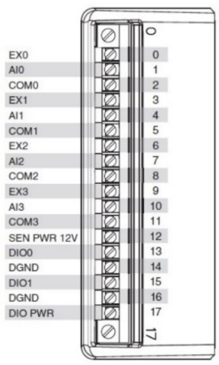



**Figure 2.2 :** Pinout characteristics of wireless nodes, adapted from National Instruments Corp. (2013).

Each node has 4 channel analog I/Os and 2 channel digital I/O pinouts. Minimum sampling interval can be configured as 1 seconds for full performance. The digital I/O pin capacitance is 2000 pF and input voltage range is between 0 to 30 VDC. (National Instruments Corp., 2013). Each node has an external sensor power out of 12V and 50mA of current in order to supply required power to nanophotonic sensors, but the detectors that are used in this study requires a power of 3W with 18V-24V DC voltage range. So that, extra 6V or 12V battery is connected to compensate the required power

In order to extend the range of sensor network, WSN nodes can be configured to operate as routers or end nodes. This network topology is called 'ad hoc network'. When nodes are configured as routers, they forward messages from connected node to one another to extend network range (National Instruments Corp., 2010).

## 2.2 WSN Network Topologies

An ad-hoc network is a network that is composed of individual devices communicating with each other directly. The data from the source is sent through a path by going through node after node until it identifies the matched receiver.

Blootech company (n.d.) describes Ad hoc wireless networks that they eliminated the complexities of infrastructure setup and administration, enabling devices to create and join networks "on the fly" anywhere, anytime, for virtually any application. Wireless Ad-hoc network systems have broad range of usage and are easy to establish as mentioned in the study of Pitterman (2000). For instance, ad hoc networks can be used for medical and military propose to achieve fast information forwarding. In fact, Ad hoc network type is not built on preexisting base, each node in network has connectivity to another and can forward data as given in Figure 2.3.

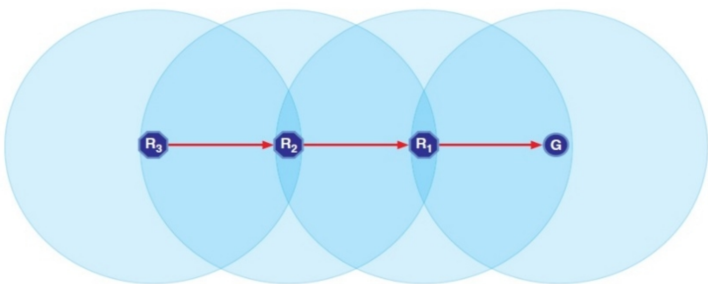



**Figure 2.3 :**The relationship between router node and gateway in an ad-hoc network, adapted from National Instruments Corp. (2010).

For instance, a node in a ad hoc network can be cofigured as a router node which is 200 meters far from WSN gateway.This node acts as only router and transfers the data from other nodes, having a distance of 100 meters, to the WSN gateway as given in Figure 2.3. So that, detection range can be extended to 300 meters according to this example. For this reason, Ad-hoc network system is preferred in this study.

### 2.3 Wireless Gateway Device

In a WSN system, a gateway in Figure 2.4 acts as the network coordinator and bridging from wireless network to wired ethernet network. By this way, measurement data can be collected and analyzed using an automation software.

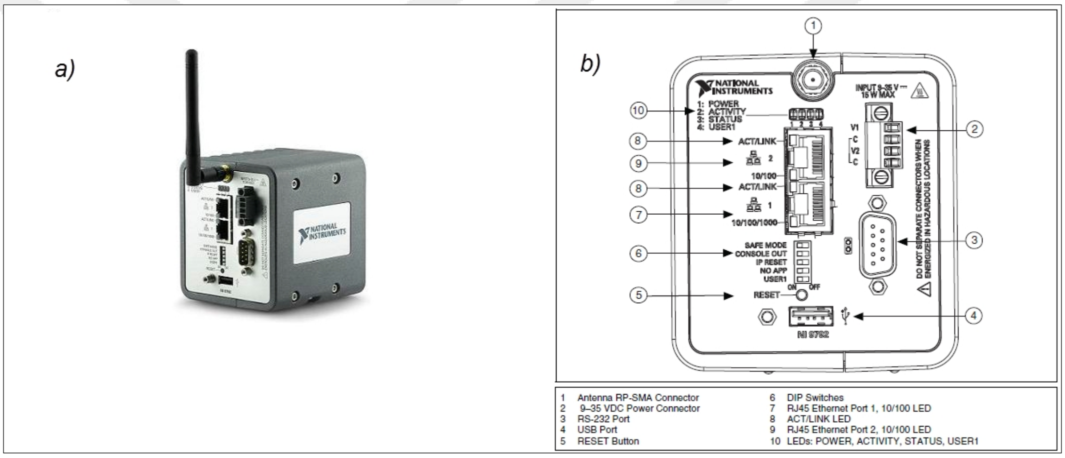



**Figure 2.4 :** (a) Programmable Gateway; (b) NI 9792 Programmable Gateway Interface, adapted from National Inst. (2010).

In this study, National Instruments(NI) 9792 model wireless gateway is used for compliance and performance purposes. Figure 2.4a shows a NI 9792 gateway. This gateway is also a real-time controller which means that it has its own processor and can operate itself without a connection to a computer. Therefore, real-time applications can run locally on this gateway which collects node data.

Figure 2.4b shows the device interface having serial ports and 10/100 Mbit/s and 10/100/1000 Mbit/s Ethernet ports, so that communication can be provided via TCP/IP or serial protocols.

NI 9792 is also good at embedded monitoring applications having 2GB of onboard storage. Therefore, data from distributed wireless measurement nodes can be aggregated easily. This gateway has integrated Web (HTTP) and file (FTP) servers, so that measurement data can be hosted for remote access via internet which provides cloud communication.

### 2.4 Fire Sensors and Nanophotonic Detection

Contrary to common belief, sensors do not detect fire, detect the symptoms of fire which can be identified as heat, smoke, odor, pressure variation and electromagnetic waves that is generated with formation of flame such as UV and IR. Odor and pressure variation are not taken into consideration in most of the sensor mechanisms for fire detection. Because odor is not effective marker and pressure variation is not dependable symptom. IMO Maritime Safety Committee (2007) stated that “Detectors shall be operated by heat, smoke or other products of combustion, flame, or any combination of these factors”. Fire sensors are produced to be activated mechanically according to some symptoms. For instance, Zhang, et al.(2008) mentioned a sensor type which measures heat and humidity symptoms of a fire at once. Since the light speed is the highest speed compared to the other detection variables, the detection of UV and IR light which are created with formation of flame will be more effective. So that, nanophotonic sensors are used in this study. There are different types of sensors, such as but mostly categorized into three groups which are heat, smoke and flame detectors.

#### 2.4.1 Heat sensors

During the combustion, the energy stored in the burning object is transformed into heat energy that causes a temperature rise in the environment. Temperature rise is a common symptom to detect fire. All environments have specific temperatures except small fluctuations. With fire rise, the temperature of environment rises slowly or quickly. Unacceptable increase of environment temperature comparad to a normal temperature is a sign of fire. Heat sensors have heat sensitive resistor with variable resistance depending on heat. These sensors are designed to be activated when changes in their resistance reach to a certain value. MSC circular (2007) stated that at higher rates of temperature rise, the heat detector shall operate within temperature limits to the satisfaction of the administration by having regard to the avoidance of detector insensitivity or oversensitivity.

The other type of heat sensors is linear type heat sensors. Working mechanism of linear sensors is based on multicore cable system which can be laid for tens of meters. There are two conductor wires in the cable which are wrapped by insulator material. In case of fire, the insulator material begins to melt and the conductors contact with one other and then activates the sensor.

### 2.4.2 Smoke sensors

Smoke is another symptom of fire which depend on burning objects. MSC circular (2007) states that smoke sensors must be activated in a smoke density of %2 - %12,5 obscuration per meter. Smoke sensors are prone to the false alarms because of their working method. Because of this situation, Wong et al. (1994) suggested a detection system evaluates the increasing $CO_2$ density of environment and makes more sensitive and precise evaluation than smoke sensor.

Smoke sensors are classified into 4 categories which are optical smoke sensors, ionization smoke sensors, photoelectric smoke sensors and air sampling smoke detectors.

## 2.4.2.1 Optical smoke sensors

These types of sensors have an infrared LED which continuously emits beam towards a standing by photodiode. The photodiode is designed so as not to take beam sent by the LED, but if there is smoke in the sensor, smoke reflect some beam to photodiode and sensor is activated.

## 2.4.2.2 Ionization smoke sensors

Ionization smoke sensors working mechanism is based on radioactivity. In sensor, two metal plates are located having 1 cm. gap between them. The radioelement constantly ionizes the air between plates, thus this provides a constant current between the plates. Probable occurrence of smoke in the environment partially obstructs the ionization and sensor is activated. But, this type of sensors are prone to false alarm as there might be reduction of current as a result of dust settlement in time.

### 2.4.2.3 Photoelectric smoke sensors

This kind of sensors have contrast working mechanism to optical smoke sensors. A beam sent by LED is continuously received by a photodiode. In case of fire, smoke reaches the sensor and obstructs some beam reaching the photodiode which results activation of sensor. According to a task group of the NFPA 72 Technical Committee and Texas A&M University in California, photoelectric sensors are less sensitive to fast growing fire than ionization smoke sensors. However laboratory and field tests indicate the photoelectric smoke sensor is the most suitable for all type of fire and has less false alarm (O'Connor, 2008).

### 2.4.2.4 Air sampling smoke detectors

Air sampling smoke sensors are sensitive detectors which are capable of detecting microscopic particles of smoke. In this kind of sensor systems, there are receiver holes placed at regular intervals on parallel lines. The air sucked by these holes is analyzed by photoelectric mechanism. Such kinds of sensors are usually applied to high-important places.

#### 2.4.3 Flame detectors

During fire, flame symptoms can be observed before smoke or heat symptoms by flame sensors. Flame sensors are activated by infrared or ultraviolet lights of fire. According to IPES-IR3 Flame Detector Operating Manual (2013), detection range of infrared flame detector varies from 10 meters to 65 meters. There are several types of flame sensor which are mainly UV detectors,IR detectors, UV/IR detectors.

Ultraviolet (UV) detectors detect light in the ultraviolet wave spectrum, Infrared (IR) detectors detect light in the infrared wave spectrum and UV/IR detectors detect light in both of ultraviolet and infrared wave spectrums . Ultraviolet sensor can detect fires and explosions in three to four milliseconds. While incredibly accurate, ultraviolet sensors could create false alarm due to some other UV sources such as sunlight, radiation, arc welding, and lightning. UV flame detectors (Figure 2.5) detects flames at once and activates an alarm output.

**Figure 2.5 :** Takex FS-5000E UV detector, adapted from Takex (2010).

This detector requires a power of DC 10V - 30V. As alarm output, dry contact relay can be used for this study. The required voltage is convenient for this system because detector power voltage on node which is 12V can correspond it. Dry contact relay alarm output is also convenient for digital I/O pinout.

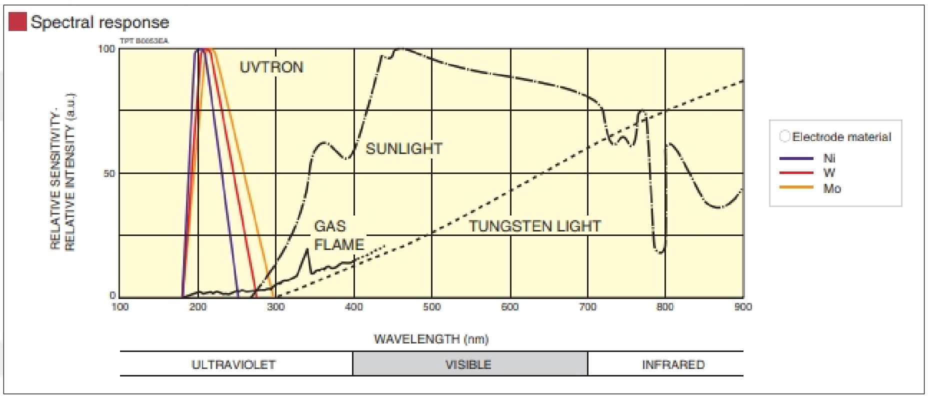



**Figure 2.6 :** Spectral respone of nanophotonic flame detector, adapted from Uvtron (2018).

According to the tests performed, this flame detector can detect the flame in 3 seconds but the detection range is about 15 meters which is not good for wide areas. Figure 2.6 shows the spectral response of nanophotonic flame detector (Takex Inc., 2010).

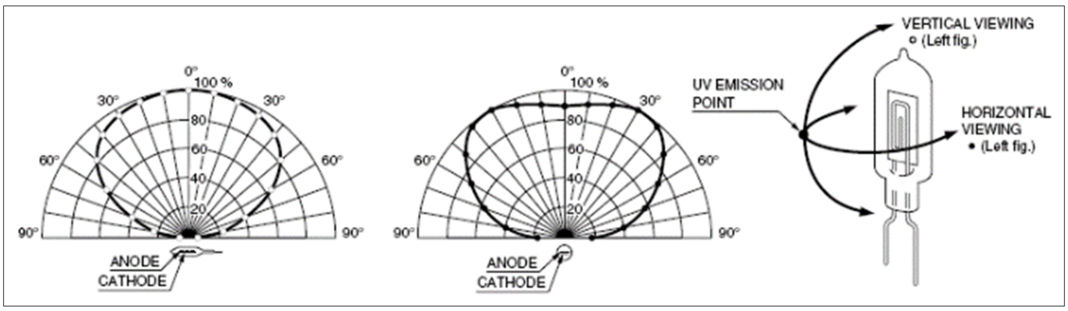



**Figure 2.7 :** Angular sensitivity (directivity) flame detector, adapted from Takex Inc. (2010).

These detectors have narrow spectral sensitivity of 185 to 260 nm and 45 degrees detecting angle. Angular sensitivity of a flame sensor is given in Figure 2.7.

Infrared (IR) flame sensors could also create false alarm, that is, IR energy emitted from heaters, lamps and heat from the sun are examples of infrared sources. But, this problem is minimized and overcome by the use of multi-band techonology which can distinguish the IR spectrum between flames and other sources of radiation (Jonathan, 2013).

UV/IR sensors use a combination of both ultraviolet and infrared technology to detect fire. These sensors gather information from an ultraviolet perspective and an infrared perspective. When these two technologies work together, false alarms are often minimized. Similarly, an IR/IR (IR2) flame detector or triple IR (IR3) detectors detect flames within two or three infrared frequencies. Thus, better performance are taken from IR2 or IR3 detectors for false alarm cases. IR detectors work by using IR sensors to select light wavelength in the Infra-Red spectrum.

**Figure 2.8 :** Virex IR2 Flame Detector (Virex, 2018).

Double infrared sensor (Figure 2.8) is used for measuring the exclusive presence of $CO_2$ signature from visible flame. This IR sensor requires a power of DC 16V - 30V and as alarm output, dry contact relay can be used. The required voltage is not convenient for this system, because sensor power voltage of WSN node which is 12V cannot correspond it. External power will be required in case of choosing this sensor. According to the tests performed, this flame sensor can detect the flame in 6-10 seconds but the detection range is about 17 meters which is shorter than other flame detectors.

Some detector companies created new generation detectors with triple IR sensors. Thanks to advanced microprocessor of flame detectors, they ensure rapid flame recognition and alarm signaling. Moreover, these detectors have multiple spectrum technology which eliminates false alarms from kinds of sources including fluorescent, sunlight, arc welder flash, etc.

Multi-IR detectors generate a true alarm signal only when detection from three different IR wavelengths confirms that fire is present in detection area. Multi-IR detectors have two “Dry Contact” relays that operate during alarm conditions and fault modes. Upon confirmation of flame or fire, the multi-IR triggers alarm relays and provides alarm signals to the WSN node. These detectors provide a visible high illumination Tri State LED that follows an industry standard protocol for operation status and alarm conditions which are:

- Green for normal operation
- Yellow for alarm condition
- Red for Fault Conditions

IR3 detectors provide superior false alarm processing making it the detector of choice. Alarms occur instantly after the proprietary False-Positive algorithm determines possible alarm states (Lizhong et al., 2013).

There kind of detectors generally require a power of DC 18V - 30V unfortunately too. The required voltage is also not convenient for this system because of the reasons explained previously, but compared to other flame detectors, this detector type is no doubt the best. So that, external batteries are connected to reach the required voltage in this study. According to the tests performed, an IR3 detector can detect the flame in between 7-15 seconds and the detection range is about 65 meters which is the best for open areas. they have an effective 45° cone of vision (horizontal) with the highest sensitivity lying along the central axis.

Since detection range of sensors are also important for this project, compared to ordinary flame sensors, next-generation IR flame detectors with a detection range of 65 meters of each are used. These flame detectors also have false alarm detection mechanism.

Based on above facts and statistics of tests, IR3 multi-spectral flame detector is chosen for this study in order to provide the optimum fire detection.

# 3. MATHEMATICAL MODELLING OF DETECTOR GEOMETRY

In Fire Detection Systems, one of the most important factors is the control area in a forest. If the control area of a system is small, but the system cost is high, then this system will not be feasible. As such, the detectors in a control area have to be positioned by maximizing their coverage without compromising their effectiveness within the proposed control area. In this section, possible modelling types of detectors are investigated in order to select the optimum one, after which the selected model is validated and graded using the Simple Multi-Attribute Rating Technique (SMART). SMART is one of the most prominent and widely accepted technique for decision support systems (Risawandi, 2016). There are two ways to optimize the detector's location for a feasible system, first being "detection by out of center" (DBOC), and the second being "detection by towards the center" (DBTC) geometry models. Both geometries can also be optimized by using "spinning detectors" instead of "fixed detectors". Fixed detectors are immovable, whereas spinning detectors spin via step motorized mechanism. In this study, one of the main objectives is to find the geolocation of the source of fire as accurately as possible, and this analysis is made possible by superposition (overlapping) of the detection areas of the detectors. Hence, when there is more superposition, there's also a more accurate fire geolocation established. An optimum superposed area in a detector geometry will be called "Optimum Effective Area" (OEA) in this study.

## 3.1 Detection by Out of Center Geometry

In DBOC geometry, the detectors are positioned in such a way that their fields of vision face out of the center of a circle.

