ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

A DISTRIBUTED HUMAN IDENTIFICATION SYSTEM FOR INDOOR ENVIRONMENTS

M.Sc. THESIS

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Department of Computer Engineering

Computer Engineering Programme

DECEMBER 2016

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KAPALI ORTAMLAR İÇİN DAĞITIK MİMARİLİ İNSAN TANIMA SİSTEMİ

YÜKSEK LİSANS TEZİ

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Emre Sercan ASLAN, a M.Sc. student of ITU Graduate School of Science Engineering and Technology 504131558 successfully defended the thesis entitled "A DISTRIBUTED HUMAN IDENTIFICATION SYSTEM FOR INDOOR ENVIRONMENTS", which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my spouse and family,

FOREWORD

This thesis is a part of studies based on a specific research about internet of things and mobile robots. As a result of living in the internet age, investments and foundations are generously done to IoT sector. Having the opportunity to combine academic researches and latest innovations in technology was my biggest change thanks to the National Scientific programme 1512 (Progressive Entrepreneurship Support Program) and Faculty Development Programme.

First of all I would like to thank to Asst. Prof. Dr. Gökhan İNCE because of his trust in me. Secondly I would like to thank my friends Ömer Faruk ÖZDEMİR and Adem HACIOĞLU for supporting me. Also, I would like to thank Barış BAYRAM for helping me on making TurtleBot robot system more stable.

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December 2016

Emre Sercan ASLAN
Research Assistant

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ABBREVIATIONS

API : Application Programming Interface
DT : Decision Tree
FPFRS : Fixed Positioned Face Recognition Systems
IFTTT : If This Then That
IoT : Internet of Things
IP address : Internet Protocol Address
JSON : JavaScript Object Notation
LBP : Local Binary Patterns
LFW : Labeled Faces in the Wild
LTS : Long Term Support
MQTT : Message Queuing Telemetry Transport
NoIR : No Infrared
PSSUQ : Post Study System Usability Questionnaire
REST : Representational State Transfer
RFID : Radio-Frequency Identification
RFT : Random Forest Tree
ROS : Robot Operating System
RPi : Raspberry Pi
RPiF : Raspberry Pi Foundation
SPS : Smart Pass Systems
SPYTS : Sabit Pozisyonda Yüz Tanıma Sistemi
SVM : Support Vector Machine
USB : Universal Serial Bus
WebRTC : Web browsers with Real-Time Communications

SYMBOLS

$\mathbf{i_c}$	: Intensity of central pixel
$\mathbf{i_p}$	: Intensity of neighbour pixel
LBP	: Local binary pattern function
s	: Sign function
$\mathbf{x_c, y_c}$	: Position of central point
$\mathbf{x_p, y_p}$	: Position of neighbour point

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A DISTRIBUTED HUMAN IDENTIFICATION SYSTEM FOR INDOOR ENVIRONMENTS

SUMMARY

Nowadays "internet of things" and "robotics" topics are getting more and more popular because "state of the art" technologies are easier to be applied in our daily lives. Utilization of "internet of things" started home automation systems to use devices at home remotely. While these automation systems aim at giving access to designated areas, they also offer solutions for unauthorized access problems by keeping logs of video records and control mechanisms as well as features for more security measures. Besides, developers are able to implement and monitor video surveillance systems to support security in the IoT platforms using low cost embedded computers.

This study presents an entire system, which is similar to home automation system and allows the login of a person entering a private property using face recognition system, video calls, sending notifications and having more components such as threat detection.

In this study statically positioned camera systems were implemented to identify people thanks to face recognition algorithms. Captured images from fixed positioned camera systems(FPFRS) had problems to process on identification. The problems were differences in distance of people to the camera and differences caused by posing. Therefore a mobile robot that has camera, was incorporated to recognize faces of people in the environment. The mobile robot can track people and keep the distance to the people constant. Thus, the mobile robot can solve the distance problem. However, the mobile robot can not track people perfectly without miss. Sometimes it can have trouble while tracking people. Thus, integrating the mobile robot to the Fixed Positioned Face Recognition System has a big potential to deal with the face recognition problem in indoor environments. Therefore an distributed approach was proposed to recognize humans in this study. The system utilizes 1) Cameras statically mounted on wall devices (FPFRS), 2) Cameras mounted on mobile robots.

FPFRS were built on a tiny embedded computer. Motion sensor and infrared camera components were used to gather data about environment. However, sometimes they can fail to recognize faces because of their fixed positions. This decreases face recognition performance of the system when FPFRS tries to recognize person from captured images. Because distance between camera and person is very important in order to obtain features of face.

To improve the performance of this system proposed method given in this thesis aims at solving the problem of fixed position with robots. Therefore a mobile robot is added to improve face recognition accuracy gathering face images from certain distance and moving around face image that is aligned to the camera of robot before captured. With the help of the mobile robot, the system becomes more interactive and information gathering from environment process is done more efficiently. As a result proposed hybrid system in this study not only uses fixed positioned captured images by FPFRS but also uses images that are taken from mobile robot.

To provide network communication between FPFRS and the mobile robot which are linked to in this distributed system, modified techniques are used which follow the rules of client-server approach. Each of the FPFRS and the mobile robot runs main program during scenarios. Inputs can be taken from the environment and enable the trigger mechanism. An FPFRS schedules its jobs and behaves according to the active jobs. After the job is done, FPFRS deactivates the jobs in the database records. These records can be manipulated from other devices. Thus communication and trigger mechanism between devices is established.

These systems are more complex and it is hard to follow this kind of systems, actions. Architecture is designed to expand by adding new FPFRSs or mobile robots to the system and each FPFRS can communicate via server. One FPFRS and a mobile robot have scenario to capture more images of people from different positions. Then each device runs face recognizer and obtains a result which consists of name of person and confidence of face recognition score. Using the results of face recognizer, various techniques, including machine learning algorithms, are applied to improve accuracy of face recognition. In addition to choosing prediction based on highest confidence in face recognition, random forest tree, decision tree, and linear SVM methods are applied to address the issue of face recognizer improvement.

Described systems are implemented and tested systematically based on various scenarios. To show the impact of the effect of changes on accuracy of face recognition system, experiments were done with and without the mobile robot.

The proposed system was evaluated using 1)Face recognition scores on a face database, 2)Performance of video calls, and 3)Case scenarios performed on human test subjects.

We have verified the effectivity of our approach by using six scenarios. In the first scenario button triggered human identification has been evaluated. In the second scenario motion triggered human identification has been analyzed. In the third scenario human identification using rotational tracking has been investigated. In the fourth scenario human identification using displacement tracking has been examined. In the fifth scenario human identification using displacement and voice combined tracking has been illustrated. In the sixth scenario human identification using robot initiated dialog has been analyzed. One or more FPFRS and the mobile robot have scenario to route the mobile robot to capture images of people on designated area of motion sensor triggered FPFRS based on the scenarios given above.

KAPALI ORTAMLAR İÇİN DAĞITIK MİMARİLİ İNSAN TANIMA SİSTEMİ

ÖZET

Bugünlerde günlük hayatımızda "nesnelerin interneti"ve "robotik" konuları uygulaması daha kolay en gelişmiş teknolojiler olarak daha popüler hale geldi. "Nesnelerin interneti" kullanımı evdeki cihazların uzaktan kullanılabilmek için ev otomasyon sistemleri başlattı. Bu otomasyon sistemleri tasarlanmış alanlara erişim izni sağlamayı amaçlarken,yetkisiz erişim problemlerini video kayıtları ve kontrol mekanizmalarıyla daha güvenli ölçümlerle çözüm sunar. Bunların yanı sıra geliştirmeciler "Nesnelerin İnterneti" platformunda düşük maliyetli gömülü bilgisayarlarla video gözlemlerini birleştirip izleme sistemleriyle güvenliği destekleyebilirler. Bu çalışma ev otomasyon sistemlerine benzer özel mülk alanlarında yüz tanıma sistemleriyle giriş izni,video aramaları, bilgilendirme gönderimleri ve tehdit unsuru tespit etme sistemlerinin tümünü sunmaktadır.

Bu çalışmada sabit pozisyonda kamera sistemleri kişi yüz tanıma algoritmaları sayesinde gerçekleştirildi. Sabit pozisyondaki kamera sistemlerinin çektiği görüntülerde tanımlama işlemlerinde problemler vardı. Bu problemler kişilerin kameraya uzaklık ve duruş pozisyonlarındaki farklılıkardı. Bu yüzden bir hareketli robot kişilerin yüzlerini tanımlamak için ortama eklendi. Bu hareketli robot kişileri takip edip mesafeleri ayarlayabilir. Böylelikle hareketli robot mesafe problemini çözebilir. Ancak hareketli robot kişileri mükemmel şekilde kaçırmadan takip edemez. Bazen kişileri takip ederken de sorun oalbiliyor. Hareketli robotu kapalı ortamlarda Sabit Pozisyonda Yüz Tanıma Sistemleriyle (SPYTS) birleştirmek büyük oranda yüz tanıma problemlerini çözümledi. Ayrıca bu çalışmada kişileri tanımada dağıtık bir yaklaşım amaçlandı. Sistem kullanımı 1) Kameralar sabit duvar cihazı olarak konumlanır, 2) Kameralar hareketli robota konumlandırılır.

SPYTS minik gömülü bir bilgisayara kuruldu. Hareket algılayıcısı ve kızılötesi kamera bileşenleri ortamdan daha fazla veri kazanımı için kullanılmıştır. Ancak bazen sabit pozisyonda olmalarından dolayı yüz tanımada hata yapabiliyorlar. Bu durum SPYTS kişilerin çekilen görüntülerinden yüz tanımaya çalışırken sistemin yüz tanıma performansını düşürür. Çünkü kişi ve kameranın arasındaki mesafe yüzü saptamada çok önemlidir. Sunulan bu tezde sabit pozisyon probleminin robotla çözülerek sistemin performansının geliştirilmesi amaçlanmıştır. Ayrıca belirli mesafeden yüz tanıma doğruluğunun arttırılması ve robota konumlandırılmış kamerayla resim çekiklmeden yüz görüntüsünün etrafında hareket edebilen bir robot eklenmiştir. Hareketli robotun yardımıyla sistem daha etkileşimli hale gelmiş ve ortamdan bilgi kazanımı süreci daha etkili olmuştur. Sonuç olarak amaçlanmış tümleşik sistemle bu çalışmada sadece SPYTS tarafından çekilen sabit pozisyonlu görüntülerle değil aynı zamanda hareketli robotttan çekilen görüntüler kullanılmıştır.

Bu dağıtık sisteme bağlı SPYTS ve hareketli robot arasındaki ağ iletişiminin sağlanması için kullanıcı-sunucu yaklaşımı kurallarını uygulayan geliştirilmiş teknikler

kullanılmıştır.Her bir SPYTS ve hareketli robot senaryo esnasında ana programlar çalıştırır. Girilecek veriler ortamdan alınır ve mekanizmayı tetikler. SPYTS görevlerini ve davranışlarını aktif görevine göre planlar.Görev tamamlandıktan sonra SPYTS veritabanı kayıtlarından görevini pasif moda çeker. Bu kayıtlar diğer cihazlar tarafından kullanılabilir. Cihazlar arasındaki bu iletişim ve tetikleme mekanizması kurulur.

Bu sistemler daha karmaşık ve uygulamalarını takip etmesi zor sistemlerdir. Mimari yeni SPYTS'ler veya hareketli robotlar sisteme ekleyerek genişletilebilir ve her bir SPYTS sunucu aracılığıyla iletişim kurabilir şekilde tasarlanmıştır. Bir SPYTS ve hareketli robot kişilerin farklı duruş pozisyonlarının daha fazla görüntülerini çekmeye programlanmıştır. Sonrasında her bir cihaz yüz tanımlamayı çalıştırır ve kişilerin isimlerini ve yüz tanıma sonuç oranlarını belirler. Yüz tanıma sonuçları kullanılarak makine öğrenmesini içeren çeşitli teknikler yüz tanıma oranının başarısını arttırmada kullanılır. Ek olarak yüz tanımada yüksek oranda başarılı tahmine dayalı seçimlerde yüz tanımlayıcı geliştirme adreslemede rastgele orman, karar ağacı ve doğrusal SVM yöntemleri kullanılmıştır.

Tanımlanan sistemler sistemsel olarak çeşitli senaryolara göre oluşturulmuş ve test edilmiştir.Yüz tanıma sisteminin gerçekleme oranındaki değişimleri etkisini göstermek için deneyler hareketli robotla ve hareketsiz robotla yapılmıştır.

Amaçlanan sistem 1) Yüz veritabanındaki yüz tanıma oranları 2) Video aramaları ve 3) Olay planında kişi test örnekleriyle çalışılarak değerlendirildi. Yaklaşımımızın etkinliğini altı senaryo uygulayarak doğruladık. İlk senaryoda tuş tetikleyiciyle kişi değerlendirildi. İkinci senaryoda hareket tetikleyiciyle kişi tanımlama analiz edildi. Üçüncü senaryoda kişi tanımlama kendi etrafında dönerek takiple sağlandı. Dördüncü senaryoda kişi tanımlama yer değiştirerek test edildi. Beşinci senaryoda kişi tanımlama yer değişikliğine ses eklemesi de yapılarak denendi. Altıncı senaryoda kişi tanımlama robot diyaloglarıyla tamamlanaraj analiz edildi.

Bir veya daha fazla SPYTS ve hareketli robot kişilerin görüntülerini çekmek için tasarlanmış alanda hareket sensörü tetikleyicili SPYTS senaryosuna dayalı hareketli robotu yönlendirme senaryosu yukarıda verilmiştir.

Deneyler sırasında toplanan resimlerin ne kadar süre içerisinde, hangi cihazın hangi aktivasyon modunda ya da davranışında ve hangi mesafeden elde edildiği kayıt altına alınmıştır. Belirli zaman aralığında çalışan bir alt program dizindeki resimleri bir dosyaya yazmaktadır. Bu sayede elde edilen verilerin hangi zaman aralığında kaydedildiği bilgisine erişilebilmektedir. SPYTS kullanılarak elde edilen resim "f_" ön ek başlangıcına sahip olurken, hareketli robot vasıtasıyla elde edilen resim "t_" ön ek başlangıcına sahiptir. Ön ek sayesinde bir resimin hangi cihaz tarafından oluşturulduğu bilgisine erişilebilmektedir. SPYTS tarafından oluşturulan örnek bir resim "f_b" ya da "f_m" tam ön eki ile kayıt edilir. Burada "f_b" tuş ile tetiklenen, "f_m" hareket ile tetiklenen aktivasyon modunda elde edilen resimleri temsilen kullanılmıştır. Bu sayede aktivasyon moduna göre elde edilen resimler bilinmektedir. Aynı şekilde hareketli robot için de "t_r" dönüşsel hareket takibi, "t_d" yer değiştirmeyle hareket takibi, "t_a" ses ve görme sensörleriyle takip ve "t_i" robot tarafından başlatılan diyalog ve ses ve görme sensörleriyle takip ön ekleri kullanılmaktadır. Farklı mesafelerle yapılan testlerin verileri de farklı dizinlere kayıt edilen sonuçlar vasıtasıyla gerçekleştirilmiştir.

Yukarıda belirtildiği şekilde bir çok sonuç kıyaslanmış ve dağıtık mimarili sistemdeki bileşenlerin sonuca katkısı mesafe, veri miktarı, aktivasyon modu ve takip davranışı türüne göre ve tüm bileşenlerin kombinasyonlarıyla incelenmiş ve sonuçları aktarılmıştır.

Dağıtık mimarili kişi tanıma sisteminin yüz tanıma üzerine çalışan giriş sistemine uygulaması da gerçekleştirilmiştir. SPYTS tuş tetiklemeli çalışan sistem uygulaması, kişinin resmini çekerek kimliğini tespit ettikten sonra mobil uygulama üzerinden kullanıcıya kişinin çekilen resmi ile kim olduğunu göstermektedir. Bu uygulamanın kullanıcı deneyimi testleri de gerçekleştirilmiştir. Kullanıcılara düzenlenen anket ve deneyimlerine çalışmanın sonuçlar kısmında yer verilmiştir.

1. INTRODUCTION

In this section motivation, purpose of thesis, and overview of thesis are introduced in detail.