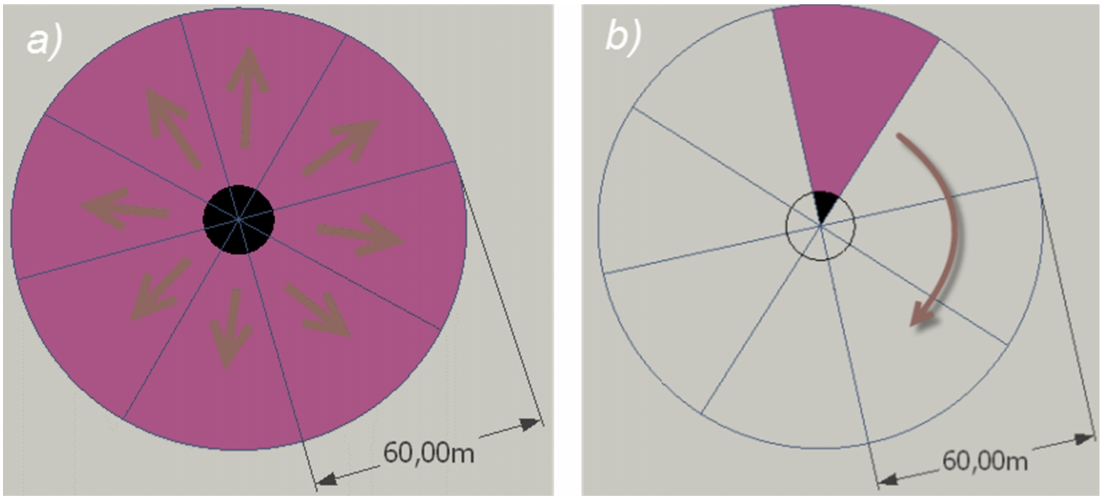


**Figure 3.1 :** DBOC Geometry: (a) 8 fixed detectors in DBOC geometry; (b) spinning detector in DBOC geometry.

In Figure 3.1a, there are 8 black coloured detectors located side by side. Since the sensors that are used in this study have a detection distance of 60 meters, 11 acres of area can be provided for detection area. For instance, in Figure 3.2a, 40 detectors, (5×8), may be used to detect an area of 54901.04 $m^2$ by DBOC's geometry, however, a mere 16 detectors in green colored (Figure 3.2b) constitute a superposed area corresponding to 20982.02 $m^2$ which is easily the optimum effective area (OEA). Mobility of the detectors increase the detection area and flexibility of the detectors. As such, instead of using fixed (immovable) detectors, detectors are mounted on a rotating (step) motor, which is revolving on its own axis and hence they are known as spinning detectors. In Figure 3.1b, there is only 1 sensor based on a step motor and this step motor rotates around 45 degrees in each step. It is the fact that 360 degree is completed with 1 spinning sensor in 8 steps which corresponds same 11 acres of detection area with fixed geometry. As a result, spinning geometry provides low cost system. Therefore, if spinning detectors are used instead of fixed ones as shown in Figure 3.2b, the use of totally five spinning detectors is required for scanning the same detection area. Each spinning detector rotates with an angle of 45$^\circ$ (corresponds to an area of 1413.29 $m^2$) at each step and full scan is completed in eight steps for completing 360$^\circ$ scan.

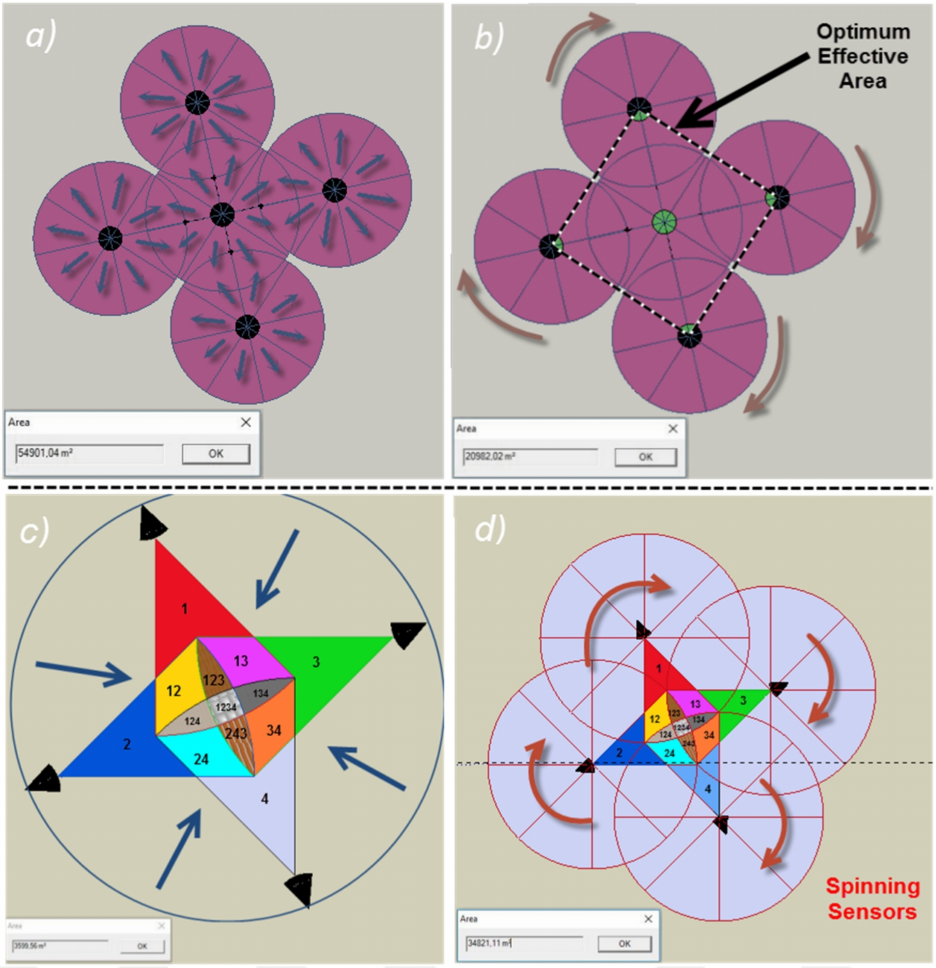



**Figure 3.2 :** Geometry types for detector positions: (a) DBOC geometry with 40 fixed sensors; (b) Created OEA by superposition of detection areas in DBOC geometry; (c) DBTC geometry with 4 fixed detectors; (d) Detection area of four spinning detectors with DBTC geometry.

Thus, spinning geometry provides a lower cost system with the same effectiveness. Statistics of the OEA in DBOC geometries with fixed and spinning detectors are given in Table 3.1. According to the Table 3.1, the same OEA and accuracy are obtained with only five spinning detectors instead of 16 fixed detectors.

**Table 3.1:** Detection areas with 4 detectors.

| Geometry Type | Detector Type (Fixed/Spinning) | Number of Detectors | Detection Area ($m^2$) | Spatial Resolution (Meters) | Optimum Effective Area($m^2$) |
|---|---|---|---|---|---|
| DBOC | Fixed Sensors | 16 | 54901.04 | 30 | 20982.02 |
| | Spinning Sensors | 5 | 54901.04 | 30 | 20982.02 |
| DBTC | Fixed Sensors | 4 | 3599.56 | 4.5-11.5 | 1500.0 |
| | Spinning Sensors | 4 | 34821.11 | 4.5-11.5 | Min.1500.0 |

## 3.2 Detection By Towards The Center Geometry

In DBTC geometry, the detectors are positioned in such a way that their fields of vision face to the center of a circle. Figure 3.2c illustrates the fixed detector view that is towards the center. As each area with different patterns are the superposed areas in the Figure 3.2c, OEA of DBTC geometry is more effective than DTOC geometry, because all detected areas are overlapped except the areas with number 1 to 4. Figure 3.2d shows the same geometry with spinning detectors. When the measured areas illustrated in Figure 3.2c and Figure 3.2d are considered, it is concluded that the use of spinning detectors in the DTOC type geometry increases the detection area about 10 times (Table 3.1). Moreover, OEA also increases proportionally with the number of detectors used.

## 3.3 Validation of the model

In order to assess the feasibility of the model, it is imperative to ascertain the current situation, the goals and challenges to be faced on the pathway. Therefore, we performed SMART analysis on all alternative models to verify that the selected model is the optimum solution. The SMART is a method used in decision support systems that is applied by giving weight values for each criterion (attribute) illustrating how crucial these criteria in relation with the other criteria (Conejar and Kim, 2014; Kasie, 2013). In order to perform SMART analysis, the methodological steps presented Figure 3.3 are applied in this study.

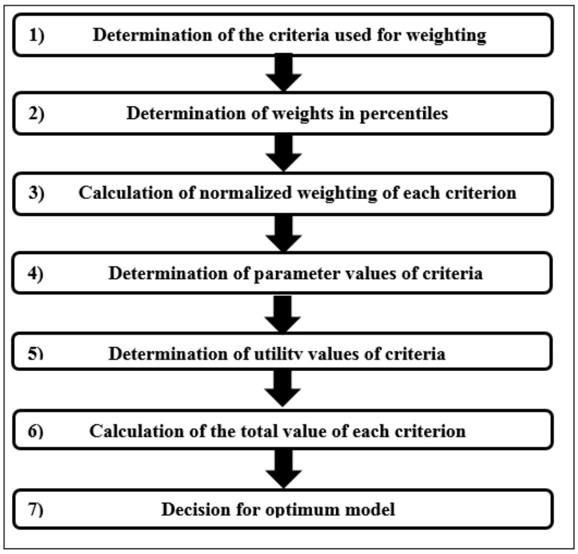



**Figure 3.3 :** Methodological steps for SMART analysis.

First, all criteria are determined and assigned a weight value. For instance, the increase in the number of superposed areas provides an increase in spatial resolution of the geolocation of fires. Furthermore, the model has to be designed in such a way that the detection areas of two or more detectors have to be superposed in just one geolocation because repetitive superposed regions cause conflicts in detection of geolocation of emerging fires. As a result, the most important criteria in forming the optimum model and their assigned weight values ($W_j$) are given in Table 3.2.

**Table 3.2 :** Decisive criteria and assigned weight values.

| Criterion No | Criterion Name | Weight Value ($W_j$) (%) |
|---|---|---|
| C1 | Total control area | 5 |
| C2 | Surface area of new superposed regions(OEA) | 15 |
| C3 | Number of new superposed regions | 10 |
| C4 | Number of repetitive superposed region formation | 25 |
| C5 | Surface area of repetitive superposed regions | 45 |

In order to allow aggregation of criteria with numerical and comparable data, these weights have to be normalized (Mare et al., 2015) by dividing the weights of criteria ($W_j$) with a total weight value ($\sum W_j$) (Risawandii, 2016). Weight values and normalized weight values of all criteria are presented in Table 3.3.

**Table 3.3 :** Normalized weight values.

| Criterion No | Weight Value ($W_j$) (%) | Normalized Weight Value ($W_i = \frac{W_j}{\sum W_j}$) |
|---|---|---|
| C1 | 5 | 5/100 = 0.05 |
| C2 | 15 | 15/100 = 0.15 |
| C3 | 10 | 10/100 = 0.10 |
| C4 | 45 | 45/100 = 0.45 |
| C5 | 25 | 25/100 = 0.25 |

In the fourth step, parameter value of each criterion is determined. That is, each criterion is grouped according to its limit values, and then rated between one and four according to their effects on detection of geolocation of fire (Table 3.4).

**Table 3.4 :** Grouping parameter value limits.

| Criterion No | Limit Values | Parameter Value rate |
|---|---|---|
| C1 (Area, $m^2$) | 2878 > | 1 (Unacceptable) |
| | 3557 – 2878 | 2 (Acceptable) |
| | 5500 – 3556 | 3 (Good) |
| | 5500 < | 4 (Ideal) |
| C2 (Area) | 1000 > | 1 (Unacceptable) |
| | 1000 – 1350 | 2 (Acceptable) |
| | 1351 – 1460 | 3 (Good) |
| | 1460 < | 4 (Ideal) |
| C3 (Number) | 22 < | 4 (Ideal) |
| | 16 – 22 | 3 (Good) |
| | 09 – 15 | 2 (Acceptable) |
| | 09 > | 1 (Unacceptable) |
| C4 (Number) | 7 < | 1 (Unacceptable) |
| | 7 – 4 | 2 (Acceptable) |
| | 3 – 1 | 3 (Good) |
| | 1 > | 4 (Ideal) |
| C5 (Area, $m^2$) | 1000 < | 1 (Unacceptable) |
| | 501 – 1000 | 2 (Acceptable) |
| | 100 – 500 | 3 (Good) |
| | 100 > | 4 (Ideal) |

Four alternative models (A1, A2, A3, A4) for the positions of detectors are illustrated in Figure 3.4. Distances between detectors vary in each individual alternative model. For instance, in Figure 3.4, (a) shows a model with the largest distance between detectors, whereas (d) has the minimum distance between detectors. Each model has advantages and disadvantages for detection of geolocation of emerged fire. For example, (d) has more superposed areas than (a), but (d) includes repetitive superposed regions. Repetitive superposed regions cause detection of geolocation of fire in multi places and can be an obstacle to pinpointing the accurate location. Hence, (a) is rated higher than (d).

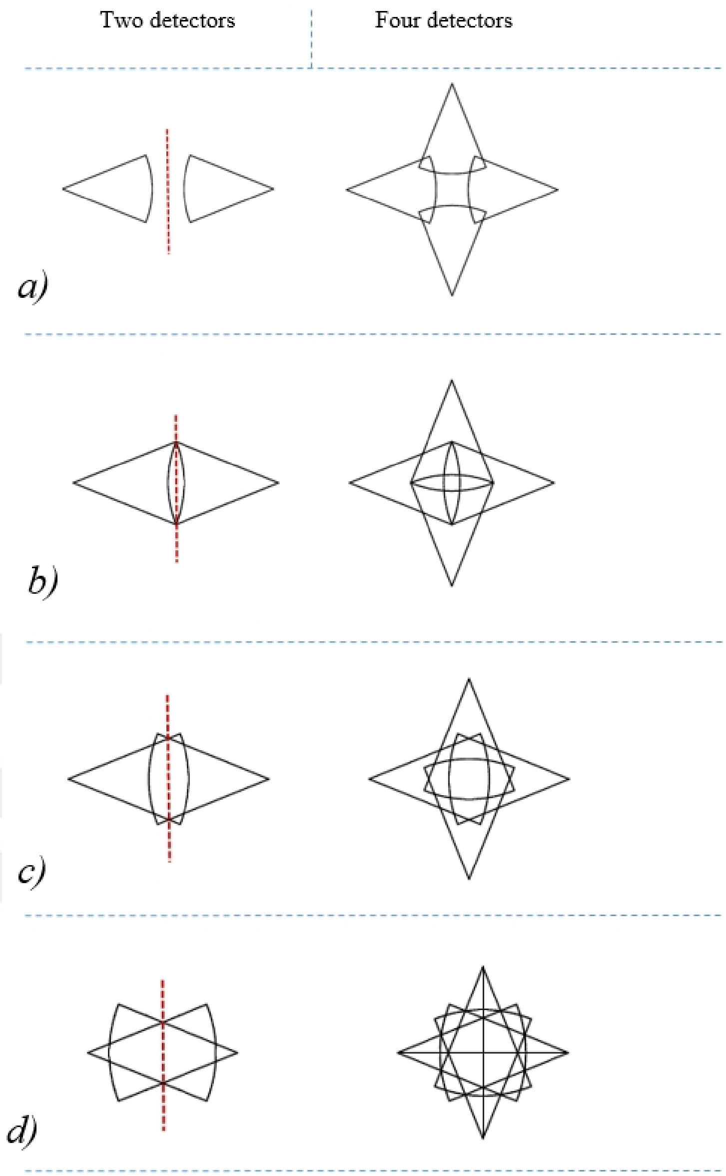



**Figure 3.4 :** Alternative models with two and four detectors: (a) Alternative model 1 (A1); (b) Alternative model 2 (A2); (c) Alternative model 3 (A3); (d) Alternative model 4 (A4).

Area measurements on alternative models according to five criteria are done with the SketchUp drawing tool and given in Table 3.5.

**Table 3.5 :** Measured values in SketchUP ($m^2$).

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| A1 | 5745 | 269 | 4 | 0 | 0 |
| A2 | 3556 | 1500 | 9 | 0 | 0 |
| A3 | 2878 | 1308 | 17 | 4 | 562 |
| A4 | 2278 | 1454 | 24 | 16 | 1046 |

→

**Table 3.6 :** Parameter value assignments.

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| A1 | 4 | 1 | 1 | 4 | 4 |
| A2 | 3 | 4 | 2 | 4 | 4 |
| A3 | 2 | 2 | 3 | 2 | 2 |
| A4 | 1 | 3 | 4 | 1 | 1 |

SketchUp files of alternative models are also provided as supplementary file. In Table 3.6, parameter values are assigned according to reference values given in Table 3.5. Table 3.6 describes the rating criteria of each alternative model. In the next step, utility values of each criterion, which is between 1 and 0, are determined using the equation (3.1) (Risawandii, 2016).

$$u_i(a_i) = \frac{C_{outi} - C_{min}}{C_{max} - C_{min}} \tag{3.1}$$

$C_{out}$ is the rating criteria of each alternative model given in Table 3.6. $C_{min}$ is the minimum value of parameter values which is 1, whereas $C_{max}$ is the maximum value of parameter values which is 4. Hence,

If the value criteria ($C_{out}$) = 4, then $u_i(a_i) = \frac{4-1}{4-1} = 1$.

If the value criteria ($C_{out}$) = 3, then $u_i(a_i) = \frac{3-1}{4-1} = \frac{2}{3} = 0.66$.

If the value criteria ($C_{out}$) = 2, then $u_i(a_i) = \frac{2-1}{4-1} = \frac{1}{3} = 0.33$.

If the value criteria ($C_{out}$) = 1, then $u_i(a_i) = \frac{1-1}{4-1} = \frac{0}{3} = 0$.

Utility values are presented in Table 3.7.

**Table 3.7 :** Utility values of each criterion (converted from parameter values).

| | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| A1 | 1 | 0 | 0 | 1 | 1 |
| A2 | 0.66 | 1 | 0.33 | 1 | 1 |
| A3 | 0.33 | 0.33 | 0.66 | 0.33 | 0.33 |
| A4 | 0 | 0.66 | 1 | 0 | 0 |

The SMART method is based on a linear weighting model. The following stage is the calculation of the total value of each alternative model by multiplying the utility value criteria with normalized weight value with corresponding equations (3.2) (Zawodnik, 2018).

$$\text{Total score} = \sum_{j=i}^{m} w_j u_i(a_i) \tag{3.2}$$

After calculating the total scores, Table 3.8 shows that the second alternative model (A2) has the highest score with **0.91** based on the SMART algorithm that validates the model used in this study.