1.1 Motivation

Technology has been improving according to the needs of humanity. People have shaped their lives upon the technology. This has revealed brand new approaches to old issues. Innovation age has started because of new demands. One of these demands was security at home. As a result of this, surveillance systems have been planted to lots of areas including private properties. However, this was not enough to keep people safe. People have demanded a lot more than the surveillance systems have supplied. They wanted to access places after a verification procedure, in which a person is recognized and information about him/her collected. These systems required to process biometric features of people. People can recognize each other using methods of perception such as taste, sight, hearing, touch and smell. With the help of various sensors, these perceptions can be realized by embedded devices and robots. A robot, which has a camera, microphone, haptic sensors etc. can gather the same information. This is the main motivation behind the study on biometric features in this system.

Smart Pass Systems (SPS) are structures that use biometric features of people, passwords or mobile phones to enter to special places such as home, office etc. and to perform various kinds of controls and generally they are built on embedded devices [1]. One of the advantages of these kind of systems is that they are more reliable than traditional entrance processes and they are relatively more practical. In contrary to keeping records of visitors on paper manually by security personnel, even using simple digital systems gives better results in security. However, a disadvantage of this kind of simple digital systems is that they can be deceived like most other digital systems [2]. To diminish this drawback there must be various security standards and these systems must contain secondary verification methods. Various additional security requirements such as the utilization of video records, voice records and threat detection systems emerged in this kind of systems. In addition, using low cost embedded autonomous systems to address this issue also has economical benefits.

1.2 Purpose of Thesis

In most cases, a device including fixed positioned camera is able to provide low-level security. However, the device can not observe the environment as well as a mobile robot does. Due to the fact of the fixed position of the camera, there can be some missed actions potentially causing threats. An intruder can enter the private property, until the device became aware of this problem.

In this study to overcome light, pose, alignment problems that are potential causes of performance degradation in fixed positioned camera, a mobile robot is used. With the addition of a mobile robot, a distributed recognition system can detect the intruder easily because of the fact that the robot is mobile and tackle the deficits of a fixed-camera based surveillance system. This also reveals an interactive system because robot moves around and captures different states. It is easier to solve the face recognition problem, if the system can gather various images of the human to be recognized from various angles.

A distributed system that consists of a Fixed Positioned Face Recognition System (FPFRS) and a mobile robot is designed to improve face recognition performance. This system proposes communication between devices, and interaction with the environment. The fusion of multiple agents brings more accurate results on face recognition than a standalone FPFRS provides. Besides, the FPFRS and the mobile robot cooperates to complete a task. If a suspicious event occurs, instead of working separately each device notifies a server. After the centralized decision mechanism generates an output, all devices connected to the server including the mobile robot take the necessary actions as directed by the central intelligence.

The FPFRS and the mobile robot are programmed to capture images, which contain face images of a person, and send them to the server. Face recognition process is done on the server side. A notification is sent to the user's smart phone. User can see the information of the person who has triggered the system. Moreover, the user can start video chatting, grant access to the visitor, make visitor listen to a voice message.

The proposed method in this study was evaluated in terms of video chat performance and success rates of face recognition. A stress test was applied to the video chat system and minimized delay was determined as a success metric. The face recognition system was examined in terms of precision and recall values. In the first scenario button triggered human identification has been evaluated. In the second scenario motion triggered human identification has been analyzed. In the third scenario human identification using rotational tracking has been investigated. In the fourth scenario human identification using displacement tracking has been examined. In the fifth scenario human identification using displacement and voice combined tracking has been illustrated. In the sixth scenario human identification using robot initiated dialog has been analyzed.

1.3 Thesis Overview

The thesis is composed of five chapters, each of them dealing with different aspects of face recognition with the hybrid recognition approach. Chapter 1 is introductory and defines basic terminology used in the thesis. This chapter describes motivation, explains importance of system and the purpose of thesis. Chapter 2 examines relevant literature. The chapter consists of fundamentals of human identification, home automation systems, which contain human identification and the issue of human identification in robotics. Chapter 3 provides an outline of the relevant system. First illustrations of the system overview is given. Then the complete system design is described in detail. Used hardware and implemented software systems are presented. Chapter 4 concentrates on experiments and results. Conclusions are drawn in Chapter 5. The main aim of the thesis is to prove benefits of human identification using distributed system and improve the performance of the security systems.

2. LITERATURE REVIEW

Smart pass systems are technologies based on granting access to a place for people who have been allowed to enter the designated areas according to access level. In this section, researches based on smart pass systems, human identification in home automation systems, and human robot interaction, where human identification technologies are used, will be discussed.

2.1 Background of Human Identification

Biometrics refers to a system which aims to isolate a person using unique features of the person. The face, fingerprint, iris, hand geometry, DNA etc. of a person keep unique information that belongs to this person specifically.

Fingerprints are most known biometric features used for person identification and verification. To identify a person from his/her fingerprint biometric feature, two methods are preferred. First method mainly focuses on extracting features from centre region of fingerprint including furrow structure [3]. Second way of extraction feature from fingerprint is examining trivial details of local ridge besides furrow structure. In a research [4], second method was implemented to address the issue of high accuracy. They evaluated different methods during fingerprint identification steps and they came up a with a novel technique based on the extraction of minutiae from the thinned, binarized and segmented version of a fingerprint image. As a result of this effort, researchers achieved approximately 92% accuracy using FVC2000 fingerprint databases [5].

Iris recognition is applied as another method in biometric systems. Iris image of a person is captured from a certain distance. Some systems make use of both irises. Daugman et al. has described the methodology of iris recognition with a high confidence in his study [6]. The iris has been presented by multi scale quadrature wavelets which enables easy matching between candidates. Daugman has evaluated this method on 9.1 million images captured from various people living in different countries like Korea, Britain, Japan and the USA. He has shown that this method is rather more reliable than other biometric recognition types.

Hand geometry is also used to extract the biometric features. Hand image is enough to obtain these features. Sanchez-Reillo et al. have applied various pattern recognition techniques such as euclidean distance based matching and neural networks to classify hand geometry features [7]. Sanchez-Reillo et al. have achieved approximately 97% success rate in hand geometry classification. This has shown that as a biometric feature hand geometry can be used to provide high secure systems. Kumar et al. have improved hand recognition adding palm print to hand geometry in their research [8]. In this study a digital camera has been used to capture images of hand. Kumar et al. have obtained palm print and hand geometry features from these images. They have proposed to combine palm print features and hand geometry features and collected data from 100 people. Using palm print features, they have achieved 98.30% success rate and using hand geometry features they have achieved 93.14% success rates.

2.2 Fundamentals of Face Recognition

Face recognition is getting more popular in recent years with the help of social media and surveillance systems. This approach is based on extraction of biometric features from specific regions of the face. To obtain these features various approaches have been investigated in the literature. Ahonen et al. applied a method based on Local Binary Patterns (LBP) to figure out features [9]. They proposed dividing face images into sub images according to specific regions before extracting the features. Then LBP is applied to these regions and features of each specific region are concatenated in a vector named as face descriptor. Using the face descriptor, which contains features of a face, recognition process is done. Taigman et al., researchers working at Facebook, proposed a modern method [10] to achieve results as close as to the results of face recognition of a human-being. Common approach to address this issue consists of detection, alignment, representation and classification stages. Taigman et al. improved alignment stage and representation stage of a traditional face recognition system. To obtain high accuracy, they have adapted 3D face modelling to alignment step and applied nine-layer deep neural network to obtain a better face representation. This improvements concluded with 97.35% accuracy when tested with Labeled Faces in the Wild (LFW) dataset [11]. Schroff et al. have proposed to use deep convolutional network to deal with the face recognition [12] and have called the project "FaceNet". This study was also tested on LFW and had 99.73% accuracy. Since this approach showed impressive results, some researchers wanted to create an open source and general use of the library based on the proposed study. Amos et al. have implemented FaceNet [12] and they shifted the focus to enable face recognition algorithms in mobile platforms. Amos et al. have provided an efficient face recognition library called OpenFace [13] that was based on common libraries such as dlib [14], OpenCV [15] and torch [16]. The proposed approach in the study starts with face detection step applied to an image. After detecting a face in the image, transformation operation is applied. Later, the processed face image is given to the neural network based feature extraction system. As a result, 128 features are extracted and the face recognition process is done using these features.

2.3 Related Technologies Used in Home Automation Systems

In the literature, there are many studies related to smart pass systems. Jain et al., created a home automation system which gets instructions via email and performs instructions. This system checks users email box to find instructions that are strictly formatted in their subject and email context. These instructions are followed and relays are triggered [1]. Instead of using phone line, this system prefers email to communicate and system checks email box every 0.5 seconds. There is another proposed system [17], which can observe energy consumption and aims to control the building in an efficient way, accessible over the web, provides control over USB interface and is controlled by a mobile phone.