**Table 3.8 :** Total scores of all alternative models.

| Alternative models (A) | Criteria (C) | Utility values | Normalized Weight Values | Total score |
|---|---|---|---|---|
| A1 | C1 | 1 | 0.05 | 0.75 |
| | C2 | 0 | 0.15 | |
| | C3 | 0 | 0.10 | |
| | C4 | 1 | 0.45 | |
| | C5 | 1 | 0.25 | |
| **A2** | C1 | 0.66 | 0.05 | **0.91** |
| | C2 | 1 | 0.15 | |
| | C3 | 0.33 | 0.10 | |
| | C4 | 1 | 0.45 | |
| | C5 | 1 | 0.25 | |
| A3 | C1 | 0.33 | 0.05 | 0.36 |
| | C2 | 0.33 | 0.15 | |
| | C3 | 0.66 | 0.10 | |
| | C4 | 0.33 | 0.45 | |
| | C5 | 0.33 | 0.25 | |
| A4 | C1 | 0 | 0.05 | 0.19 |
| | C2 | 0.66 | 0.15 | |
| | C3 | 1 | 0.10 | |
| | C4 | 0 | 0.45 | |
| | C5 | 0 | 0.25 | |

### 3.4 Detection of Fire Location by Uniform Circular Motion

Spinning detectors may also assist finding accurate location of fire. Each detector has angle of view about 45 degree which creates 8 areas in a 360 degree. Boundaries of each area is defined in Figure 3.2. Step motors provide uniform circular motion and constant spinning speed. Since minimum detection duration of sensors is about ~8 seconds, spinning speed must be set to a value which each area can be completed in minimum 8 seconds, otherwise emerged fire cannot be detected in that area. So that, ~8 seconds lag must be considered according to the time of sensors detection. The time T required for one complete revolution is called the ‘period’. In this system period (T) of spinning sensors must be about 8×8= 64 seconds. In Figure 3.5, blue lines refer to boundaries of detection area of 1$^{st}$ detector, whereas green lines refer to boundaries of detection area of 2$^{nd}$ detector. Red holes are the intersection points during spinning in a superposed area (purple). Figure 3.6 shows a sample detection during spinning of two detectors.

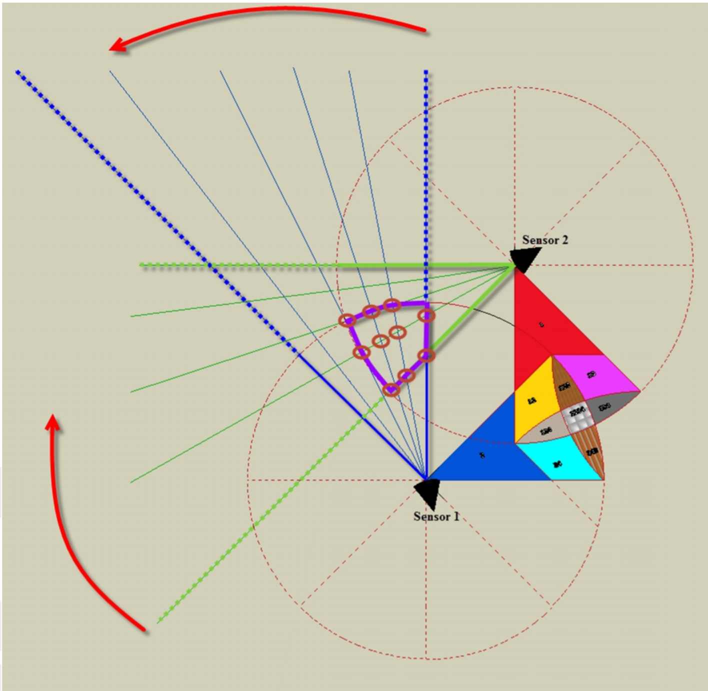



**Figure 3.5 :** Intersection of boundaries of detection areas during spinning.

Detection duration is independent with distance between coordinates of emerged fire and coordinates of related detectors. For instance, in Figure 3.6, the geolocation of emerged fire is estimated to be at any point on the first blue straight line according to first detector.

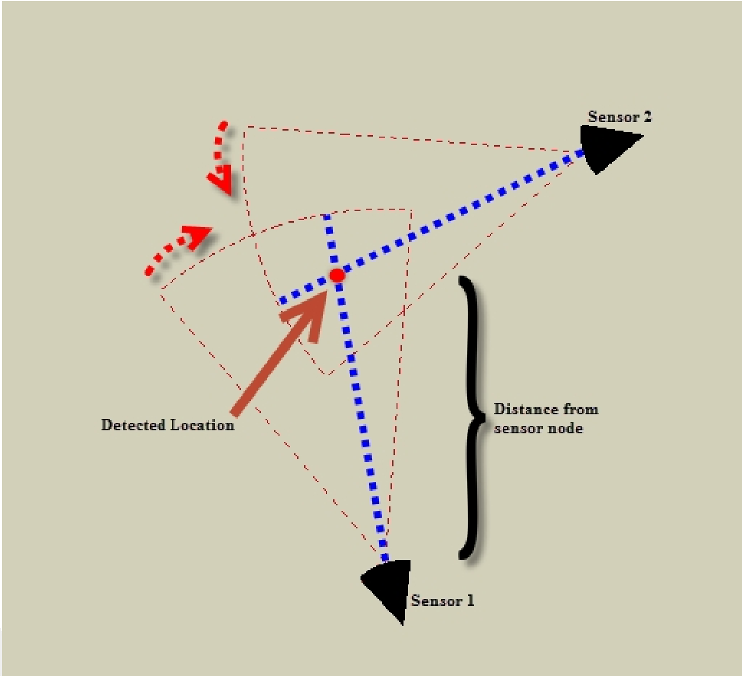



**Figure 3.6 :** Intersection of boundaries in detection area.

Similarly, one another estimation is also done by the second detector to be at any point on the other blue straight line. Since the direction of each blue straight lines are known due to angle of each step motor rotation, the exact geolocation of emerged fire can be calculated by the instersection point of straight lines. However, this method is more useful in case of using more detectors (more than 8), because geolocation estimation with spinning detectors is not much effective in unoverlapped areas. Since four detectors in this study cause more unoverlapped areas, fixed detector approach is preferred for geolocation estimation.

### 3.5 Sample Location of Base System on Google Earth

In this study, fire detection system with 4 detectors according to DBTC geometry are implemented in Darica Zoo in Kocaeli/Turkey.  In Figure 3.7 and Figure 3.8, geolocated drawings are illustrated. 3D drawings of detection areas of the detectors are created with Google Sktechup program and converted to Google Earth KMZ file in order to locate the drawing on Google Earth.

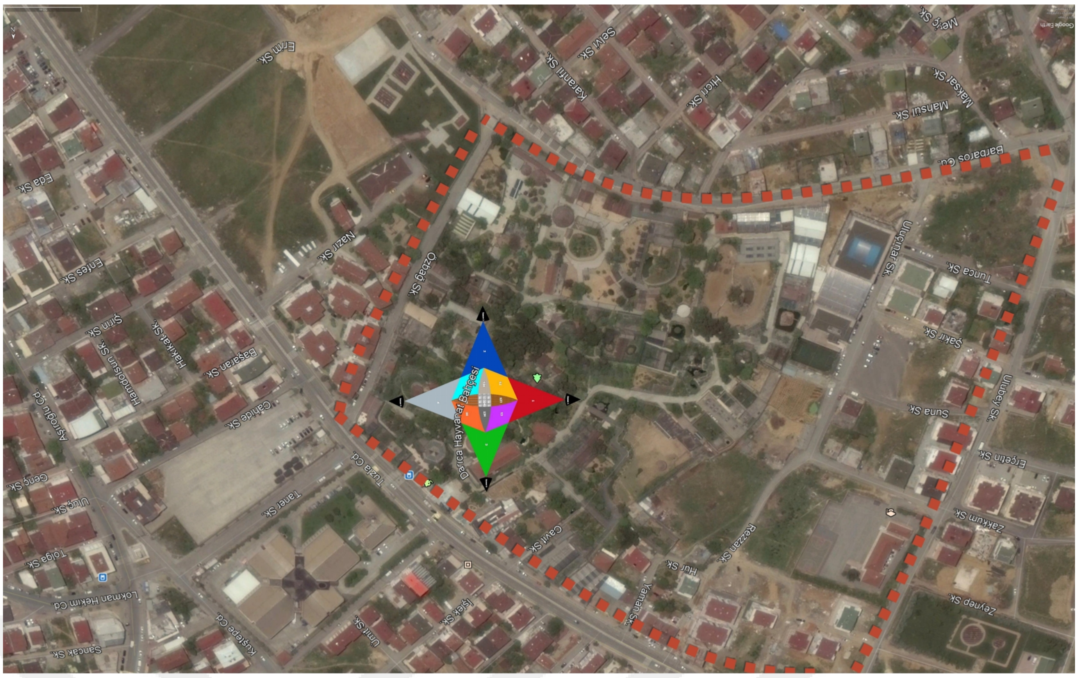


**Figure 3.7 :** Detection Areas of detectors on Darica Zoo / Kocaeli in 2D view.

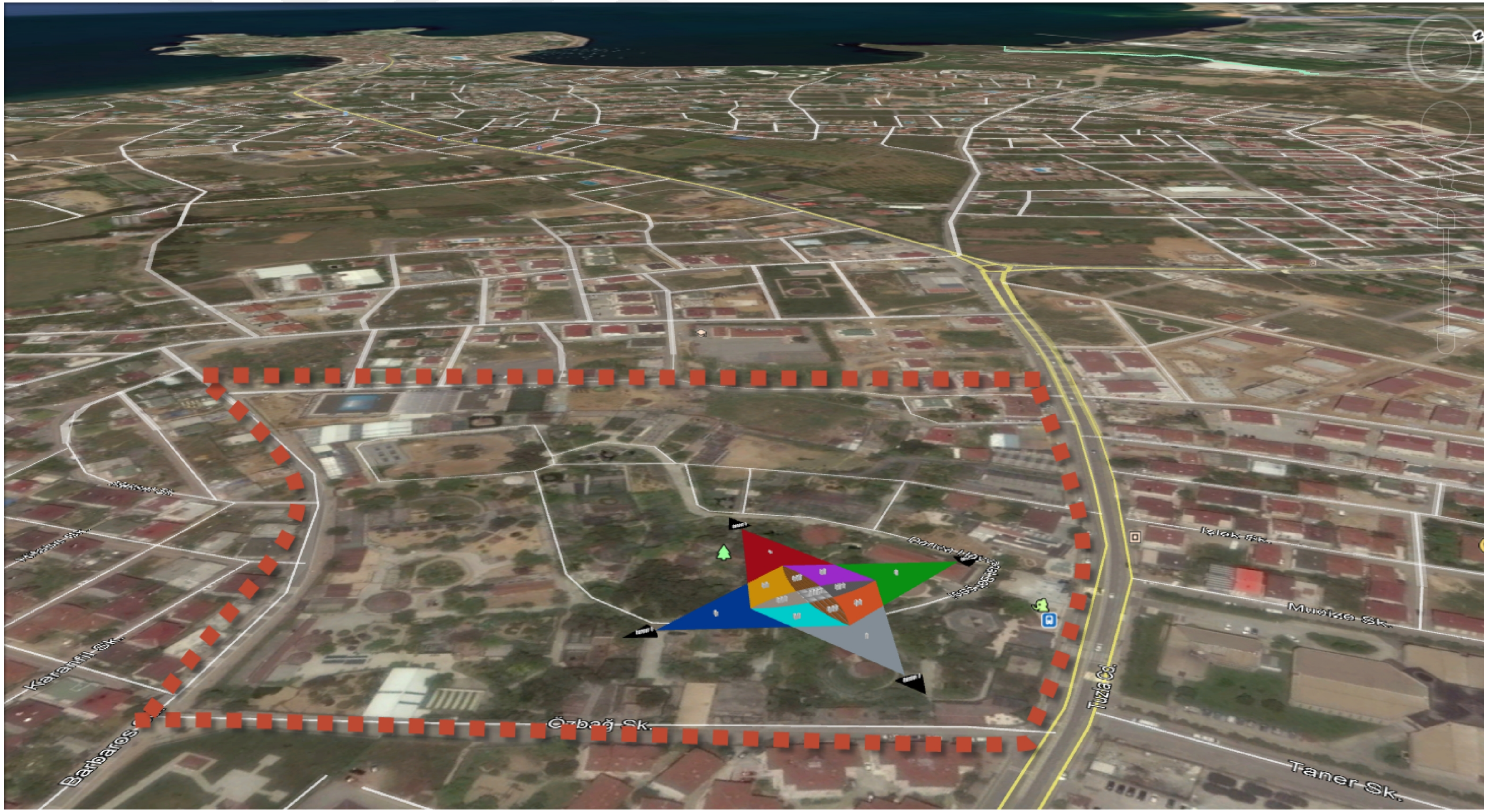



**Figure 3.8:** Detection Area on Darica Zoo / Kocaeli in 3D view.

In order to establish a multi-located GIS monitoring system, more detectors are required indeed. If one more fire monitoring system is established on different locations, both system can be monitored on FireAnalyst. For instance, a 3D model is also geolocated at Istanbul Technical University (ITU) – Maslak Campus in Figure 3.9. If both fire detection system are integrated on the cloud, both Darica Zoo and the area in ITU can be kept under control againt fire disasters.

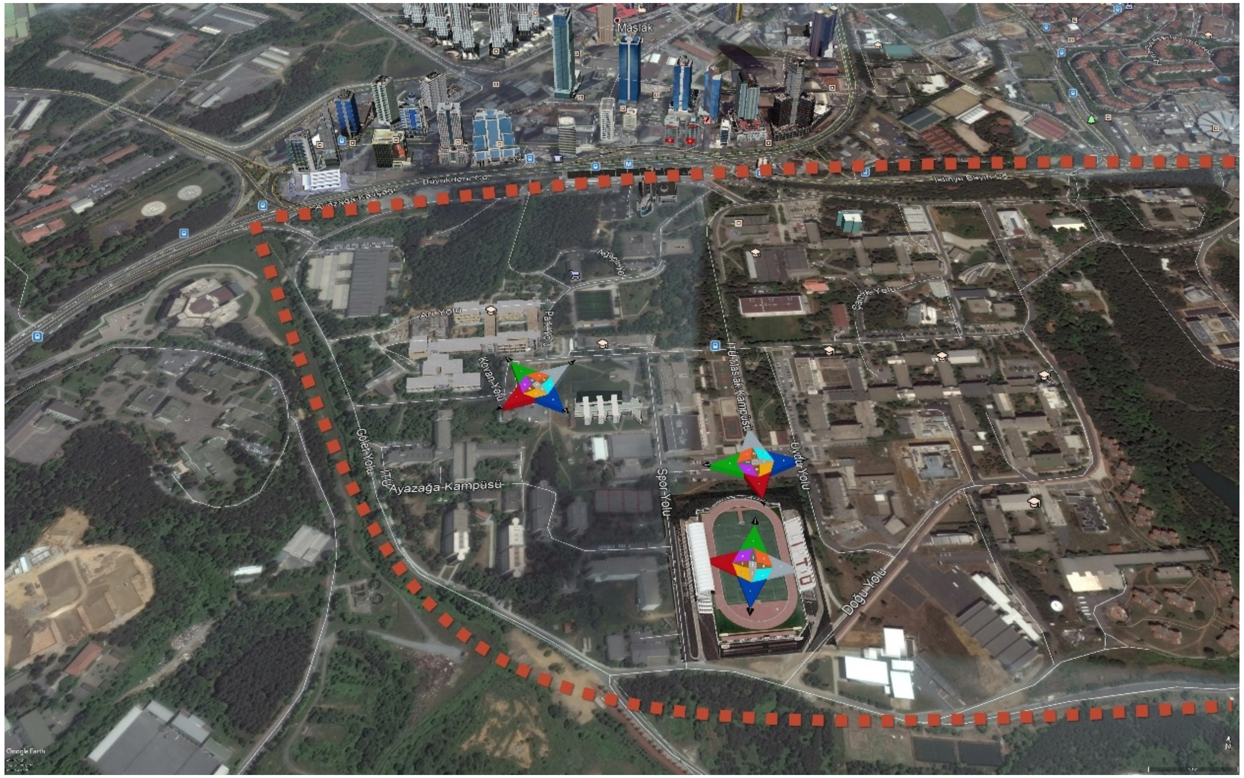



**Figure 3.9 :** Possible detection areas on Istanbul Technical University Maslak Campus in 3D view.

# 4. INSTRUMENT CONTROL SOFTWARE

## 4.1 Measurement & Automation Explorer (MAX)

The software that is used to configure WSN is called Measurement & Automation Explorer (MAX) utility. Figure 4.1 and 4.2 show sample windows from this software. MAX provides adding or removing measurement nodes and configuring wireless settings.

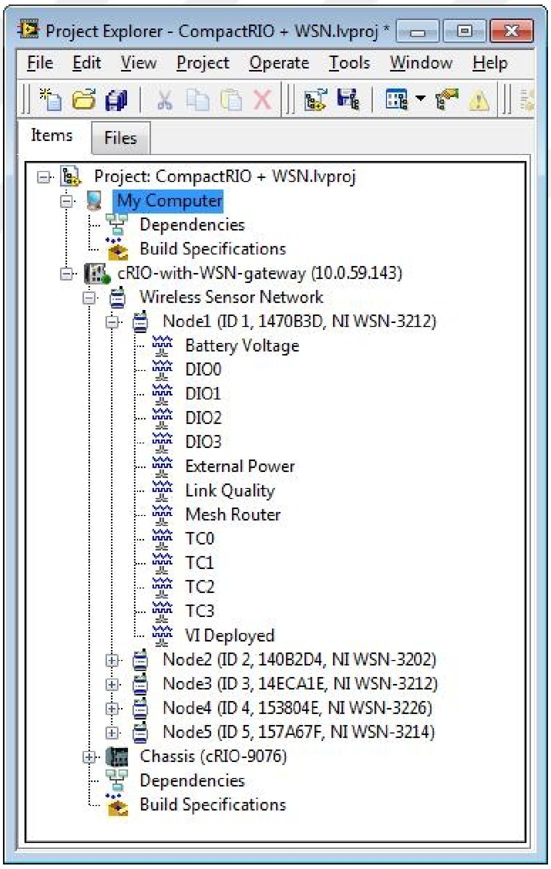



**Figure 4.1:** NI Measurement & Automation Explorer.

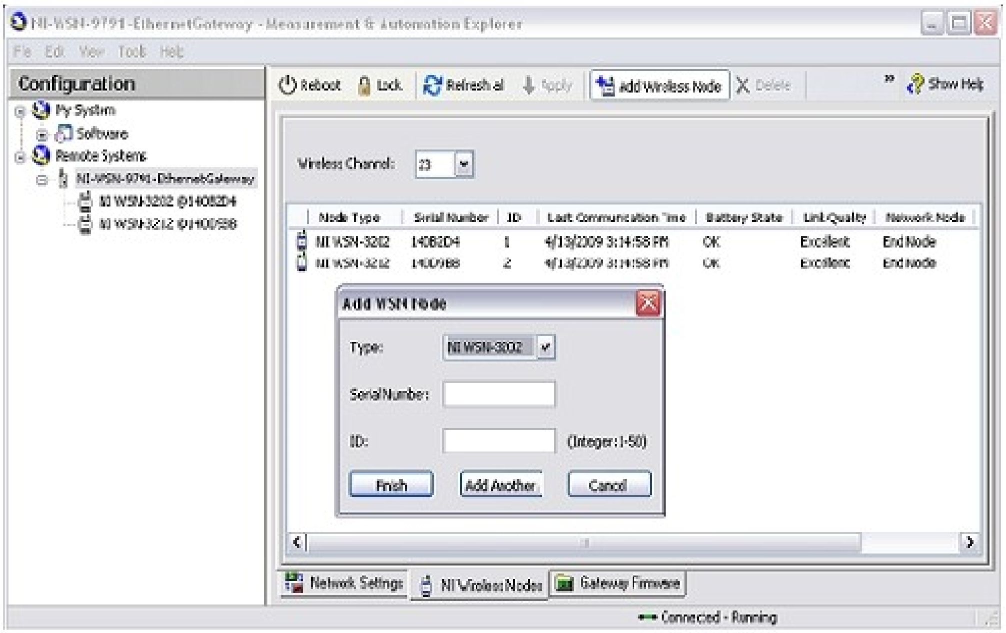



**Figure 4.2 :** MAX Node Configuration Window.

To set up a Wireless network, WSN gateway is connected serially to a PC via an ethernet cable, so that PC can detect the gateway under Remote Systems in MAX interface. After registering WSN gateway, wireless nodes are assigned to the gateway by entering the serial number of nodes. The WSN nodes can automatically reconnect to gateway.

MAX utility is also used to view all properties of the nodes in wireless network, such as their last communication time, battery status, and link quality. In addition, MAX provides an interface to set the ZigBee communication channel, configuring the gateway IP address, wirelessly updating firmware on the measurement nodes and configuring a node to act as an end node or a router node. Since this gateway is a programmable device, these operations can also be performed from a web browser by navigating gateway IP to address bar. Figure 4.3 shows local web configuration page.

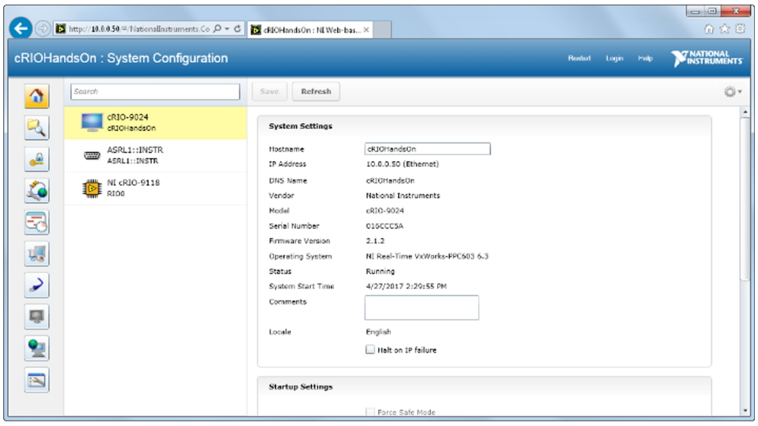



**Figure 4.3 :**Web Configuration Page.

## 4.2 Construction of Algorithm in LabVIEW

There is another method of writing standard programming language and computing platforms like Java or .Net which is called “graphical (block diagram) programming”. This method is a new and modern programming based on dragging and connecting a variety of graphical functions or block diagrams. It is different from traditional programming, because there is no need to know the traditional programming language syntax. Block diagram tools increasingly used to develop an algorithm, model a process or simulate a design in all engineering and technology disciplines due to ease of implementation. Moreover, it is also required to acquire data, control of hardware instruments and embed the developed algorithm into gateway in order to manage the alarm data. According to these requirements of this study, there are a couple of famous instrument control software such as LabTech®, Agilent® or NI LabVIEW® etc. In order to create a compatible solution for this study, NI LabVIEW as software and NI WSN as hardware are preferred. The graphical LabVIEW software is used for:

- Collecting, processing and analysing data from WSN nodes,
- Making accurate estimations of geolocation and behavior of fire,
- Providing integration with WSN and FireAnalyst Portal,
- Providing visual dashboards to monitor fire and hardware of system.

LabVIEW has also a module called Pioneer module for WSN devices which provides wirelessly downloading the designed graphical code to run on WSN measurement nodes. This allows to optimize the sensor nodes for this unique application. That is, it allows to optimize node behavior in terms of sample rate and battery life.

The default behavior of a measurement node is to send collected data to the gateway in a sample frequency. Since battery life is also important in this study, rate of transmission can be decreased by this Pioneer module which provides a uniqe function in order to extend battery life. LabVIEW has two main views which are block diagram (Figure 4.6) and front panel (Figure 4.7).

The block diagram contains graphical source code of a LabVIEW program. The purpose of the block diagram is to separate the graphical source code and show components in a simpler logical manner. LabVIEW has a lot of fundamental operating elements to use on block diagram such as functions and structures. Functions are used for operations like, addition, subtraction, multiplication. As can be seen from Figure 4.4, there are many type of functions and also numeric constants and strings.

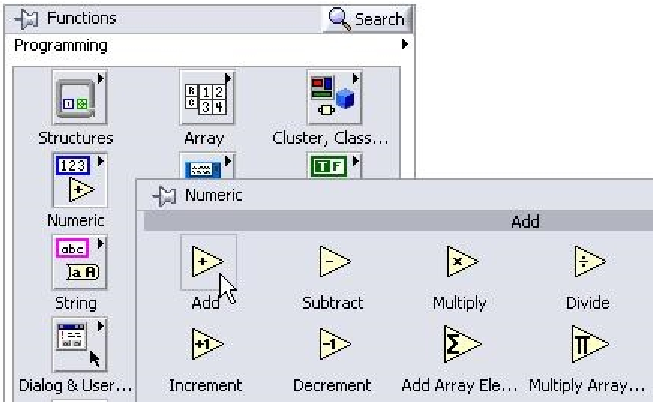



**Figure 4.4 :** Type of functions blocks.

Structures, which include for loops, case structures and while loops, are used for process control. For instance, case structures are used instead of traditional if statements in programming languages. Likewise, Figure 4.5 is a True-False case structure used in this system. This case structure returns the output of inner blocks if the input, connected to a WSN node, takes logical 1 signal.

When input is 1, below events occur respectively in this structure:

1. "Get Date/Time In Seconds" Function takes instant timestamp and sends to "Format Date/Time String" Function in order to separate hours, minutes and seconds
2. A build array concatenates hour,minute,seconds variables and some strings to write to data table as string.
3. The data on the table is converted to numbers by "Decimal String To Number" Function block.
4. All hours, minutes and seconds variables are summed in terms of seconds.
5. As a result, a "t" variable (detection time in seconds) are created for code block.

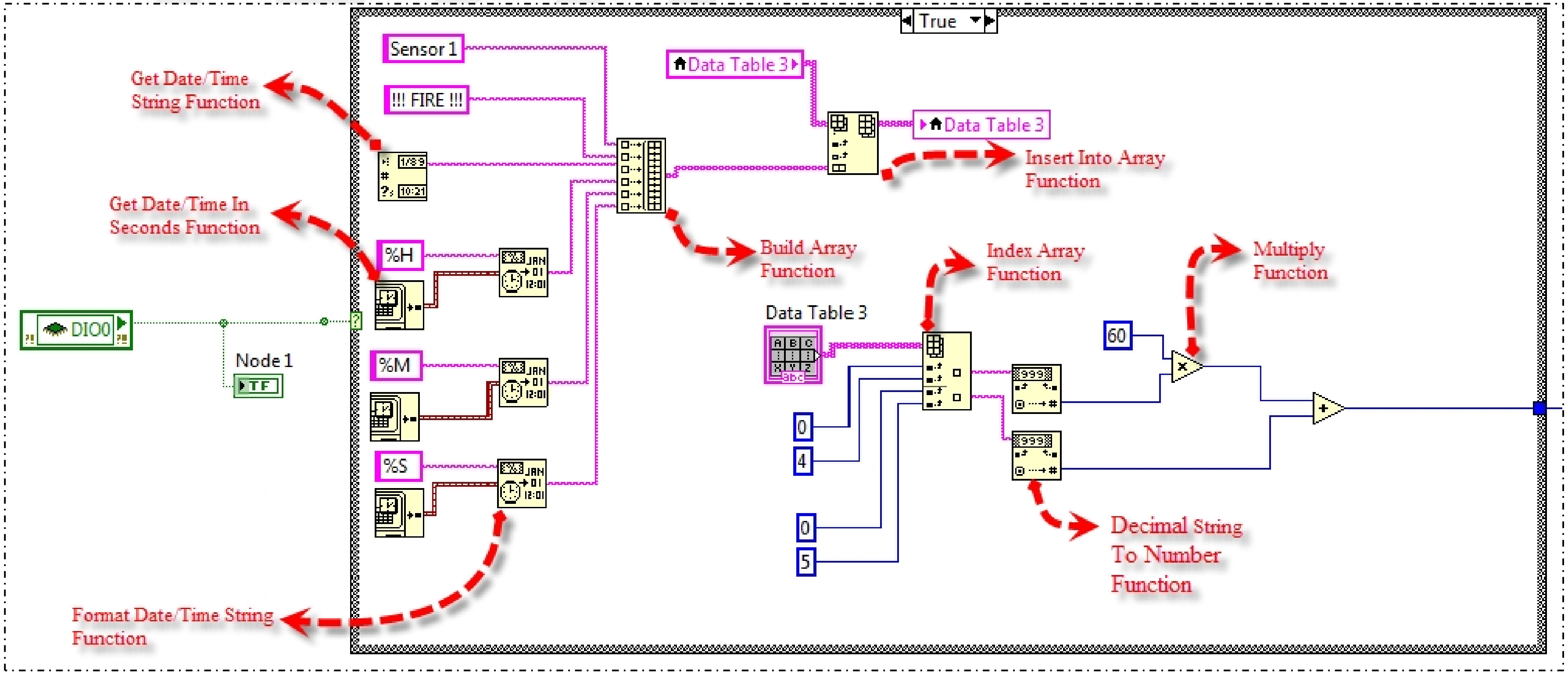



**Figure 4.5 :** A True-False case structure.

LabVIEW measurement tool plays important role in this study, because data of each WSN node is analyzed and algorithmic calculation is performed. The whole block diagram of this study is given in Figure 4.6. In this figure, four rectangle blocks (Figure 4.6d) are case structures which are triggered by green inputs. Those green inputs (Figure 4.6c) are logical variables that are fed from WSN Nodes. In case structures, there are algorithms to fill each cell of data table and a time calculation alghoritm to analysis behavior of fire. The rectangle that contains C++ code (Figure 4.6e) is called “Formula node block” which is an engine that takes inputs from nodes and case structures to make decision about fire behavior, fire speed and predictive shape of area that is under fire. This structure evaluates mathematical formulas and expressions similar to C++ language on the block diagram. As inputs, it takes logical signals from WSN nodes’ variables (n1,n2,n3,n4) and time variables (t1,t2,t3,t4) from case structures. As outputs, it gives case number, c, which means fire area polygon number, fire_speed variable and fire_behaviour variable.

A sample code in Formula node block is below **:**

```
//this is comment: the case for fire region “123”:
else if(n1==1&&n2==1&&n3==1&&n4==0){
if((t2-t1)>=7&&(t3-t2)>=7){
c=123;                                  //first 1, then 2, then 3
fire_behaviour=10203;
fire_speed=0.01/((t3-t1)/3600);
}
else if((t2-t1)<=7&&(t3-t2)>=7){
c=123;                                  //both 12, then 3
fire_behaviour=1203;
fire_speed=0.01/((t3-t1)/3600);
}
else if((t3-t2)<=7&&(t3-t1)<=7){
c=123;                                  //whole 123
fire_behaviour=0;
fire_speed=0;
}
}
```

As illustrated in the code, formula node block takes all “n0, n1 ,n2 ,n3, n4” and “t1, t2, t3, t4” as inputs variables and gives “c, fire_speed and fire_behavior” as output variables. The whole C++ code is presented on Appendix A2.

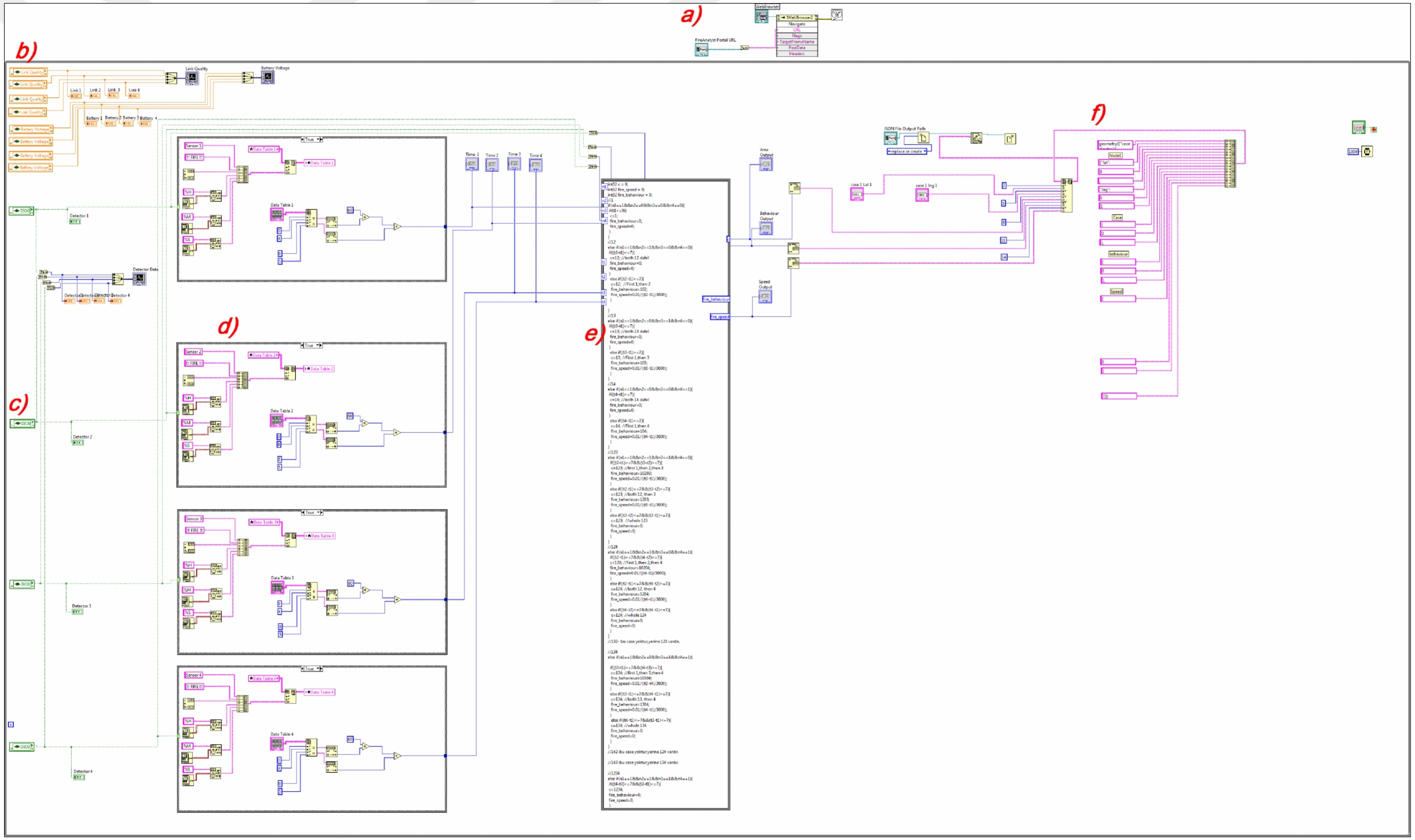



**Figure 4.6**: Fire Detection System LabVIEW Whole Block Diagram: (a)Web Browser function block; (b) Shared variables of WSN node; (c) Shared variables of WSN node output; (d) T-F case structures; (e) code block ; (f) Function blocks for creating JSON file.

The pink blocks and wires (Figure 4.6f) are used for creating a JSON file template which is required for integration and communication of LabVIEW with interactive GIS Map portal. The orange blocks (Figure 4.6b) consist of shared variable that are fed from WSN nodes in order to draw battery information data and wireless link quality data on dashboards. Lastly, Figure 4.6a is web browser function block that runs dynamic JavaScript code for interactive FireAnalyst portal.

When a detector detects flame, below events starts occurring in the system respectively:

1. The WSN node connected to active detector sends a logical 1 signal to LabVIEW via WSN Gateway.
2. Node 1 green led turns to red color as shown in Figure 4.8c.
3. Data table below node 2 starts listing instant time stamps for every seconds until logical signal turns back to 0.
4. The code block in LabVIEW gets detection timestamps (t1, t2, t3, t4) and logical outputs (n1, n2, n3, n4) from all nodes as inputs. Then, all those inputs of code block are analyzed to give 3 outputs which are fire speed, fire behavior and fire area polygon code to be visualized on the map.
5. Outputs of code block, coordianates of reference node 1 and JSON template strings are concatenated in a build array to create a JSON file for real-time communication with interactive GIS map.

### 4.3 Function blocks and JSON file creation

JavaScript Object Notation (JSON) is a syntax for storing and exchanging data. In order to provide communication between the Javascript portal and LabVIEW outputs, JSON notation is used. Therefore, LabVIEW must export the outputs in JavaScript object notation to a file.

So that, array functions, file operation functions, outputs and strings are used together to export outputs to a file in JSON format. Detailed information about JSON will be explained in 5.3 section. In this study, JSON file is created by LabVIEW array function blocks as shown in Figure 4.7.