Thanks to low cost embedded computers, remote control of devices have been lately used more frequently. In some studies in addition to remote control, smart home concept is also proposed [18]. In this system, to decrease usage of wireless network interface and to save energy, wireless sensor network and power line communication are used. A system, which has smart control mechanism applied to the lambs, that can be set according to the brightness of room, can decrease energy consumption at least 40% both on sunny and on cloudy day [18].

Face recognition systems are also integrated to security pass systems. There is a home automation system proposed which has features such as face recognition, remote monitoring and visitor controlled door opening [19]. In this system communication is provided via Zigbee based wireless network. Zuo achieved 95% recognition rate, processing 3 to 4 images in a second with real time face recognition running in an embedded device in his study [20]. After recognizing a person, the system runs special services based on the identification result of a person.

Using low-cost small computers (Arduino, Raspberry Pi, etc.) remote control studies provide monitoring environmental information. In another proposed study [20], a web server, which is hosted on Arduio, communicates with an Android application to manage lambs and power points at home, to observe environmental information such as temperature and humidity etc. This system can also get instructions via voice command.

Some researches have been done on the cloud based server systems. The system proposed by Xu has features like remote controlled cameras via mobile application, use camera and audio sensors to enable device live broadcasting, transfer operation of captured photo to mobile phone and to watch later transfer operation of videos and photos over cloud system [21].

Another Android based home automation system [22] presents an interface to both a mobile application and a website. This system consists of three parts; a local device to transfer signals to home appliances, a web server to keep records and support service, and a smart mobile device to run the application. Google services are used to provide messaging between the components. To evaluate this system, 20 volunteers used a prototype of the system and shared their experiences. Volunteers answered questions and rated features of this system with marks between 1 to 5. According to the questionnaire, system has been scored using criteria such as hardware safety, power saving, ubiquity, cost, response delay etc.

An implementation of the sensor web node as a part of Internet of Things (IoT) using a Raspberry Pi [23] was proposed to provide fully customizable and programmable small computer with support for a large number of peripherals and a network communication. The system presents various use cases within a wide range of activities such as monitoring and fire detection in a building. Applying methods of Vujović et al. have proposed, these monitoring and fire detection systems can be created and developed starting from scratch.

Bluetooth technology is also used in home automation systems [24]. Designed system in this study has a network, which contains one remote (mobile host controller) and several client modules (home appliances). Client modules and host controller communicate with each other through Bluetooth.

To control electronic devices using a mobile application on a smart phone a framework [25] was proposed. In addition to controlling, this system also monitors the amount of consumed electricity that has been used in the amount of dollars. The system determines the cost of electricity that has been used in every electronic device within the network. This results in saving electricity.

Some researchers have observed disabled people and designed home automation systems [26] to deal with the problems of disabled people. This system's ability to make predictions about the user's daily habits and secure system that pre-alerts. Feed-forward and recurrent neural networks were used to implement these smart features in the system.

The habit of working at home has increased over the recent years. Researchers investigated how this experience can be more comfortable and special to person. In the proposed study [27], researchers created a virtual home to observe behaviours of 254 volunteers. In addition to arranging information about volunteers' daily life, they also focused on work related activities. This study analyzed two features, one was the integration of work activities with daily activities and the second was localization of work activities in the house. Their conclusions with teleworking refers to how it can be more efficient.

2.4 Human Identification in Robotics

Robots have various sensors such as depth sensor, camera, microphone etc. to observe the environment. A human can be detected by robots using these sensors. Robots can interact with people to help on occasion or do a task for people. In that sense, they have started to be a part of our daily life. They have been used as an interactive guide in various places such as museums [28], shopping malls [29] etc. They also have served as security guards [30] [31] in buildings to detect state of emergency such as fire, intrusion etc.

Thrun et al. proposed to use robots as a guide. A robot called MINERVA [28] was successfully exhibited in Smithsonian Museum as an interactive tour guide. This robot served for two weeks and interacted with thousands of people. During guidance, the robot traversed more than 44 km and speeded up to 163 cm/sec. The study aimed to address problems like safe navigation in unmodified and dynamic environments without harming the humans, and improved human robot interaction.

Another research about guide robots were done in a shopping mall [29]. This study aimed to help customers while interacting and giving information about shopping. Taking into account that people come to shopping malls repeatedly, researchers implemented an identification feature to interact with people individually. This feature provides a chance to the system for multiple interactions. They used Radio-Frequency IDentification (RFID) tags to identify each person. The robot was semi autonomous; namely a human operator helped because of the difficulty of applying speech recognition robustly in a shopping mall. The system was tested in a shopping mall for 25 days. The robot has interacted with nearly 100 groups of customers, and researchers invited customers to sign up RFID tags. These customers also participated in questionnaires. As a result, the robot detected that 63 out of 235 people went shopping. This study showed that robots can be used in shopping malls efficiently.

Instead of humans, robots can be used as security guards. In a study [30], an intelligent robotic system was designed to perform remote surveillance using a security robot. Secure or restricted areas were determined and the robot automatically was able to verify an intruder passing through these areas. The robot also had the ability to alert remote security personnel and to track the intruder. The robot could be used easily in teleoperation since it only needed at least 33.6 kb/s internet connection. This approach revealed that low cost, remotely controlled mobile robots can provide security and identify a potential intruder.

Security is indispensable for intelligent buildings, thus researchers examined robots as sensor based smart secure guards. As a result of this study [31], they achieved to build robots that can detect abnormal and dangerous situations and notify users. Their Intelligent Security Robot (ISR) had 50 cm diameter, 130 cm height and 100 kg weight. Researchers developed various capabilities like avoiding obstacles and motion planning, and included image system, sensor system, remote supervising system and other systems into the robot. A Multi-sensor based sensor system and multi-sensor fusion algorithms were used to make accurate decisions. In this study [31], user could remotely control the appliance with a cell phone through GSM modem. Feedback mechanism provided reaction results to the user. As a complete real world example, they implemented fire detection system. Based on a scenario if a domestic fire occurred, ISR was able to find out source of fire using the fire detection system. In intruder detection scenario, they developed a similar approach like fire system(intruders). ISR was able to send messages using a GSM modem as a result of an event such as fire detection and intruder detection.

In another study [32] a mobile robot was used to track and identify people with a vision based approach in real time. Researchers proposed a new approach of using thermal images and a fast contour model together with a particle filter. This approach also solved the problem of person detection, if the person was not close or did not come face to face with the robot.

2.5 Positioning of This Thesis

In this study, an FPFRS and a mobile robot cooperates to identify a human and the integrated system provides various services such as surveillance, security, video talk, entrance access etc. FPFRS runs a face detection process using Haar Cascades [33] to find faces in the captured images. The mobile robot detects a human with Haar Cascades using a depth sensor and audio sensor, and tracks human to capture better face images. OpenFace [12] [13], state of the art face recognition algorithm, is utilized on images taken from the mobile robot and FPFRS to recognize people. Combination of the captured images from different sources such as the mobile robot and FPFRS is assumed to give better results when compared to standalone systems that consist of only a mobile robot or FPFRS.

Kanda et al. [29] have used RFID tags to identify people instead of using biometric features of human. This approach has a restrictive constraint on the recognition because the system requires a RFID tag to recognize a human. Proposed study in this thesis, enables people to have the system running without the requirement such as RFID card, password etc., reducing the additional burden of the user.

Bayram et al. have proposed audio-vision-based single human [34] and multi-person [35] tracking for active robot perception. In our study, human tracking system is based on these researches. The integration of the mobile robot to the FPFRS-based recognition system is realized within the scope of this study. In addition, a robot-initiated dialog behaviour is added to the mobile robot with the intent of attracting people's attention. The mobile robot gained a new feature. Instead of only detecting and tracking face, it recognizes the faces thanks to distributed human identification system.