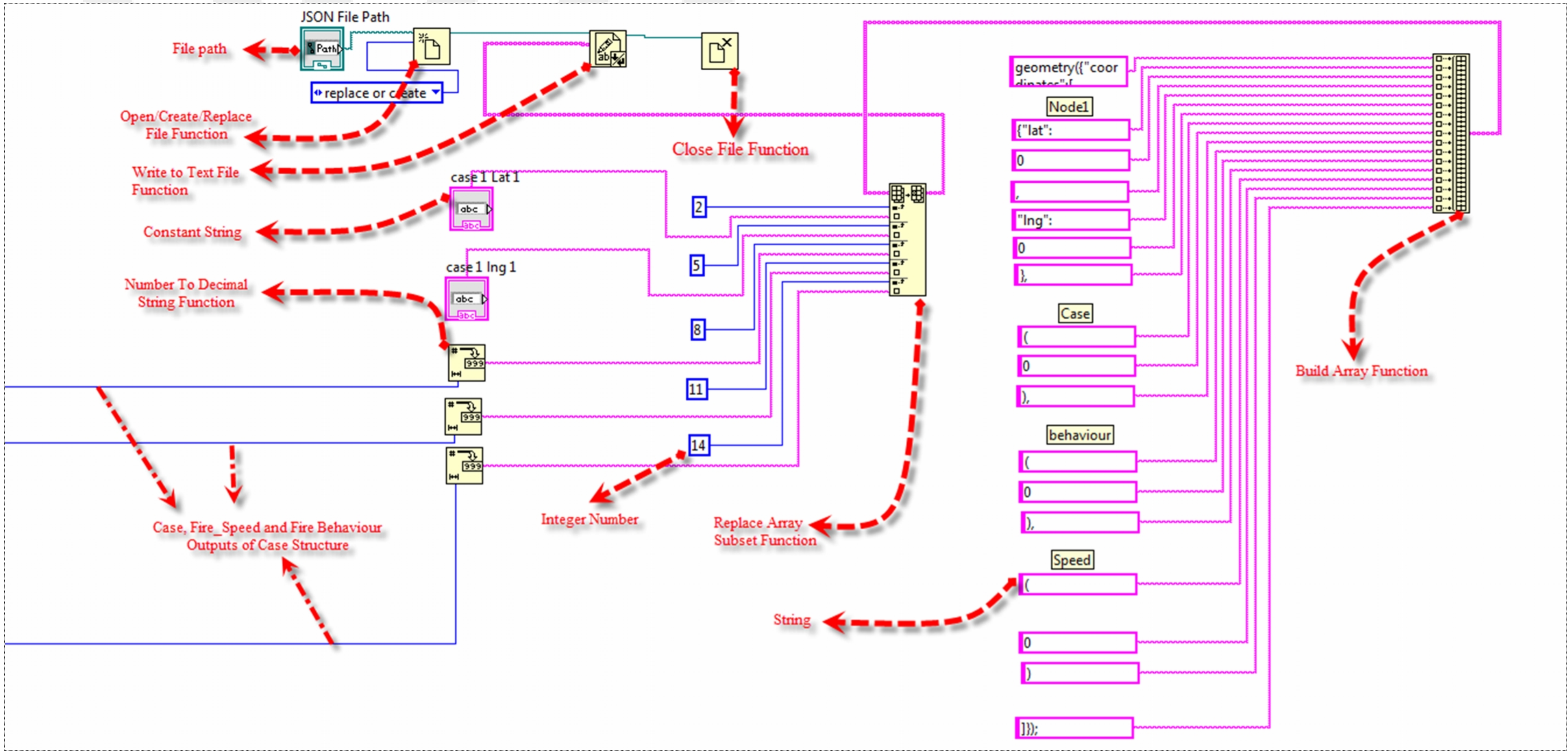



**Figure 4.7 :** Array Function Blocks and JSON File Creation.

The content of JSON file must be in this notation:

```
geometry({"coordinates":[
{"lat":
40.785.600,00
"lng":
29.369000},
(13),
(103),
(4)
]});
```

During JSON File Creation, below operations occur in LabVIEW Automation Softwate respectively:

1. When LabVIEW System is in running state, “build array function” containing default JSON temlate strings pass all array elements to “replace array subset function”.
2. Replace array subset function takes 6 inputs in order to replace all default array elements of build array function. All inputs of replace array function are,
   - case variable
   - fire_speed variable
   - fire_behaviour variable
   - Node 1 coordinates(reference coordinates for offset computing of other nodes)
   - Build array function output.

   In running state, this function replaces all elements at every seconds. This replacement is required for real-time variables such as fire_speed variable or case variable. Blue integers below each input is used to determine the index number of elements to be replaced in build array function.
3. The replaced array elements of build array function are sent to “write to text file function” to pass all elements to a .js file created by “Open/Create/Replace File Function”.
4. The js file created with the path given by “file path instrument” is ready to be read by Javascript in interactive GIS portal.

## 4.4 Front Panel and Properties of FireAnalyst


**Figure 4.8 :** FireAnalyst Front Panel View: (a) Detected fire geolocation; (b)Nearby fire stations discovered; (c) Indicator LEDs; (d) Data tables of WSN nodes ; (e) Info dashboards for WSN nodes; (f) Admin section.

Front panel objects appear as terminals on the block diagram. Changes on the block diagram reflect corresponding front panel objects and vice versa. In Figure 4.8c, Green and red circles are indicator LEDs which show the state of each IR3 detector. Figure 4.8d are data tables that show detection time in minutes and seconds. Three dashboards (Figure 4.8e) show battery information, wireless link quality and logical state of each WSN node. Figure 4.8f section is for administrator. Results of technical analysis, such as fire speed, fire behavior and defined area code; fire detection time in seconds and reference coordinates of node 1 are displayed here.

On FireAnalyst portal, each WSN node is colored to white, red, green and blue for being distinguishable. When a fire is detected by a Multi-IR detector, related indicator LED changes from green to red first. Then, the data table, below the red LED, starts writing detection timestamps of this node instantly. Next, LabVIEW algorithm starts analyzing inputs to create JSON file read by interactive portal. Thereafter, interactive GIS map shows the estimated geolocation of fire and draw routes to nearby fire station with a radius of 5 KM (Figure 4.8b).

FireAnalyst map can simulate the geolocation of fire in street view as illustrated in Figure 4.8. Therefore, fire operators have available satellite imagery, as well as 3D trees and terrain images. Moreover, the fire region can be zoomed into to see the precise location of fire and can even be dived into for a 360° perspective with the street view function. FireAnalyst has various available map types, such as Roadmap, Satellite, Hybrid and terrain. The more detailed visualization about fire is provided in Roadmap view which is explained in section 5.

# 5. CLOUD BASED INTERACTIVE GIS MAP

## 5.1 Integration of Geospatial Information with Javascript

Javascript is a dynamic computer programming language and is a client side scripting language developed by Netscape for dynamic content. Javascript can be embedded in HTML pages and interpreted by browsers. Due to those properties, FireAnalyst interactive GIS map is designed with Javascript. FiraAnalyst can work as distributed architecture, i.e., fire operators can control all areas on which FireAnalyst are installed over cloud technology. For instance, if two FireAnalyst systems are installed on different regions, such as Darica Zoo Izmit (Figure 3.7) and ITU campus – Istanbul (Figure 3.8), both systems can be monitored as real-time on interactive GIS map. The system refreshes its Java functions for every 3 seconds to poll for fire signal. When there is no fire, the GIS map displays whole Turkey map with a green font page as in Figure 5.1.

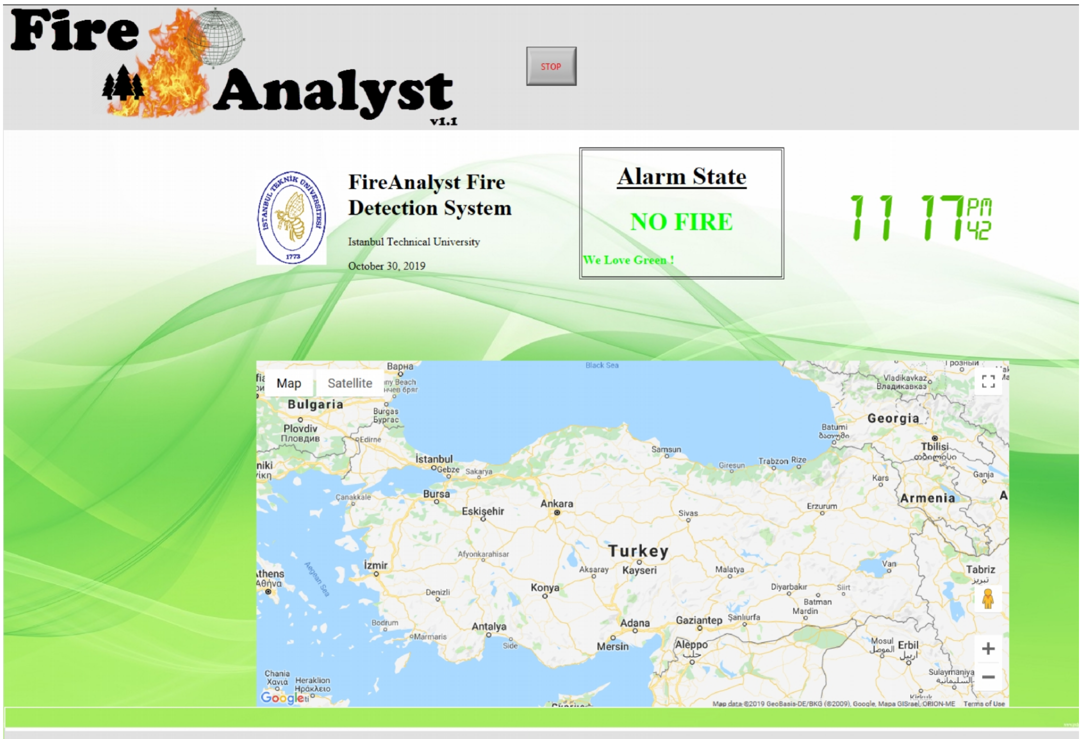



**Figure 5.1 :** FireAnalyst in No Fire state.

In case of fire, below actions occur on interactive GIS portal (Figure 5.2):

1. The portal switches its background from green to red,
2. Fire alert is played in the background,
3. Alarm state text changes to “Fire Detected”,
4. A dynamic polygon is drawn on the map in where fire emerged.
5. Nearby fire stations are listed on the map with a fire engine icon (Figure 5.2b).
6. Information of each nearby fire station are listed on the portal (Figure 5.2d) such as,
    a. source of fire,
    b. nearby fire station addresses,
    c. distances to fire regions,
    d. arrival time with real-time traffic effect.
7. When a fire station is clicked on the map,
    a. Shortest route from fire station to fire region is drawn on the map (Figure 5.2a).
    b. Information bubble appears on fire engine icon showing fire station info (Figure 5.2c).

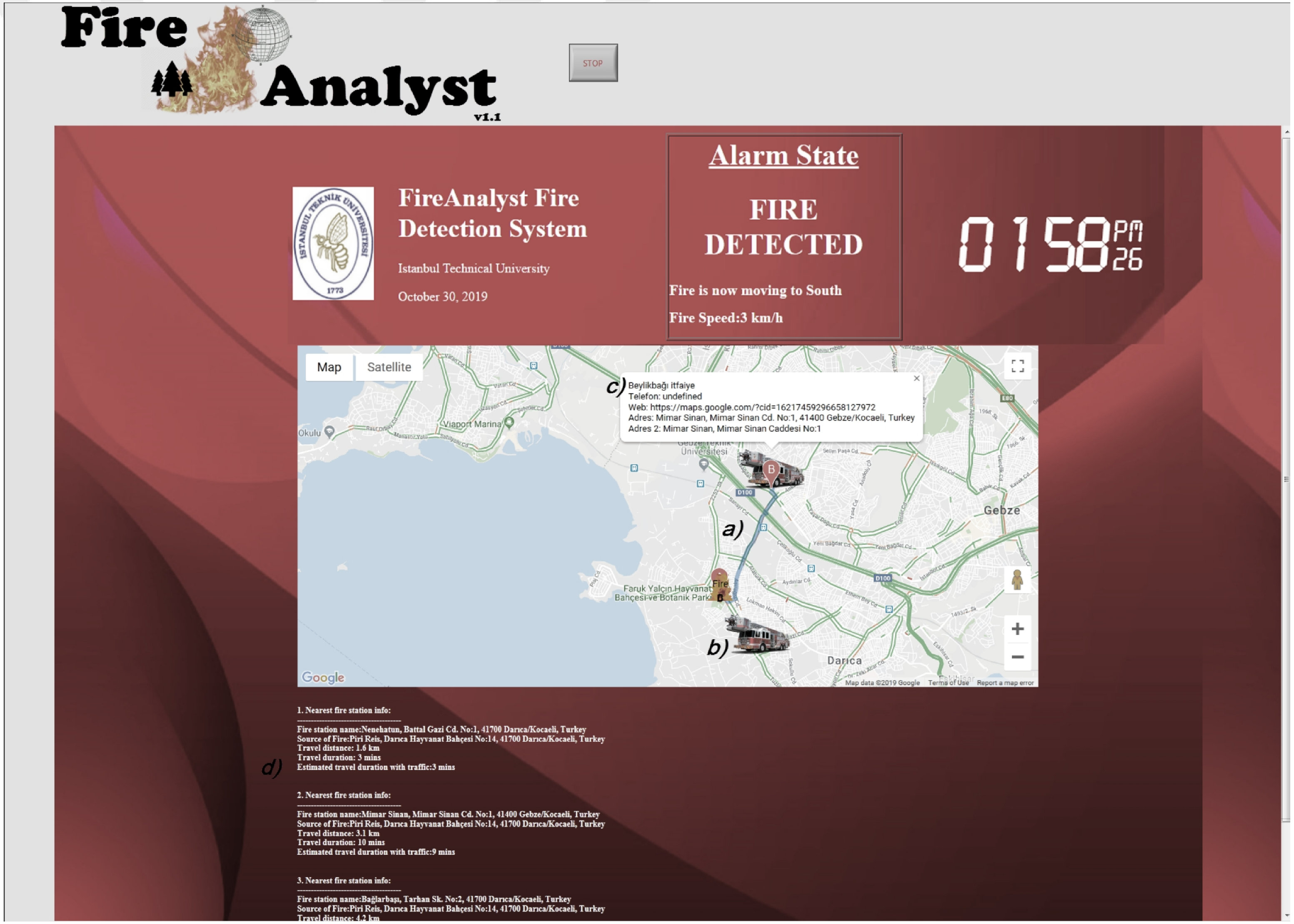



**Figure 5.2**: Interactive GIS Map during Fire Case: (a) Shortest route to the fire geolocation; (b) A nearby fire station; (c)Information bubble of a nearby fire station ; (d) Detailed real-time route information from fire stations.

### 5.2 Cloud API Services

In this study, Cloud Javascript APIs of Google are used for GIS solutions. With Google Cloud Platform (GCP), applications in all programming languages can be built, tested, and deployed for web and mobile solutions on Google's highly-scalable infrastructure. Google Cloud Platform provides cloud services for computing such as building location-based applications. In FireAnalyst, some of Web APIs of Google are used which are:

- Geocoding API,
- Distance Matrix API,
- Javascript API,
- Directions API,
- Places API.

Google has also a web console providing a web-based, graphical user interface that is used to manage Cloud Platform projects, resources and API services for application administrators. Figure 5.3 illustrates cloud platform management console. In this console, active cloud services and some monitoring statistics, such as request traffic per seconds, error ratios and median latency of each service can be monitored from this console for software performance.

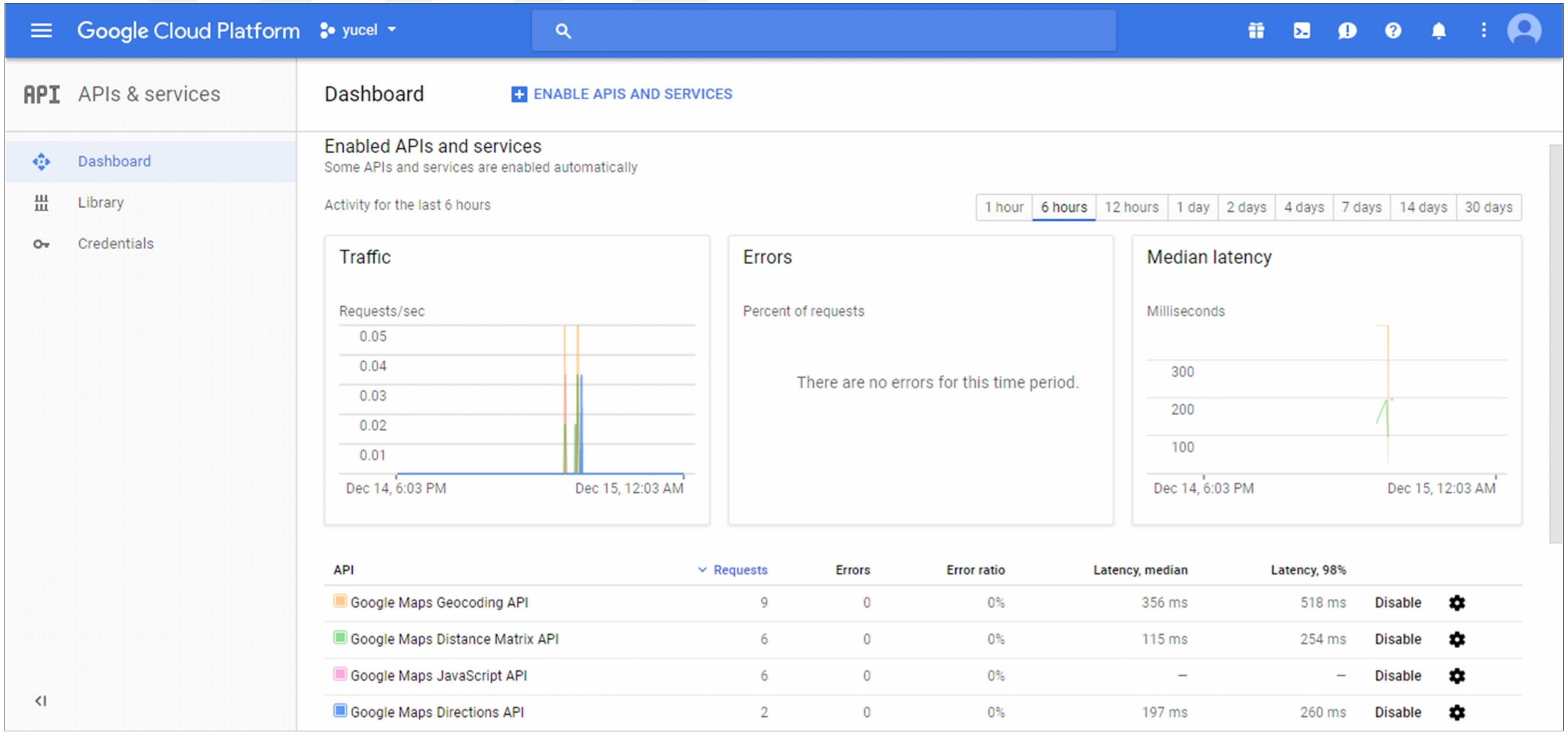



**Figure 5.3 :** Cloud Management Console.

### 5.3 Communication of Spatial data with GIS Map

JSON is used for storing and exchanging data. Since it is just a text, any JavaScript can be converted object into JSON and send JSON to the server. Any JSON received from the server can also be converted into JavaScript objects. Thanks to this way, data as JavaScript objects can be worked with no complicated parsing and translations. Thus, JSON is used for communication method between GIS portal and LabVIEW server in this study.

Content of sample JSON file for this study is below:

```
geometry(
{"coordinates":[{"lat":40.785119,"lng":29.368914},(123),(10203),(2)]}
);
```

In the code above, there is a geometry function and it includes some values to pass variables in GIS portal Javascript code. That is,

```
var script = document.createElement("script");
        script.type = "text/javascript";
        script.src = "data.js";
        document.getElementsByTagName("head")[0].appendChild(script);
                }
        function geometry(response) {
        jsondata = [
        {lat: response.coordinates[0].lat, lng: response.coordinates[0].lng},
                                                        //Node 1 coords.
        (response.coordinates[1]),                      //Case
        (response.coordinates[2]),                      //Behaviour
        (response.coordinates[3])                       //Speed
                ];
        var durum = jsondata[1];                        //Detection Area Code
        var fire_behaviour = jsondata[2];               //Behaviour Number
        var fire_speed = jsondata[3];                   //Fire speed Number
```

In the code block above, the variables in bold are assigned with values in JSON file.

## 5.4 Auto-calculation of position of detectors in FireAnalyst Portal

JavaScript API of Google Maps is used for calcutating the polygon coordinates of fire area.This API has geometry library and it provides utility functions for the computation of geometric data on maps. This library includes a namespace called spherical. It contains spherical geometry utilities which allows to compute angles, distances and areas from latitudes and longitudes. Therefore, this library is used in Javascript HTML code. When fire area which will be monitored is selected, coordinates of 1st sensor established in area is assigned from JSON file. After passing the coordinates of 1st sensor to Javascript code, 'computeOffset' function in Geometry library creates fire area polygon by auto-calculating the other coordinates of this polygon.

The code block below shows the alghoritm of creating a fire area polygon with 'durum=1' situation.

```
if (durum == '1') {                                   //detected fire case
var point11 = new google.maps.LatLng(jsondata[0]);    //reference coordinates
var point12 = new google.maps.geometry.spherical.computeOffset(point11, 42.42, -157.5);
var point13 = new google.maps.geometry.spherical.computeOffset(point11, 32.47, 180);
var point14 = new google.maps.geometry.spherical.computeOffset(point11, 42.42, 157.5);

polygonCoords = [
            point11,
            point12,
            point13,
            point14,
            ];
      }
```

In the code above, all coordinates are calculated by referencing "point11". According to 'durum' variable, polygon coordinate points are auto-calculated up to "the angle and distance to reference point". For instance, point12 is 42.42 meters far from point11 and has -157,5 degree angle of slope to reference point.


**Figure 5.4 :** Created fire area polygon samples on Map for: (a) Case: 134 polygon; (b) Case: 4 polygon; (c) Case: 12 polygon; (c) Case: 1234 polygon.

After creating point11,point12,point13,point14 points, fire area polygon is created. Figure 5.4 shows a few sample polygons drawn on map according to fire geolocation visually.

## 5.5 Monitoring Fire Behaviour

The FireAnalyst software receives instant information from the detectors, thereby allowing it to perform time dependent fire behavior analysis, such as fire speed and fire direction. The Eq. (5.1) gives approximate speed ($\vartheta$) of fire according to detection time of detectors. $\gamma$ in the equation is the approximate distance from midpoint of detected area to the border where the fire moves.

$$\vartheta = \frac{\gamma}{\Delta t}\ km/h \tag{5.1}$$

So that, if the detector 1 and detector 2 detect a fire at 07:03 PM simultaneously and detector 4 also starts detecting the same fire at 07:05 PM, FireAnalyst can analyze that the fire is moving from '12' area to '124' area (to south) (Figure 1.1b). Distance of $\gamma_{12\to124}$ is predefined as 7.16 meters (0.00716 km) as given in Figure 1.5c and $\Delta t$ value is assigned as 2 minutes ($0.0\overline{3}$ hours) which is the difference between 07:03 and 07:05. Consequently, fire's direction is determined as being "Moving to the South" in FireAnalyst's portal (Figure 1.1b) and the fire speed is calculated as:

$$\vartheta = \frac{\gamma_{12\to124}}{\Delta t} = \frac{0.00716}{0.03} \cong 2.39\ km/h$$

When fire exists in a control area, this system starts monitoring it. If fire grows and other sensors also starts detecting fire, a yellow fire route is drawn on map with a dynamic red arrow showing fire direction up to the movement of fire as shown in Figure 5.4a-b. Behaviour of fire is defined up to below variables in JavaScript code:

```
var durum = jsondata[1];                          //fire area number
var fire_behaviour = jsondata[2];                 //fire propogation route number
var fire_speed = jsondata[3];                     //speed of fire
var line_point1 = new google.maps.LatLng(0,0);    //start point of route
var line_point2 = new google.maps.LatLng(0,0);    //end point of route
```

### 5.5.1 Detection of fire direction

Yellow line starts with line_point1 point and moves through line_point2 till line_point3. Variables like below samples starting with orta* are fixed points used for directing yellow line on map.

```
var orta1 = new google.maps.geometry.spherical.computeOffset(point11, 21, 180);
var orta2 = new google.maps.geometry.spherical.computeOffset(point11, 64, 212);
var orta3 = new google.maps.geometry.spherical.computeOffset(point11, 62, 150);
var orta4 = new google.maps.geometry.spherical.computeOffset(point11, 91, 180);
var orta12 = new google.maps.geometry.spherical.computeOffset(point11, 46, 195);
var orta123 = new google.maps.geometry.spherical.computeOffset(point11, 44, 180);
.
.
.
continues...
```

In Javascript code block, nested if statements defines fire route as written below:

```
if(fire_behaviour=='103'){
                        var line_point1 = orta1;
                        var line_point2 = orta13;
                        var line_point3 = point32;
                }
```

Above code means that WSN node 1 detected a fire, then sensor 3 detected fire a couple of seconds later.

### 5.5.2 Detection of fire speed

Estimated average fire speed is defined according to detection time of two consequtive detectors. This value is derived by C code embedded in 'LabVIEW Formula Node Block' and passed to JSON file with variable 'fire_speed'. This JSON value is read by GIS portal as real-time. Below code is a sample code embedded in Formula Node Block for "case:13":

```
//13 region polygon is drawn
else if(n1==1&&n2==0&&n3==1&&n4==0){
        if((t3-t1)<=7){
                c=13;
                fire_behaviour=0;
                fire_speed=0;
        }
                else if((t3-t1)>=7){
```

```
                c=13;                         //First 1,then 3
                fire_behaviour=103;
                fire_speed=0.01/((t3-t1)/3600);
        }
}
```

Above code means that,

- if value of 'durum' variable is 13 and the difference between detection time of 3rd and detection time of 1st sensor is **less** than 7 seconds, then it is estimated that fire is emerged on region number 13.

- if value of 'durum' variable is 13 and the difference between detection time of 3rd and detection time of 1st sensor is **more** than 7 seconds. The fire emerged on 1st region firstly and moved to 3rd region. In this case, fire_speed is defined by dividing 10 meters (approximate distance between regions ) by time difference (Eq. 5.1).

### 5.6 Auto-Discovery of Nearby Fire Stations

The Places API of Google provides 'radar search' function which allows querying for place information on lots of categories, such as: establishments, fire stations,schools.

A Nearby Search function allows search for places in a specific area. Some parameters are needed for a Nearby Search request such as location,radius or type, etc. Below code block has 3 inputs. 'Location' parameter refers to coordinates of emerged fire. 'Radius' input refers searching of 1 km around location.'Type' variable is the type of search which is assigned to 'fire_stations' value. Below Javascript code searches nearby fire stations within 1km distance in case of fire detection in the area. when clicked on discovered fire station, detailed information is displayed as shown in Figure 5.2.

```
function radarSearch(location,rad,searchTerm) {
    var request = {
    location: location,
    radius: rad*1000,
```

```
    type: searchTerm    };
  return new Promise(function(resolve,reject){
    service.radarSearch(request, function(results,status) {
      if (status == google.maps.places.PlacesServiceStatus.OK) {
        resolve(results);
      }else {
        reject(status);
      }
    });
  });
}
```

### 5.7 Calculation of Routes and Travel Duration from Nearby Fire Stations

FireAnalyst can calculate route and travel duration from each nearby fire stations to detected fire coordinates. Effect of online traffic information also considered and displayed on GIS map portal as shown in Figure 5.2. By this way, fire operators are informed about which fire station can arrive fastly. Directions are calculated using a couple of transportation method by communication of 'DirectionsService' object with Google Maps API. Travel time depends on some primary factors, such as 'TravelMode', 'optimistic-pessimistic decissions' or online traffic effect on the route drawn.

Below code block shows how to draw route between selected fire station and fire area on GIS Portal.

```
function calculateAndDisplayRoute(directionsService, directionsDisplay,
pointA, pointB) {
  directionsService.route({
      origin: pointA,
      destination: pointB,
      avoidTolls: true,
      avoidHighways: false,
      travelMode: google.maps.TravelMode.DRIVING
  }, function (response, status) {
      if (status == google.maps.DirectionsStatus.OK) {
```

```
            directionsDisplay.setDirections(response);
        } else {
            window.alert('Directions request failed due to ' + status);
        }
    });
}
```

In the code block, PointA is assigned to origin location which is selected fire station where PointB is coordinates of detected fire.

Another API of Google named Distance Matrix API is used for creating detailed information about route such as travel duration, distance and travel duration with traffic effect. As shown in the code block below, A new web service named ‘service1’ is created in JavaScript code to use Distance Matrix API, because web services are used as an interface for requesting data from Maps API.

```
var service1 = new google.maps.DistanceMatrixService;
        service1.getDistanceMatrix({
          origins: [origin1],
          destinations: [destinationA, destinationB],
          travelMode: 'DRIVING',
          unitSystem: google.maps.UnitSystem.METRIC,
                        drivingOptions: {
                                departureTime: new Date(Date.now() + 1),  // for the time N
milliseconds from now.
                                trafficModel: 'pessimistic'
                                }
        }
```

The Distance Matrix API returns predicted travel times with traffic. In order to receive predicted travel time, a traffic model is specified such as optimistic or pessimistic which affects the predicted duration when calculating route. In Figure 5.2, detailed travel information is shown under GIS Map. For each route (or each nearby fire station) possible route details are printed in sub-line thanks to nested if function shown in below code block.

```
for (var i = 0; i < originList.length; i++) {
        var results = response.rows[i].elements;
        geocoder.geocode({'address': originList[i]},
        showGeocodedAddressOnMap(false));
        for (var j = 0; j < results.length; j++)  {
                geocoder.geocode({'address': destinationList[j]},
                showGeocodedAddressOnMap(true));

                outputDiv.innerHTML += "<br />" + "<br />" + (j + sabit) + ".
                Nearby Fire Stations:" + "<br />" + "-----------------------------------
                ---" + "<br />" + "Fire Station:"  + destinationList[j]  + Fire
                Source::'  + originList[i] +
              "<br />" + " Travel distance= " + results[j].distance.text + "<br />"
              + ' Travel duration= ' +
              results[j].duration.text + '<br />' + 'Traffic effected travel
              duration=' + results[j].duration_in_traffic.text + '<br />' ;
        }
}
```

The code block shows each passed variables, such as address of fire station, distance and duration of each route with/without traffic.

## 6. RESULTS AND DISCUSSION

We have implemented the proposed fire detection model in Faruk Yalcin Zoo & Botanical Park – Darica, Turkey. The implemented system infrastructure is designed to detect fire and fire behavior in real-time. FireAnalyst, the control software of the system, can simulate the real-time geolocation of fires as shown in Figure 5.4.

When 1st, 3rd and 4th detectors trigger an alarm, FireAnalyst simulates the fire inside the corresponding polygon, area "134", as in Figure 5.4a. According to detection time differences, software algorithms calculated the fire's speed as 2.4 km/h and its direction as "moving to southwest", according to method explained in Section 5.5. Similarly, when only the 4th detector triggers an alarm, FireAnalyst displays the fire within the area "4" as in Figure 5.4b. FireAnalyst GUI can also simulate the geolocation of fire in street view as illustrated in Figure 4.4. Therefore, fire operators have available satellite imagery, as well as 3D trees and terrain images. Moreover, the fire region can be zoomed into to see the precise location of fire and can even be dived into for a 360° perspective with the street view function.

In this system, number of overlapped areas in the mathematical model is an important factor for the detection of an accurate geolocation. When assessing the DBOC and DBTC geometry types, the OEA values for DBOC geometry pattern did seem to be greater than DBTC one (as seen in Table 1), however the number of overlapping areas and the overall spatial resolution in the DBTC pattern was found to be significantly greater than the DBOC one. Therefore, in terms of feasibility it was decided to position of the detectors in the DBTC geometry pattern. This results were then also validated with the SMART method.

Table 6.1 shows approximate spatial resolution of geolocation of fire calculated from SketchUp software. According to Table 6.1, fire can be detected within a range of 4.5 – 11.5 meters in 3518.28 $m^2$ area with 4 detectors.

**Table 6.1 :** Average fire geolocation estimation for all cases with four detectors.

| Active Detector No | Area Name | Surface Area ($m^2$) | Spatial Resolution of Fire Geolocation (m) |
|---|---|---|---|
| 1 | 1 | 527.14 | 11.5 |
| 2 | 2 | 527.14 | 11.5 |
| 3 | 3 | 527.14 | 11.5 |
| 4 | 4 | 527.14 | 11.5 |
| 1 & 2 | 12 | 252.40 | 7.1 |
| 1 & 3 | 13 | 252.40 | 8.0 |
| 2 & 4 | 24 | 252.40 | 8.5 |
| 3 & 4 | 34 | 252.40 | 6.0 |
| 1 & 2 & 4 | 124 | 100.03 | 5.4 |
| 1 & 3 & 4 | 134 | 100.03 | 4.6 |
| 1 & 2 & 3 | 123 | 100.03 | 6.1 |
| 2 & 3 & 4 | 234 | 100.03 | 6.2 |
| 1 & 2 & 3 & 4 | 1234 | 81.24 | 4.5 |
| | **Total Area** | **3518.28** | |

When more detectors are used to enlarge the fire control area, this resulted in more overlapped areas being gained with a higher location accuracy (as illustrated in Table 6.2).

**Table 6.2 :** Cases with more spinning detectors.

| Number of Sensors | Detection Area ($m^2$) | Spatial Resolution (Meters) | Approximate OEA ($m^2$) |
|---|---|---|---|
| 4 | 3518.28 | 4.5 - 11.5 | Min. 1500.0 |
| 12 | 104000.4 | 3.5 - 11.5 | Min. 53000.0 |
| 16 | **128761.3** | 3.0 - 11.5 | Min. 71000.0 |

According to the results in Table 6.2, which are measured in a SketchUp drawing file, the spinning detector geometry pattern with 16 detectors had a coverage area of 128761.3 $m^2$ which was the most effective case. Figure 6.1 shows the DBTC geometry with 16 spinning detectors.

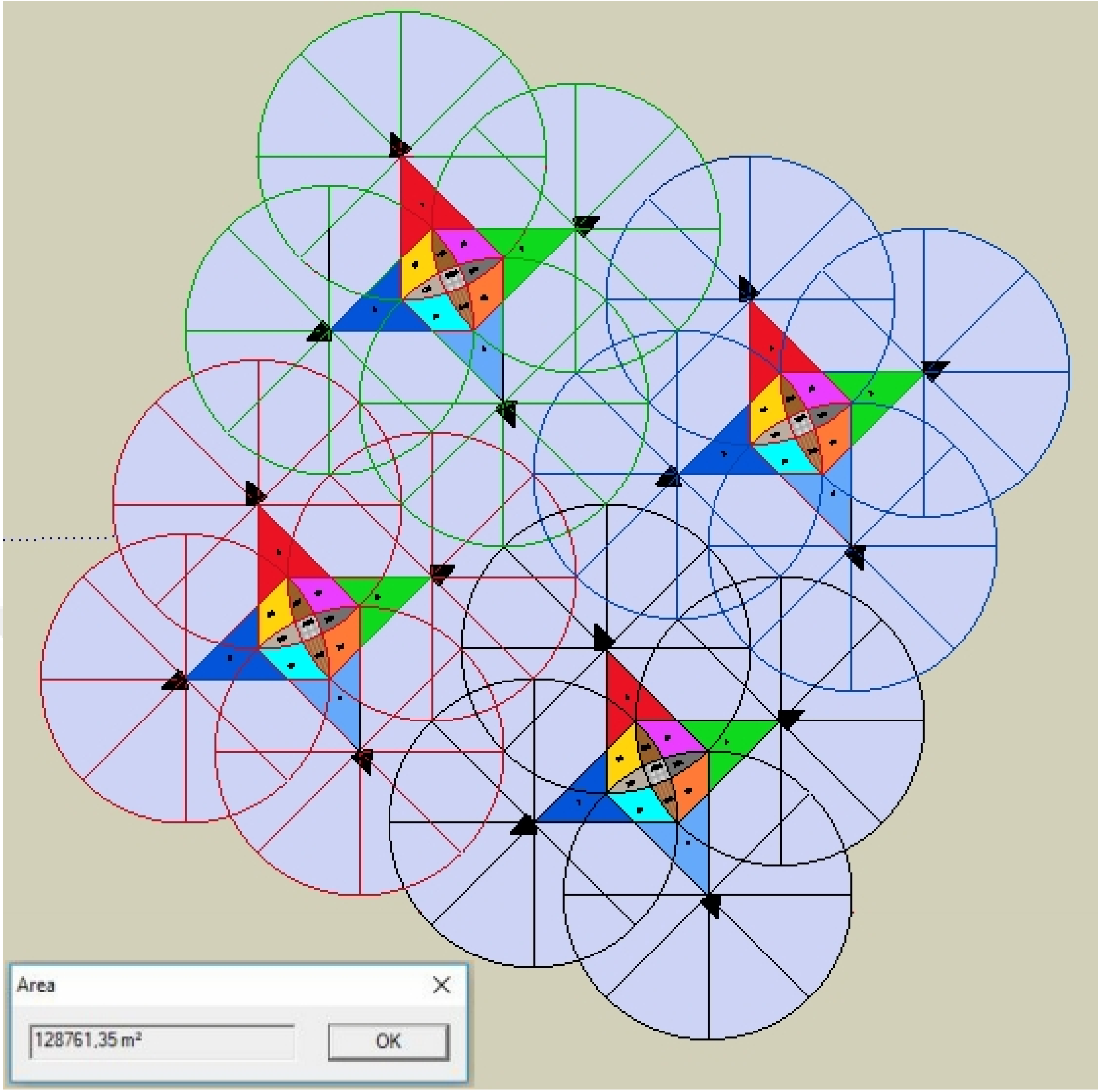



**Figure 6.1 :** DBTC geometry with 16 spinning sensors.

There's no perfect fire detection system for every application, all have challenges, however, choosing correct sensor has a significant importance for fire detection. Advantages and disadvantages of different type of sensors are given in Table 6.3.