Proposed hybrid system in this study, computes confidence scores of face recognition to improve the accuracy of human identification. A labelled set of captured images of people, is used as the training set of face recognition. Application of face recognition process is tested in different platforms such as mobile robot and FPFRS. Each attempt of recognition on captured image ends up with two outputs; 1) Label of the recognized person 2) Confidence score for the recognition. Various integration methods using machine learning algorithms were applied to achieve the distributed approach in the laboratory experiments such as winner-takes-it-all: Choose result of face recognition which has highest confidence score, Linear SVM, Decision Tree and Random Forest Tree. In real world experiments, FPFRS and the mobile robot intend to identify humans based on scenarios using different features of platform; 1)Different activation modes such as, button or motion triggering and 2)Different robot behaviours such as rotational motion, displacement, audiovisual human tracking and robot initiated dialog.

We also compared the performance of the face recognition using the distributed hybrid approach in the laboratory experiments to the scores of the unimodel approaches. For each real world experiment the confidence of recognition, precision, recall, f-score, and confusion matrices were determined as evaluation criteria.

3. SYSTEM ARCHITECTURE

In this section the proposed distributed recognition system is explained. After the hardware components of the system are illustrated, software modules of the system are introduced. Activation modes for human identification and behaviours of the robotic platform for the recognition system are presented.

3.1 System Overview of the Distributed Recognition System

The proposed system consists of five components; 1)Smart phone, 2)Fixed Positioned Face Recognition System (FPFRS), 3)Mobile robot, 4)Domestic server, and 5)Web server

1. *A smart phone* serves as the human-computer interface for the distributed recognition system. Smart phones are an indispensable part of IoT platforms because of their mobility and having the capability to realize tasks such as video talk, sending and getting notifications, performing data transfer via internet etc.

2. *An FPFRS* is used to create the IoT platform of the system. It is equipped with a camera, a motion sensor, an electronic relay, a microphone, and a speaker. It is intended to be used in a fixed position around the height of a human.

3. *A mobile robot* is a mobile platform which is equipped with a camera, a depth sensor and a microphone array to observe the environment. The mobile robot has the ability to perform rotational and displacement motion that enables it to capture images from different angles and positions in contrary to the fixed position of FPFRS.

4. *A domestic server* is a computer which runs on Linux OS. It is placed locally and used as a server, which regulates the communication between the robot, FPFRS, and the smart phone, as well as runs the program for human identification due to its high computational power.

5. *A web server* is a hosted website which keeps Internet Protocol (IP) addresses of FPFRS, the mobile robot, and the domestic server.

The proposed distributed human recognition approach is structured on gathering and processing images taken from one or more FPFRS and one or more robots as described in Fig. 3.1. Domestic server and web server set a communication network between devices.

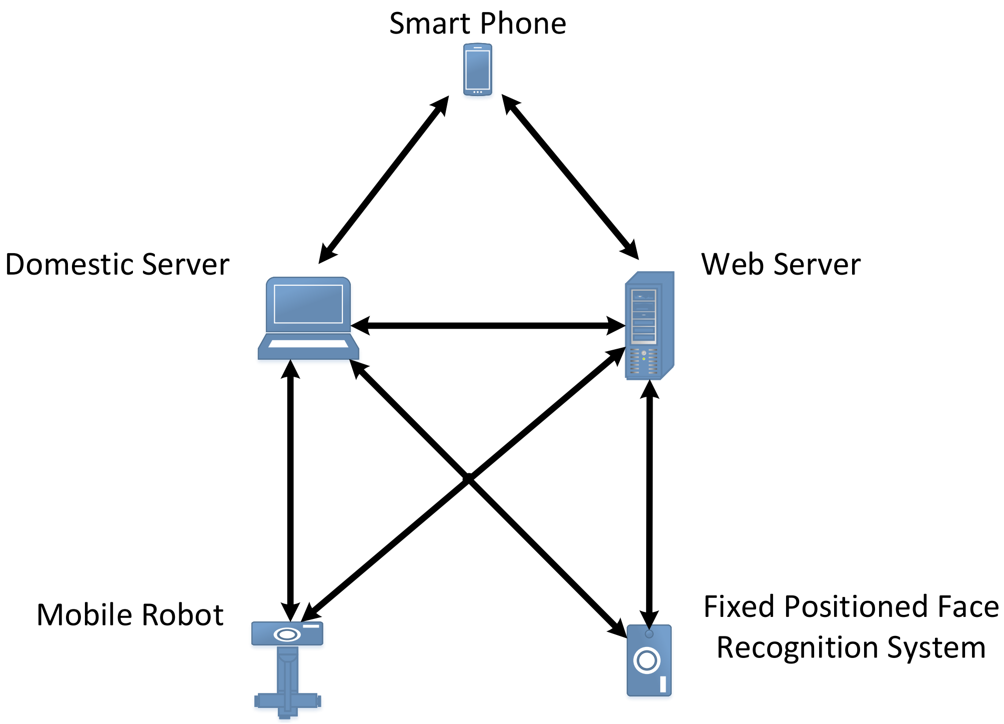


Figure 3.1 : System overview.

FPFRS has two activation modes. One is button triggered image capturing process. The other one is motion triggered image capturing process.

The mobile robot has four interaction behaviours. All of them are based on tracking the face of a person; complementarily in the first mode it moves around itself (rotational motion) whereas in the second mode it takes a linear path additionally (displacement motion). In the third mode, however, the capability of tracking a person not only via vision but also via audio modality is added to the displacement motion behaviour. In that sense, the third mode not only uses voice as a source of human localization and tracking, but it also uses the depth sensor to track the person. Fourth mode involves a dialogue initiated by the robot in order to make the human approach towards the robot and force him/her to utter something to improve the sound localization, thus enhance the human identification process.

FPFRS, mobile robot and domestic server have a main program always running on the system that sends IP addresses to web server. This main program checks local and internet IP addresses whether they have changed recently or not. If one of them changes, program sends a request to the corresponding web service of web server to update database records. Domestic server gets IP addresses of the robot and FPFRS from the web server as FPFRS and the robot get IP address of the domestic server.

Distributed system is designed to be based on the client-server relation. After FPFRS is triggered via the button or motion sensor, it notifies domestic server, waits for an instruction from domestic server to capture images used in recognizing the person and upload the images to the domestic server. After the domestic server gets the notification, it sends instructions to all FPFRS's and the mobile robot to capture images and upload. After the mobile robot gets the instruction, it behaves according to the instruction to realize rotational motion, displacement motion, audiovisual human tracking or dialog management. Main steps of the interaction flow are illustrated in Fig. 3.2.

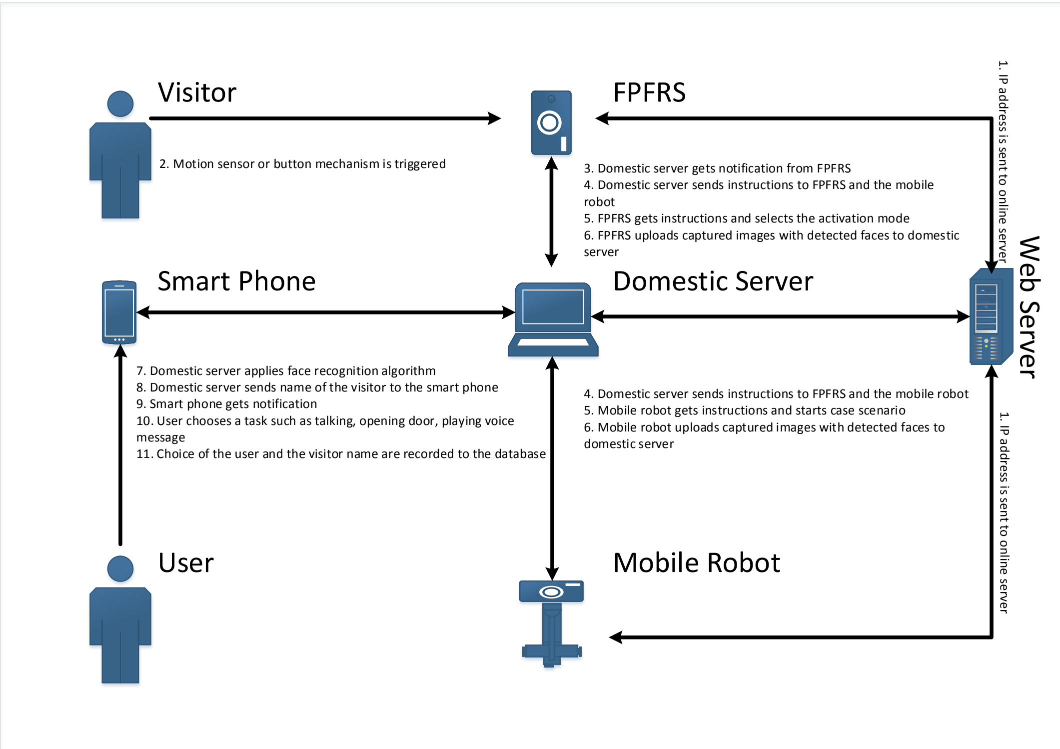


Figure 3.2 : Main steps of the system interaction.