**Table 6.3 :** Advantage and disadvantages of different type of sensors.

| Detector Type | SUB-TYPE | PROS | CONS | DETECTION RANGE |
|---|---|---|---|---|
| HEAT DETECTOR | Linear type | Specific usage | Point Type | Room Distance |
| SMOKE DETECTORS | Optical Flame Detectors | Long term usage<br>Less false alarm | Need of cleaning | ~7.5 meters |
| | Ionization Flame Detectors | More sensitive | More false alarm<br>Hardness of recycling<br>Need of frequent cleaning<br>Having a limited radioactivity | |
| | Air Sampling Detectors | Long term usage | False alarm<br>High cost | |
| | Photoelectric Flame Detectors | Long term usage<br>Less false alarm | Need of cleaning | |
| FLAME DETECTORS | Ultraviolet Flame Detectors | Time delaying system<br>Most sensitive | More false alarm<br>(if false alarm mechanism is not included) | ~10 meters |
| | Infrared Flame Detectors | Time delaying system<br>Most sensitive | More false alarm<br>(if false alarm mechanism is not included) | ~65 meters |

The main key factor for detector selection in this study is fast and accurate detection. In addition, since false alarm tendency is also important factor, existance of false alarm mechanism is considered. In the light of those information above, flame detector are most suitable for this system.

The maximum control area of the outdoor fire detection systems depends on purpose and surface roughness. Since this study is designed as a state-of-the-art monitoring system that focuses on detection of the geolocation of the fire at the level of meters, the fire monitoring area is not as hectares as the fire watch towers can monitor, but is as much as the monitoring ranges of long-range multi-IR detectors. However, the fire control area can be expanded by implementing the wireless mesh network method. Therefore, implementation of this system in smaller areas with sensitive boundaries such as High Conservation Value Forests (HCVFs) or botanical parks (which possesses valuable plant species) is what makes this system more feasible in terms of cost-benefit.

Generally, the experimental validation of an early-fire-detection system is a very hard task. There are a couple of standard datasets but there aren't widely accepted or agreed-upon evaluation criteria (Ko et al.,2009). The model used in this study is validated with the SMART method which supports the compared mathematical findings, but in order to validate the effectiveness of the proposed approach. The functionality of the proposed system was compared with some preceding related studies, and an experimental fire test was conducted to verify whether FireAnalyst can detect the exact geolocation of fire or not. In terms of vision-based fire detection methods, although studies of Chen et al., (2016) and Truong et al. (2012) has a novel approach for fire detection, those systems cannot be viable solutions for wildfires because color video cannot capture video at night. Moreover, the video camera itself cannot acquire video in dense forests as trees represent a major visual obstacle in the video capturing process. Therefore, estimating the location of a fire in an accurate way is nearly impossible with vision-based systems, but the proposed system in question here can detect IR rays in both day and night.

Monedero et al. (2019) do not use any detectors for fire monitoring, instead, they benefit from existing mathematical models of fire. Hence, their system cannot keep track of the geolocation of instant fires. In the proposed study, a real-time system in a predefined control area is presented to detect an exact geolocation. In terms of traditional watchtowers methods, although detection towers are widely being used for long distance fire detection, there is a long delay from the point of ignition to the moment the fire starts producing noticeable smoke that can be detected by human or sensor cameras (Mathews, 2010; Alkhatib, 2014), in contrast FireAnalyst can detect fire within a few seconds  thanks to multi-IR detection. On top of that, the cameras on watchtowers may not even detect the location of fire correctly over long distances due to the rugged terrain as portrayed in Figure 6.2a.

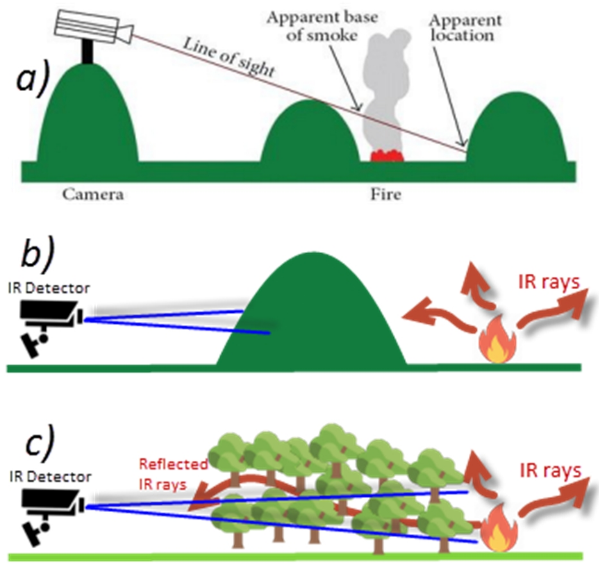



**Figure 6.2 :** Flame detection handicaps: (a) Location error, adapted from Mathews (2010); (b) Rugged terrain case; (c) Trees case.

Unfortunately, rugged terrain and trees are still a handicap for both watchtowers and FireAnalyst as multi-IR detectors also have to make visual contact with open flames just as much as traditional cameras do. Thus, if the fire starts and spreads in terrain that is behind a hill, FireAnalyst would not be able to detect the fire (Figure 6.2b) immediately. However, the proposed multi-IR detectors can detect the IR rays reflected through trees. That is, if a flame exists in a location behind the trees that is not in vision directly, multi-IR detectors can still detect the fire as portrayed in Figure 6.2c.

As for real-time fire behavior analysis, neither watchtower approach or the traditional vision-based fire detection studies mentioned have the ability to calculate a fire's direction and speed like the proposed system can, but can only keep track of its position.

Overall, results of the experimental fire tests in Figure 4.4, Figure 5.2 and Figure 5.4 proved the effectiveness of FireAnalyst. The proposed approach outperforms all comparable studies and adds with functionalities like as real-time fire behavior analysis and the detection of fire with maximum spatial resolution.

# 7. CONCLUSIONS

Forests, factories or industrial zones are fire risk areas and they show similarities in terms of fire potential. In addition, they may contain combustible or exlosive substances too. Those critical areas are needed to be appropriately managed, since they are very sensitive to fire outbreaks and consequences of such incidents could be in a disaster scale. Therefore, early fire detection, detection of fire behavior - determination of 'source of fire' and 'spread speed of fire' - have vital roles for firefighting in order to prevent it from becoming a disaster.

Over the last decade, Geographical Information Systems (GIS) have been used in extensive range of forestry applications , however, detection of coordinates of fire by wireless sensor networks method has not yet been studied before this study. Studies over fire detection systems are generally focused on satellite-based detection, video-based or watchtower.

In this study, we propose a new effective approach for fire detection system in valuable forested areas that can detect fires from very early stage by using mathematical modelling of detector geometry (section 3.3). Geolocation and behavior of the fire (spread speed and direction) are also estimated with maximum spatial resolution by superposition of the detection areas of multi-IR detectors. Moreover, geolocation of fire is simulated visually on the map portal thanks to specially created standalone software called FireAnalyst. Experimental results showed that monitoring fire with FireAnalyst, using multi-IR detectors positioned DBTC geometry, outperformed other fire detection methods providing high spatial resolution in detection of geolocation of fire and short detection duration.

For future studies, we are currently conducting research on an automation system that can extinguish the detected flames using FireAnalyst within seconds with water cannons, as water cannons can shoot a high-velocity stream of large volumes of water to precise coordinates. In addition, while the detection of the geolocation of fire with the four spinning detectors shows excellent performance, it is required that additional computations be done on the software with more than 16 detectors. Therefore, we are researching software algorithms for uniform circular motion geometry to simplify the complexity with more than 10 detectors.

Automatic fire detection systems are designed to meet both life safety and property protection fire safety objectives and are installed to give early warning of a fire. Generally, the response of a detector to a fire is transformed into a visual and/or audible signal. However, If those systems are directly connected to an alarm receiving centre, the fire brigade will automatically be summoned and, assuming adequate and effective response, enhanced protection can be anticipated in the event of a fire. Therefore, we recommend researchers do not only concantrate on detection systems, but also develop compatible extinguisher systems. Moreover, fire behavior analysis can be improved by interpreting all spatial data obtained by adding daylight sensor and wind sensor to this system.

Like most fire engineering disciplines, fire detection and alarm system technology has evolved over recent years, however, the volume of unwanted alarm signals relayed via remote alarm receiving centres to the fire service increased which resulted inevitably impacts on the operational and financial effectiveness of fire. Therefore, we also recommend scholars studying fire detection system focus on their false alarms of their newly created detection systems.

Moreover, they should provide the reliability and dependability of their created system by the adequacy of the design, the reliability of the components used, the quality of the installation and how effectively the system is inspected, maintained, tested and managed on a daily basis.

# REFERENCES

**Alkhatib, AAA.** (2014). A review on forest fire detection techniques. *International Journal of Distributed Sensor Networks,*10. doi:10.1155/2014/597368.

**BlooTech Corp**, (n.d.). In *White Paper for BlooTech*, pp.1-2, date retrieved 10.04.2018, address: http://www.parnell-eng.com/wp/upload/docs/presentations/Blootech-Whtp3.pdf

**Bogue, R.** (2013). Sensors for fire detection, *Sensor Review*, 33, 99-103. doi:10.1108/02602281311299635.

**Chen, X., and Dong, F.** (2016). A dual-band flame detector based on video, *Optik* 127, 478-483. doi:10.1016/j.ijleo.2015.09.238

**Chopde, N.R., and Nichat, M. K.** (2013). Landmark Based Shortest Path Detection by Using A* and Haversine Formula. *International Journal of Innovative Research in Computer and Communication Engineering,* 1. doi:10.15680/IJIRCCE.

**Eugenio, F. C., Santos, A. R., Fiedler, N. C., Ribeiro, G. A., Silva, A. G. et al.** (2016). GIS applied to location of fires detection towers in domain area of tropical forest. *Science of The Total Environment*, 562, 542-549. doi:10.1016/j.scitotenv.2016.03.231.

**Erciyes, K., Dagdeviren, O., Cokuslu, D., Yilmaz, O., Gumus, H.**, (2011). Modeling and simulation of mobile ad hoc networks, *Mobile ad hoc networks: current status and future trends*. CRC Press/Taylor & Francis, Boca Raton/London.

**Erdem, E.** (1997, 15 Şubat). Haber/Facia. *Milliyet Newspaper*. Address: http://www.milliyet.com.tr/1997/02/15/haber/facia.html.

**Erden, F., Töreyin, B. U., Soyer, E. B., Inaç, I., Günay, O., et al.** (2012). Wavelet based flickering flame detector using differential PIR sensors, *Fire Safety Journal*, 53, 13-18. doi:10.1016/j.firesaf.2012.06.006.

**ESP Safety Inc.**, (2013). *IPES-IR3 Flame Detector Operating Manual*, 2013. Date retrieved 10.09.2017, address: http://www.espsafetyinc.com/cms/userfiles/files/IPES%20IR3%2003_28_2012.pdf.

**Ganesh, U. A., Anand, M., Arun, S., Dinesh, M., Gunaseelan, P. et al.** (2013). Forest fire detection using optimized solar – powered zigbee wireless sensor networks. *International Journal of Scientific & Engineering Research,* 4, 586-596.

**Garcia, E. M., Serna, M. A., Bermúdez, A., Casado R. ( 2008).** Simulating a WSN-based Wildfire Fighting Support System. In IEEE ISPA'08. *IEEE International Symposium on Parallel and Distributed Processing with Applications*, Sydney, NSW, Australia, 10-12 Dec.

**Gardiner, B., Ahmad, W., Cooper, T.** (2011). Collision Avoidance Techniques for unmanned Aerial Vehicles. (Report Number: CSSE11 - 01). Alabama,USA: Auburn University, National Science Foundation, Research Experience for Undergraduates.

**Hartung, C., Han, R.** (2006). FireWxNet: A Multi-tiered Portable Wireless System for Monitoring Weather Conditions in Wildland Fire Environments. In MobiSys'06. *Proc. of 4th International Conference on Mobile Systems, Applications and Services*, Uppsala, Sweden, 19-22 June.

**International Maritime Organization.** (2007). Fire Safety Systems (FSS) Code: International Code for Fire Safety Systems, *Resolution MSC.98(73)*, pp. 19–21.

**International Maritime Organization.** (1974). Adoption: 1 November 1974; Entry into force: 25 May 1980, *International Convention for the Safety of Life at Sea (SOLAS).*

**Jonathan, S.** (2013). *Flame Detection and Minimizing False Alarms,* date retrieved: 17.05.2019, address: https://www.emersonautomationexperts.com/2013/safety/flame-detection-and-minimizing-false-alarms/

**Ko, B. C., Cheong, K., Nam, J.** (2009). Fire detection based on vision sensor and support vector machines. *Fire Safety Journal*, 44, 322–329. doi:10.1016/j.firesaf.2008.07.006.

**Lizhong, Y., Zhihua, D., Weicheng, F., Qing'An, W.** (2011). Experimental Study on Characteristics at Early Stage of Fire—Measurement and Analysis on Early Development of Flame Image Area*, Journal of Fire Sciences*, 19, 190-203. doi: 10.1106/DE8L-YU0B-AJQN-N4CV.

**Lioret, J., Garcia, M., Bri, D., Sendra, S.** (2009). A Wireless Sensor Network Deployment for Rural and Forest Fire Detection and Verification, *Sensors*, 9, 8722-8747. doi: 10.3390/s91108722

**Liu, K., Sakurai, M., Aono, M.** (2010) ZnO-Based Ultraviolet Photodetectors, *Sensors*, 10, 8604-8634. doi:10.3390/s100908604.

**Mare, G.D., Granata, M. F., Nestico, A.** (2015). Weak and strong compensation for the prioritization of public investments: Multidimensional analysis for pools. *Sustainability,* 7, 16022-16038. doi:10.3390/su71215798.

**Mathews, S., Ellis, P., Hurle, J. H.** (2010). Evaluatuion of three systems (Report Number: CSE-BDA-002). Australia: Australia Bushfire Cooperative Research Centre.

**Monedero, S., Ramirez, J., Cardila, A.** (2019). Predicting fire spread and behaviour on the fireline. Wildfire analyst pocket: A mobile app for wildland fire prediction. *Ecological Modelling*, 392, 103-107. doi:10.1016/j.ecolmodel.2018.11.016.

**National Instruments Corp**, (2013). *User Guide And Specifications of NI WSN-3226 20-Bit Voltage/RTD Node*, date retrieved 10.09.2019, address: http://www.ni.com/pdf/manuals/373007b.pdf.

**National Instruments Corp**. (2010) *User Guide and Specifications of NI 9792 WSN Real-Time Gateway*, date retrieved 10.09.2017, address: http://www.ni.com/pdf/manuals/372998b.pdf.

**National Instruments Corp.** ( 2010). *Wireless Sensor Network Topologies and Mesh Networking*, date retrieved 10.09.2019, address: http://www.ni.com/white-paper/11211/en/.

**Owrutsky, J. C., Steinhurst, D. A., Minor, C. P., Rose-Pehrsson, S. L., Williams, F. W., et al**. ( 2005). Long Wavelength Video Detection of Fire in Ship Compartments, *Fire Safety Journal*, 41, 315-320. doi: 10.1016/j.firesaf.2005.11.011.

**O'Connor D., Aron O., Christian, D., Gifford, W., Lee, A., D., et al**. (2008). Minimum Performance Requirements for Smoke Alarm Detection

Technology, *Task Group report*, California. Date retrieved 10.07.2019, address: https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Detection-and-signaling/Task-Group-on-Smoke-Technology-Performance-Final-Report-February-2008.ashx?la=en.

**Pitterman, B.** (2000). Telcordia Technologies: the journey to high maturity, *IEEE Software*, 17, 89-96. doi: 10.1109/52.854074.

**Risawandi, and Rahim, R.** (2016). Study of the simple multi-attribute rating technique for decision support. *International Journal of Scientific Research in Science and Technology,* 2, 491-494.

**Sun, J., Guo, G., Zhang, X.** (2014). Research on UV Flame Detector. In IMCCC'14. *4th International Conference on Instrumentation and Measurement, Computer, Communication and Control*. Harbin, China, 18-20 Sept.

**Sevin, A., Bayilmis, C., Erturk, I., Ekiz, H., Karaca, A.** (2013). Design and Implementation of a Man Overboard Emergency Discovery System based on Wireless Sensor Networks. *Turkish Journal of Electrical Engineering & Computer Sciences*, 24, 762-773. doi: 10.3906/elk-1308-154.

**Takex FS5000E Instruction Manual**. (n.d.). FS-5000E. Date retrieved: 17.05.2018, adress: http://takex.com/fs-5000e-pr-789.php

**Truong, T. X., and Kim, J.** (2012). Fire flame detection in video sequences using multi-stage pattern recognition techniques. *Engineering Applications of Artificial Intelligence* 25, 1365-1372. doi:10.1016/j.engappai.2012.05.007.

**Url-1** <https://www.sketchup.com/try-sketchup>, date retrieved 29.06.2019.

**Uvtron Uv Flame Sensor Catalog**. (n.d.). Discharge/Flame sensor UVTRON. Date retrieved: 17.05.2018, adress: http://www.hamamatsu.com/resources/pdf/etd/UVtron_TPT1034E.pdf

**Virex Infra-red Flame Detector Catalog**. (n.d.). Intrinsically safe version detectors. Date retrieved: 17.05.2018, adress: http://www.eleksyangin.com/files/ek_dosyalar/add2252c1.pdf

**Wong, J., and Barbara, S.** (1994). U. K. Patent No: 5,369,397. London: U.K. Patent and Trademark Office.

**Wu, H., Wu, D., Zhao, J.** (2019). An intelligent fire detection approach through cameras based on computer vision methods. *Process Safety and Environmental Protection*, 127, 245-256. doi:10.1016/j.psep.2019.05.016.

**Xihuai, W., and Jianmei, X**. (2000). Ship Fire Alarm System Based on Fuzzy Neural Network. In WCICA'00. *Proceedings of the 3rd World Congress on Intelligent Control and Automation (Cat. No.00EX393)*, Hefei, China, 26 June-2 July.

**Yu, L., Wang, N., Meng, X**.( 1995) Real-Time Forest Fire Detection with Wireless Sensor Networks. In WiCom'95. *Proceedings of Wireless Communications, Networking and Mobile Computing*, Wuhan,China, 26-26 Sept.

**Zawodnik, A., and Niewada, M.** (2018). Multiple criteria decision analysis (MCDA) for health care decision making – overview of guidelines. *Journal of Health Policy & Outcomes Research*, 2. doi: 10.7365/JHPOR.2018.2.4.

**Zhang, J., Li, W., Han, N., Kan, J.** (2008). Forest Fire Detection System Based on a Zigbee Wireless Sensor Network, *Frontiers of Forestry in China*, 3, 369-374.

**5442 numbered Provincial Administration Law** (1975). Karada Çıkabilecek Yangınlarla, Deniz, Liman Veya Kıyıda Çıkıp Karaya Ulaşabilecek Ve Yayılabilecek Veya Karada Çıkıp Kıyı, Liman Ve Denize Ulaşabilecek Yangınlara Karşı Alınabilecek Önleme, Söndürme Ve Kurtarma Tedbirleri Hakkında Yönetmelik. *Republic of Turkey Official Newspaper*, 865, 8 September 1975.

**APPENDICES**

**APPENDIX A.1 :** Whole Formula Node Block C++ Code

**APPENDIX A.2 :** Sensor Geometry Samples with more Spinning Sensors

**APPENDIX A.1 :** Whole Formula Node Block C++ Code

```
int32 c = 0;
int32 fire_speed = 0;
int32 fire_behaviour = 0;
//1
if(n1==1&&n2==0&&n3==0&&n4==0){
        if(t1>=0){
                c=1;
                fire_behaviour=0;
                fire_speed=0;
        }
}
//12
else if(n1==1&&n2==1&&n3==0&&n4==0){
        if((t2-t1)<=7){
                c=12;  //both 12 dahil
                fire_behaviour=0;
                fire_speed=0;
        }
                else if((t2-t1)>=7){
                        c=12;  //First 1,then 2
                        fire_behaviour=102;
                        fire_speed=0.01/((t2-t1)/3600);
                }

}
//13
else if(n1==1&&n2==0&&n3==1&&n4==0){
        if((t3-t1)<=7){
                c=13; //both 13 dahil
                fire_behaviour=0;
                fire_speed=0;
        }
                else if((t3-t1)>=7){
                        c=13;  //First 1,then 3
                        fire_behaviour=103;
                        fire_speed=0.01/((t3-t1)/3600);
                }
}
//14-no case.There are 124,1234 ve 134 instead.

//123
else if(n1==1&&n2==1&&n3==1&&n4==0){
                if((t2-t1)>=7&&(t3-t2)>=7){
                        c=123; //first 1,then 2,then 3
                        fire_behaviour=10203;
                        fire_speed=0.01/((t3-t1)/3600);
                }
```

```
                    else if((t2-t1)<=7&&(t3-t2)>=7){
                              c=123; //both 12, then 3
                              fire_behaviour=1203;
                              fire_speed=0.01/((t3-t1)/3600);
                    }
                    else if((t3-t2)<=7&&(t3-t1)<=7){
                              c=123;  //whole 123
                              fire_behaviour=0;
                              fire_speed=0;
                    }
}
//124
else if(n1==1&&n2==1&&n3==0&&n4==1){
                    if((t2-t1)>=7&&(t4-t2)>=7){
                    c=124; //first 1,then 2,then 4
                    fire_behaviour=10204;
                    fire_speed=0.01/((t4-t1)/3600);
                    }
                    else if((t2-t1)<=7&&(t4-t2)>=7){
                              c=124; //both 12, then 4
                              fire_behaviour=1204;
                              fire_speed=0.01/((t4-t1)/3600);
                    }
                    else if((t4-t2)<=7&&(t4-t1)<=7){
                              c=124; //whole 124
                              fire_behaviour=0;
                              fire_speed=0;
                    }
}
//132-no case.There are 123 instead.
//134
else if(n1==1&&n2==0&&n3==1&&n4==1){

                    if((t3-t1)>=7&&(t4-t3)>=7){
                              c=134; //first 1,then 3,then 4
                              fire_behaviour=10304;
                              fire_speed=0.01/((t3-t4)/3600);
                    }
                    else if((t3-t1)<=7&&(t4-t1)>=7){
                              c=134; //both 13, then 4
                              fire_behaviour=1304;
                              fire_speed=0.01/((t4-t1)/3600);
                    }
                              else if((t4-t1)<=7&&(t3-t1)<=7){
                              c=134; //whole 134
                              fire_behaviour=0;
                              fire_speed=0;
                    }
}
//142-no case.There are 124 instead.
```

```
//143-no case.There are 134 instead.

//1234
else if(n1==1&&n2==1&&n3==1&&n4==1){
        if((t4-t3)<=7&&(t2-t1)<=7){
        c=1234;
        fire_behaviour=0;
        fire_speed=0;
        }
                else if((t2-t1)>=7&&(t3-t2)>=7&&(t4-t3)>=7){
                        c=1234;         //first 1,then 2,then 3,then 4
                        fire_behaviour=1020304;
                        fire_speed=0.01/((t4-t1)/3600);
                }
                else if((t2-t1)<=7&&(t3-t2)>=7&&(t4-t3)>=7){
                        c=1234;         //both 12, then 3 then 4
                        fire_behaviour=120304;
                        fire_speed=0.01/((t4-t1)/3600);
                }
                else if((t3-t2)<=7&&(t3-t1)<=7&&(t4-t1)<=7){
                        c=1234;         //whole 1234
                }
                else if((t3-t2)<=7&&(t3-t1)<=7&&(t4-t1)>=7){
                        c=1234;         //both 123 then 4
                        fire_behaviour=12304;
                        fire_speed=0.01/((t4-t3)/3600);
                }
                else if((t2-t1)<=7&&(t4-t3)<=7&&((t4-t3)-(t2-t1))>=7){
                        c=1234;         //both 12,then 34
                        fire_behaviour=12034;
                        fire_speed=0.01/((t4-t1)/3600);
                }
}
```

**APPENDIX A.2 :** Sensor Geometry Samples with more Spinning Sensors

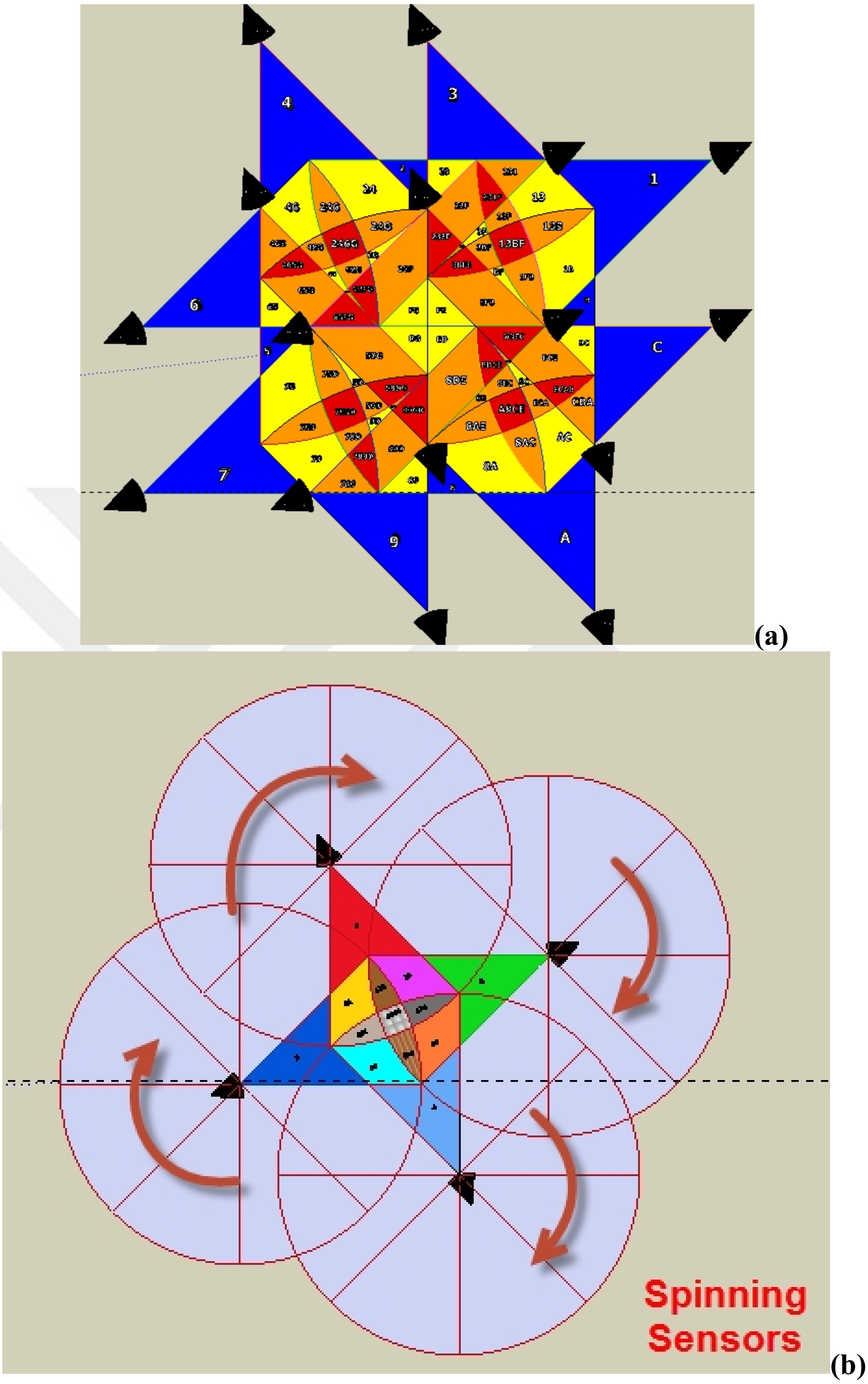
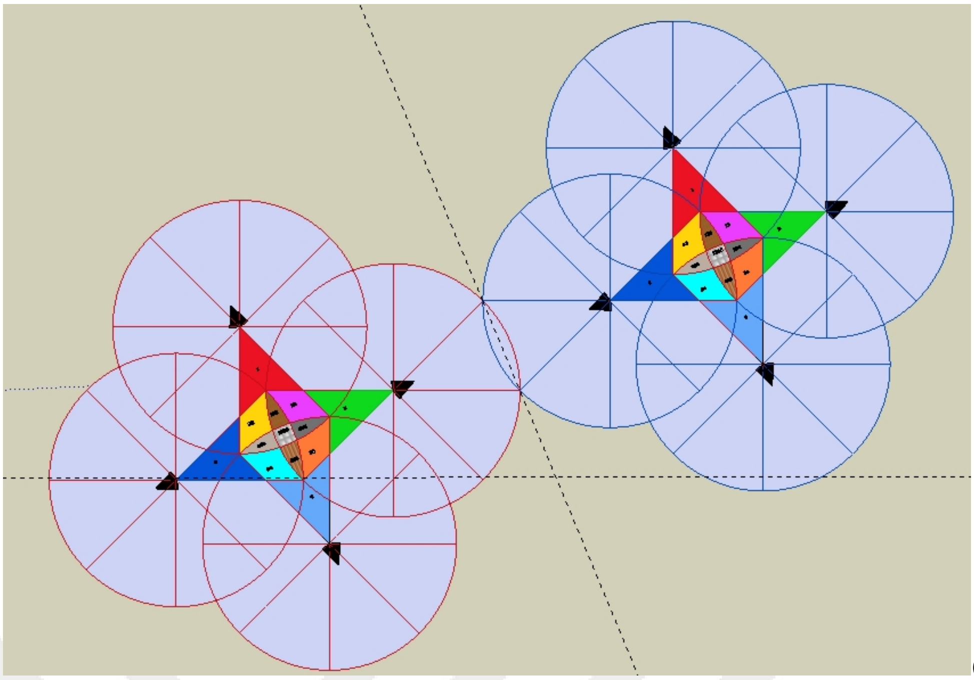
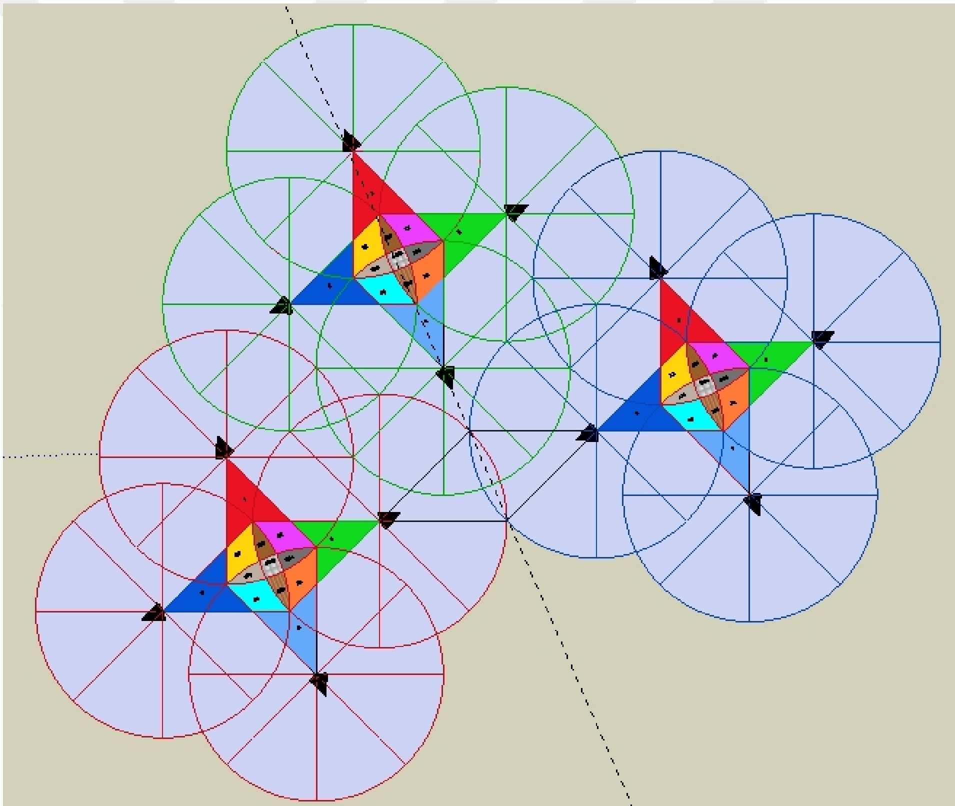



**Figure A.1 :** Mesh Network of Spinning Sensor Geometries: (a) Fixed Sensor Geometry with 16 Sensors (b) Spinning Sensor Geometry with 4 Sensors.



(c)



(d)

**Figure A.1 (Continued):** (c) Spinning Sensor Geometry with 8 Sensors. (d) Spinning Sensor Geometry with 12 Sensors.

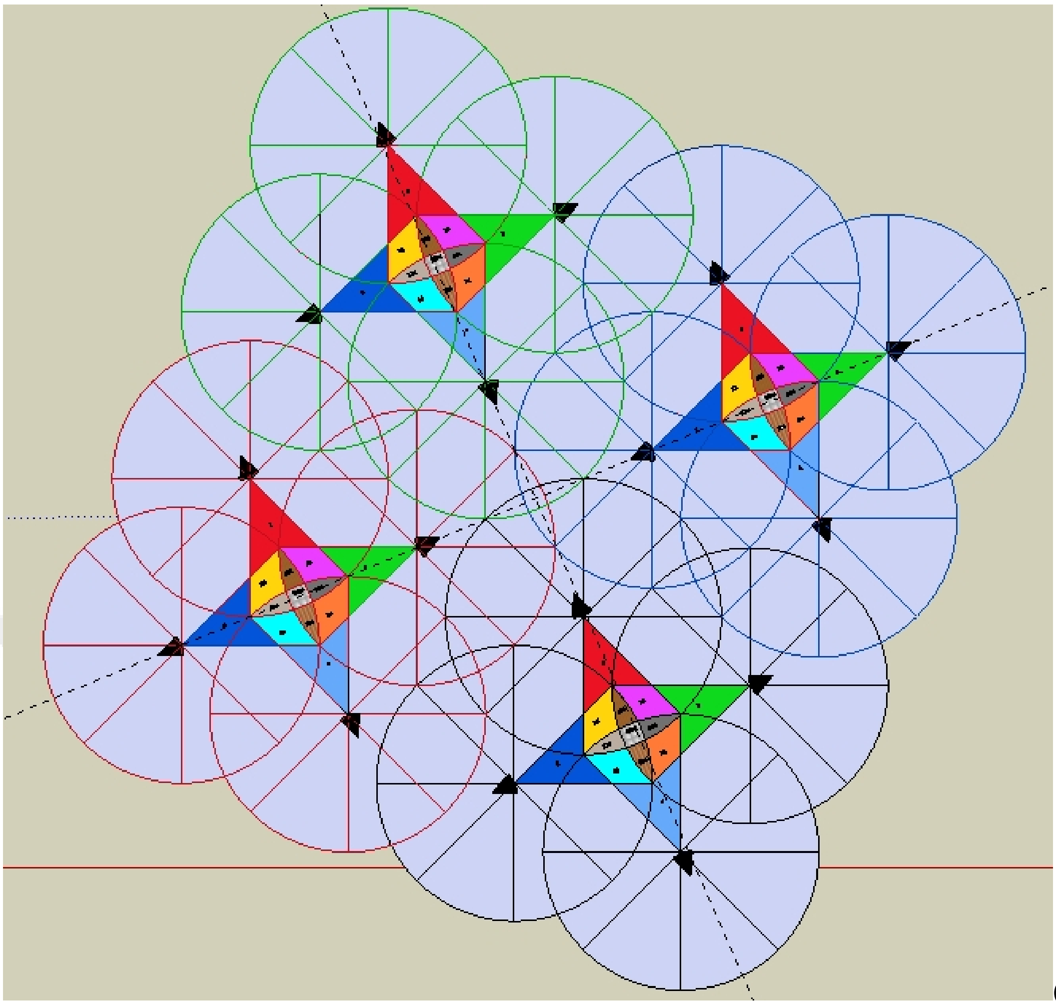

(e)

**Figure A.1 (Continued):** (e) The best effective geometry with 16 sensors.

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**PUBLICATIONS/PRESENTATIONS ON THE THESIS**

**Journal Articles (SCI-E Indexed)**

- **Gulluce, Y.,** and Celik, R. N. (2019). FireAnalyst: An effective system for detecting fire geolocation and fire behavior in forests using mathematical modelling. *Turkish Journal of Agriculture And Forestry*. doi: 10.3906/tar-1907-11. Forthcoming 2019.

**Proceedings**

- **Gulluce, Y.,** and Aydogdu, Y. V. (2014). Design of A Next-Generation, Early Fire Detection System With Ultrasensitive Flame Sensors for Port And Shipyard Areas. In *International Science and Education in Modern World Conference*, Bolashak, Kazakhstan, 21-22 February 2014.

- **Gulluce, Y.,** and Celik, R. N. (2013). Design Of A Cloud Sub-Structured, High Performance, Next-Generation, High Available Geographic Information System Infrastructure And Its Application. In ESRUC'13, *4th Eurasian Silk Road Universities Consortium*, Bhubaneswar, India, 1-3 November 2013.

- **Gulluce, Y.,** and Aydogdu, Y. V. (2013). Nanophotonic Early Fire Detection System in Ships and Ports with Next-Generation Extinguishing System. In Nanotr-9. *9th International Nanoscience And Nanotechnology Conference*, Erzurum, Turkey, 24-28 June 2013.

- Aydogdu, Y.V., and **Gulluce, Y**. (2013). Design of A Next-Generation, Early Fire Detection System With Ultrasensitive Flame Sensors for Port And Shipyard Areas. In BSAMI 2013. *1st International Conference Black Sea Association of Maritime Institutions*, 25-27 June 2013, Novorossiysk, Russia.