3.2 Hardware Components of the System

In this section FPFRS and the mobile robot's hardware components are introduced.

3.2.1 Fixed positioned face recognition system

FPFRS is a face recognition system (Fig. 3.3) which is built on a low-cost, credit card-sized embedded computer. FPFRS is equipped with various sensors and components such as motion sensor and camera to observe environment. FPFRS can be utilized in different systems such as video surveillance system, smart home automation system, smart pass system etc. using additional components such as relay, electronic lock, and button.

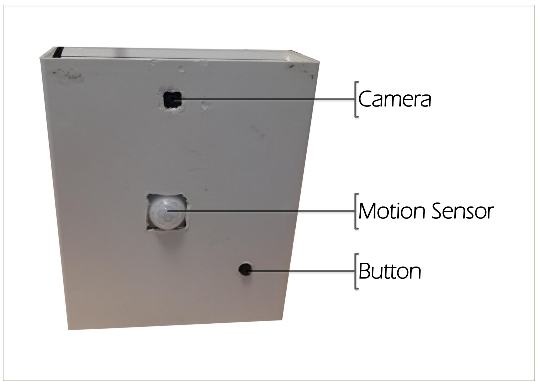


Figure 3.3 : Fixed Positioned Face Recognition System (FPFRS) designed and developed entirely within the scope of this thesis.

In the design stage, FPFRS is intended to be a portable, and a small box with low energy consumption. These features lead us to use an embedded computer which is not only tiny to fit to the box, but also have a processor with high computational power. Chosen embedded computer is required to realize the image processing tasks in this context. Additionally, components must be compatible with each other and easily integrated into the system.

The components used in the FPFRS are introduced as following.

- ***Microcontroller :*** In this study, Raspberry Pi (RPi) (Fig. 3.4) has been used as low-cost embedded computer to build FPFRS. The RPi [36] is a credit card-sized single-board computer developed in the United Kingdom by the Raspberry Pi

Foundation (RPiF) to promote the teaching of basic computer science in schools and developing countries. The RPi 3 is the third generation of this embedded computer.

Figure 3.4 : Microcontroller of FPFRS (Raspberry Pi).

- ***Camera :*** In October 2013, the RPiF announced that they would begin producing a camera module without an infrared filter, called the Pi NoIR (Fig. 3.5). This camera is used in FPFRS because it is one of the most suitable cameras for RPi; it has even a unique slot on embedded computer. Moreover, it comes with Picamera library[1], which is coded in Python to perform processes such as capturing images and recording video. In addition, this library enables to use features of camera to the bitter end. Some of these features are changing brightness, resolution and frame rate, besides supporting different formats for capturing images and recording videos, and flipping video stream vertically or horizontally.

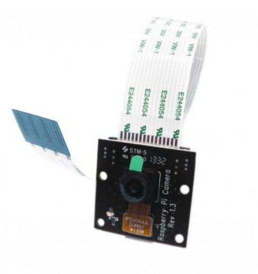


Figure 3.5 : Camera of FPFRS (Raspberry Pi NoInfrared camera).

- ***Relay :*** Relay component (Fig. 3.6) is used to trigger the electronic lock which opens or closes the door. In a typical smart home system more than one relay is required for establishing different control mechanisms. In our proposed system, it only locks or opens the door. However, it has the potential to manage other equipment such as lights, blinds, air conditioner etc. for a smart environment.

[1]http://picamera.readthedocs.io/en/release-1.12/

Figure 3.6 : Relay used in FPFRS.

- ***Electronic Lock :*** This component needs to be triggered by the relay to handle the process of opening or closing doors. When current is provided to the electronic lock (Fig. 3.7) circuit, it locks the door, otherwise it opens the door. This component makes sure that when electricity is turned off, the door is automatically opened.

Figure 3.7 : Electronic lock used in FPFRS.

- ***Motion Sensor :*** A motion sensor (Fig. 3.8) detects motion performed at a certain distance. This sensor helps to observe the environment especially when a human enters or leaves a place.

Figure 3.8 : Motion sensor component used in FPFRS.

- ***Button :*** A button is integrated to simulate the door bell and realize the calling function for the property-owner. It is also used as a trigger to start the activities of FPFRS. These activities are intended to replace the old-fashion door bell systems.

  The button is designed to be multifunctional. Pressing the button for up to 5 seconds long operates as doorbell whereas pressing the button 5 to 20 seconds long serves to *"capture images to create image set for training"*. Additionally, pressing the button more than 20 seconds triggers *"train a model from the image set"* operation.

- ***Design of FPFRS :*** In this part the circuit design is introduced. The circuit consists of an embedded computer, motion sensor, relay, electronic lock, and button and circuit design is given in Fig. 3.9.

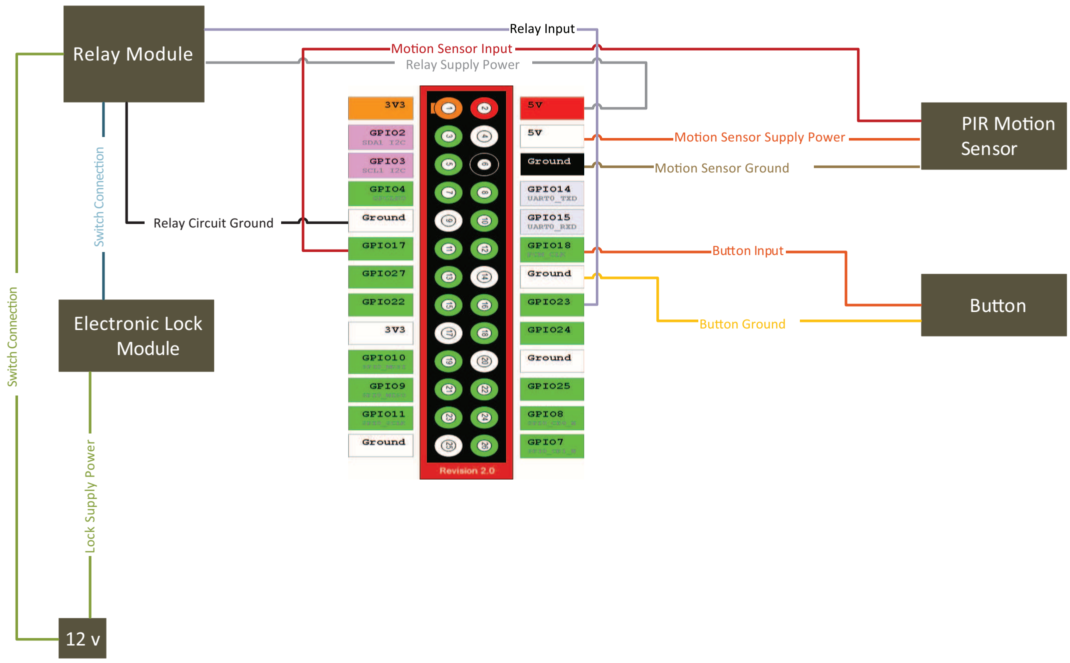


Figure 3.9 : Circuit design of FPFRS.

A plastic box is used as a cover. Square and circle shaped holes are drilled in the front side of the box. Camera, motion sensor, button, etc. components are connected and tested using diagnostic tools to find out whether they are correctly connected. Camera is placed on top of the cover, motion sensor is located at the center and button is positioned at the right-bottom of the cover. An FPFRS is built in following these steps given in Fig. 3.10.

3.2.2 Mobile robot

In this thesis we used TurtleBot, which is a low-cost robot that is supported by open source hardware and software [37] (Fig. 3.14). The robot consists of another robot base, which is named as Kobuki (Fig. 3.13), a depth sensor, a camera, and a microphone array. Since the robot uses open source software, it can be easily controlled by the Robot Operating System (ROS) [38] applications.

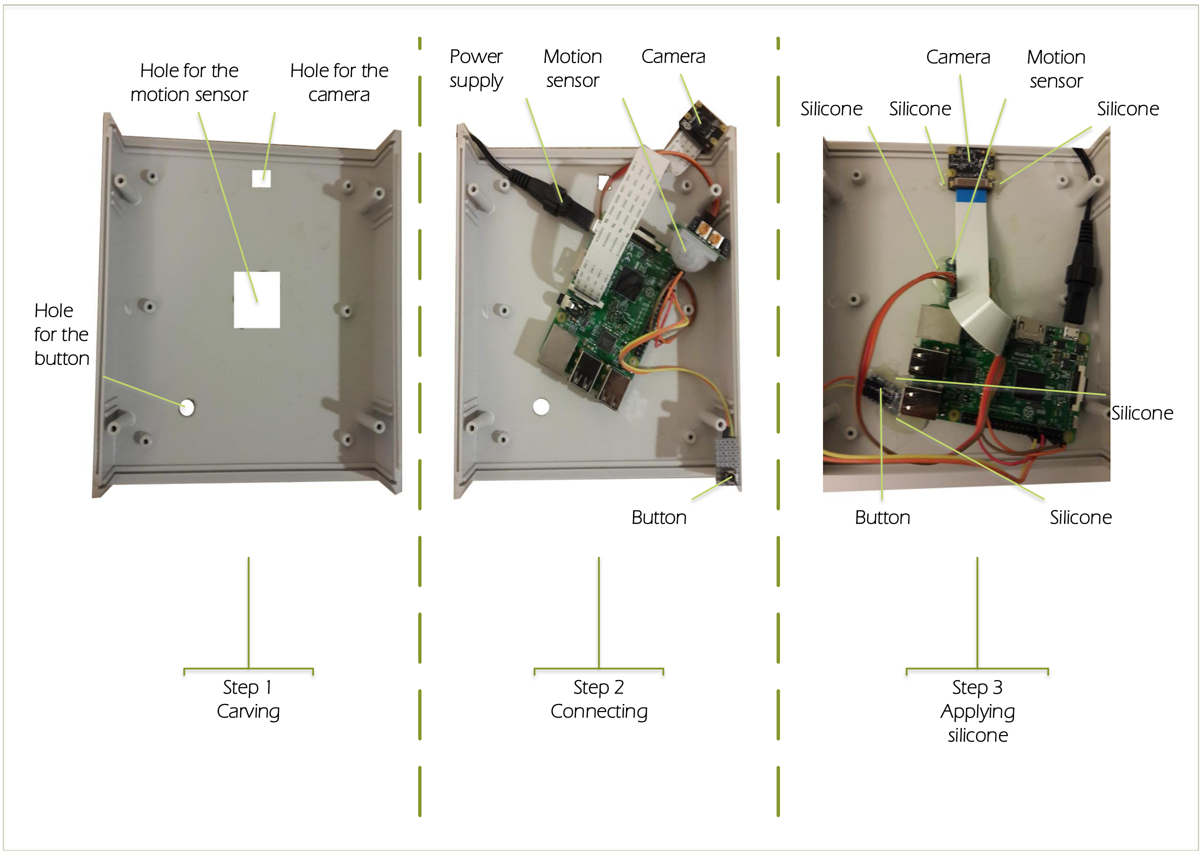


Figure 3.10 : Building stages of FPFRS.

- ***Kinect #1 :***This sensor is located at the top of the mobile robot and used for determining distance between robot and people. Also, it enables to detect people using video stream of Kinect's camera (Fig. 3.11).

Figure 3.11 : Kinect camera and depth sensor.

- ***Kinect #2 :*** This sensor is same as the other Kinect sensor (Fig. 3.11). Difference between them is only purpose of usage. This Kinect is located at the bottom of the mobile robot to observe obstacles on the floor. Its depth sensor is used for obstacle avoidance.

- ***Microphone array :*** This specific microphone (Fig. 3.12) is used to find the source of audio. Location estimation is made by utilizing array of microphones. Each microphone records audio in the environment separately. Then, using various distance metrics the records are processed to extract location of source.

Figure 3.12 : Microphone array, which located top of the mobile robot.

- ***Robotic base :***This component is a product of Yujin Robot[2] company and called as Kobuki[3] (Fig. 3.13). It has odometry and battery. In addition, it can provide power for an external sensor and actuator.

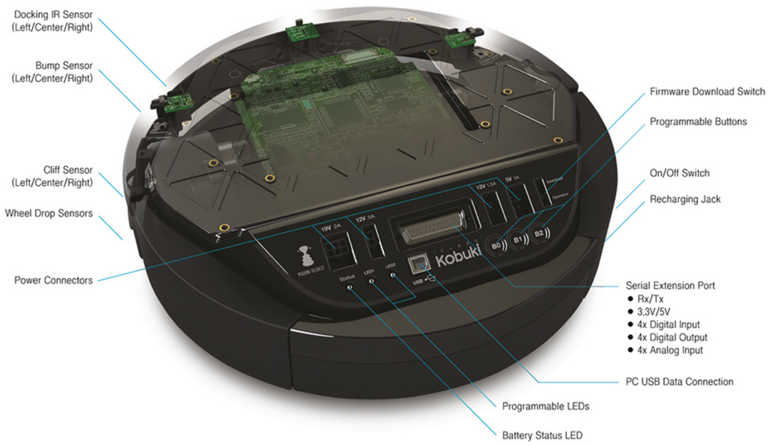


Figure 3.13 : Base of the mobile robot, Kobuki.

[2]Yujin robot company:`http://www.yujinrobot.com`
[3]Kobuki: `http://en.yujinrobot.com/archives/portfolio-items/kobuki`

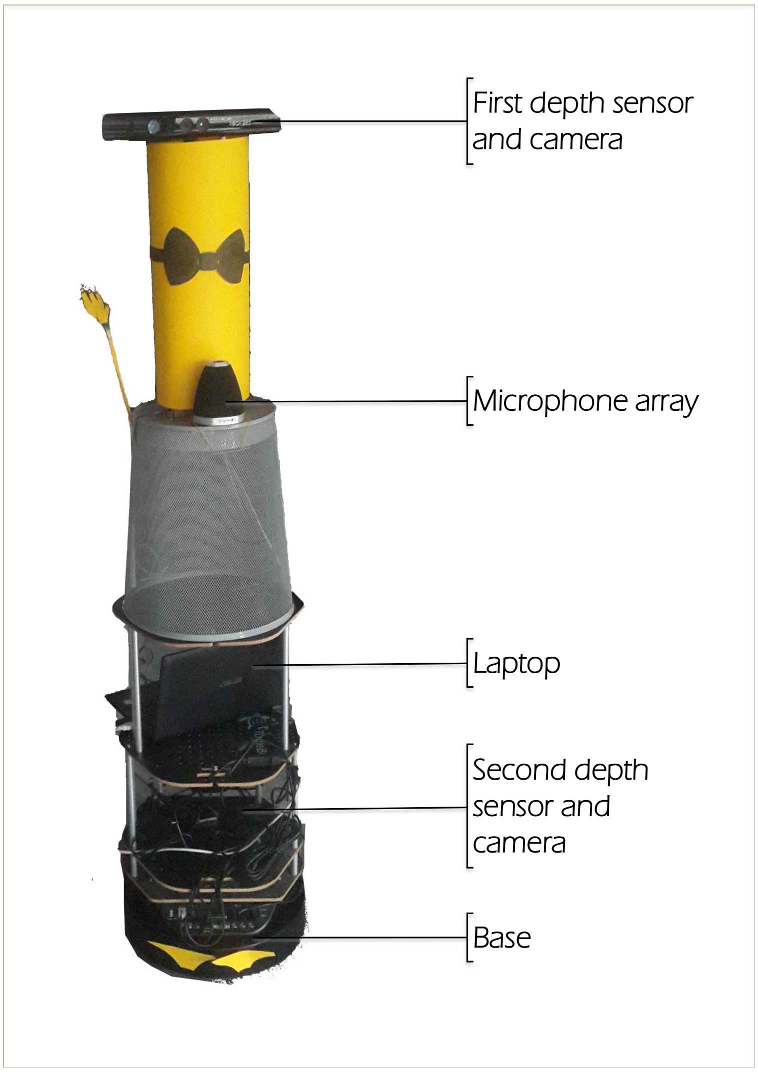


Figure 3.14 : Modified TurtleBot used in the proposed system.

3.3 Software Modules of the System

In this section communication of devices, used face recognition algorithms, security module, web page and mobile application are explained in detail. Detailed flow chart diagram of the software running on the system is illustrated in Fig. 3.15. Each process belonging to a device is illustrated in Fig. 3.15 using different colors such as green for mobile robot, gray for FPFRS, orange for domestic server, blue for web server and yellow for smart phone.

3.3.1 Communication module

There can be multiple FPFRS's in a system and all instances are expected to communicate with each other as well as with the mobile robot. To maintain

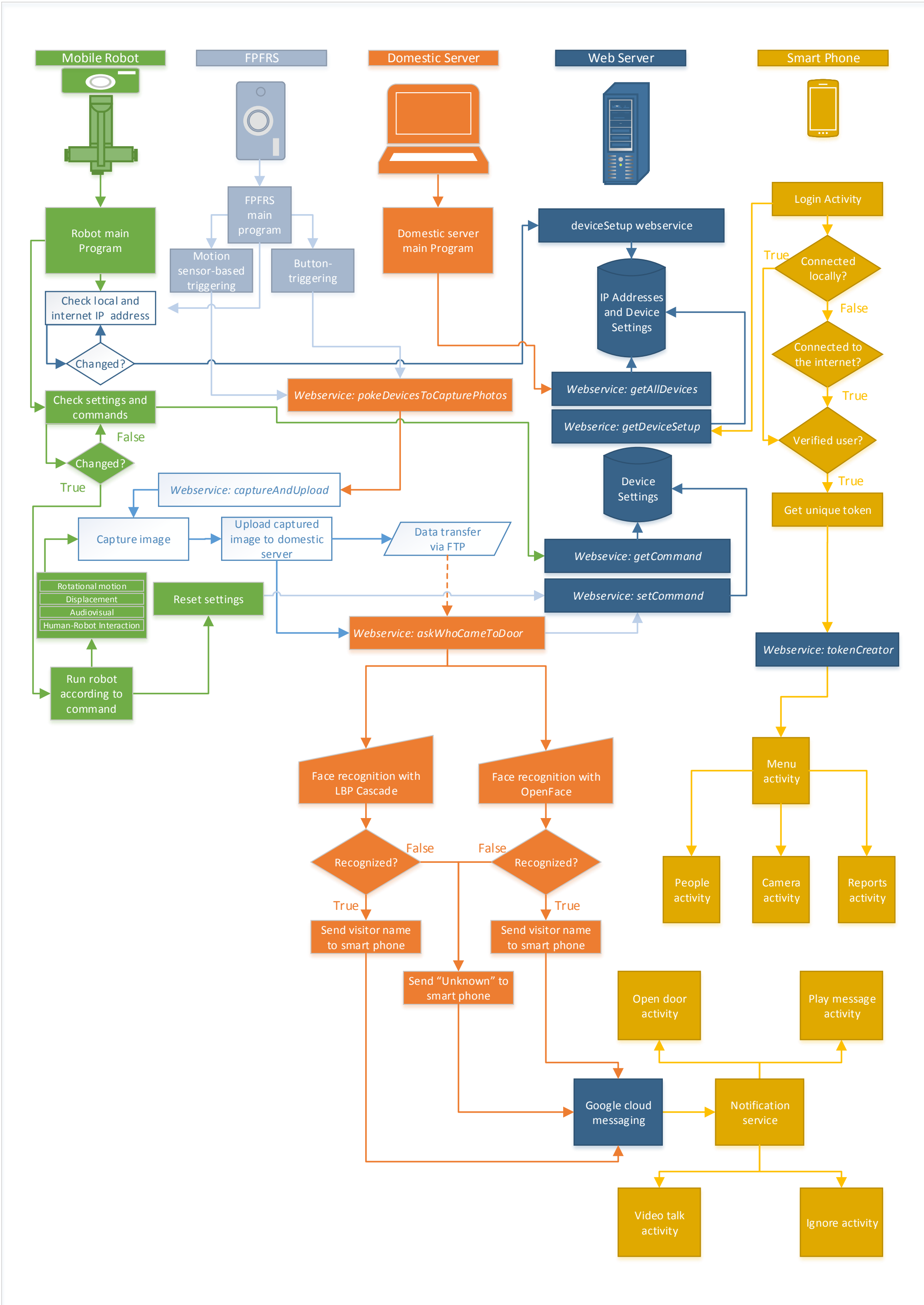


Figure 3.15 : Detailed flow of processes in the proposed system architecture.

communication properly, this module is planned to be open for extensions. In general, communication module provides communication between domestic server, web server, one or more FPFRS, one or more mobile robots, smart mobile phone and web browser. Applied methods for each communication link between devices are given the in the subsections below.

3.3.1.1 Communication between the device and mobile application

System design is based on client and server protocol. FPFRS's observe environment and response actions as post requests to the domestic server. FPFRS's can retrieve and update records in domestic server via web services. Also the mobile application can retrieve records in the domestic server via web services.

When an action is triggered on FPFRS side, its results are recorded to the domestic server. When an action is triggered on the mobile application side, its outputs are handled by the domestic server or FPFRS side. Domestic server is used to link communication between mobile application and FPFRS's.

Mobile application is written in Java language and it can be loaded to any Android OS whose version is higher than Android Lollipop 5.0.

3.3.1.2 Button triggered capturing process

For the sake of clarity, below we describe a system consisting of one FPFRS and one mobile robot below, however the reader should take into account that the system can be extended to support multiple of them.

When a visitor comes to the door and he/she pushes the button, FPFRS sends post requests to domestic server to trigger image capturing mechanism. Domestic server checks the list of the online devices (clients) to send *"capture image"* command. Domestic server sends post request to get online clients list from web server via a web service called *getAllDevices*. After sending *"capture image"* command to clients, different types of clients run different processes. FPFRS captures images and uploads them to the domestic server. Simultaneously, the mobile robot observes environment and tracks the position of the visitor. After finding the person, the mobile robot starts to capture his/her images. Both the FPFRS and the mobile robot upload images to the domestic server. The domestic server waits until upload process is finished and runs the face recognition algorithms to identify the person. After the identity of the person is revealed, the domestic server sends notification to the system owner's smart phone. The system owner selects an action from the notification screen on the mobile application.

3.3.1.3 Sending notifications

Domestic server sends special commands to the mobile application. Information is sent as comma separated values and embedded to this special command. Using the format *"X, Y, Z"* where *X* stands for action, *Y* and *Z* denotes the action's parameters. Mobile application side separates information according to commas. For example a command like *"0, 192.168.2.215/esasp/door.jpg, Emre Sercan Aslan"* means that *Emre Sercan Aslan* is recognized at the door and his images are saved to the given URL. *0* stands for simulating phone call when someone came and push button, *192.168.2.215/esasp/door.jpg* denotes the location of captured image of visitor, and lastly *Emre Sercan Aslan* indicates identification of recognized visitor.

There are a lot of services that helps to notice users about the recent actions and states. Google Cloud Messaging (GCM) system is one of the most popular of these services. Yilmaz et al. [39], have evaluated GCM in terms of applicability to the real world examples. These experiments have shown that GCM is not suitable for time sensitive applications. However, GCM have performed well at broadcasting an information to a crowded user group. According to the experiment, GCM has delivered notification to nearly 40% of its subscribers in 10 seconds. This proved that the GCM can be used to notify users, if a reasonable delay is acceptable. Additionally, adapting GCM to the mobile application is easy and fast. Within a short time a notification system based on GCM can be applied to mobile applications. Therefore, our proposed system uses GCM while sending notifications to user.

3.3.1.4 Video chat

Several technologies for video streaming are implemented. Video chat is one of the most challenging parts of the system because it is hard to implement a video chat running on FPFRS built on RPi. Most of video stream libraries such as VLC, GStreamer have been generally designed to be running on computers, not embedded computers. When a program based on these libraries is executed at FPFRS, their performance drops because of the low computational power of the processors as expected.

Before the final integration of the video conference method VLC Player[4], GStreamer[5] and WebRTC[6] technologies are applied and tested. Streaming with VLC is not feasible because of the voice echo and delays up to 5 seconds. Streaming with GStreamer gives better results than VLC in terms of delay. However, neither VLC nor GStreamer solves voice echo problems. WebRTC technology, a real-time communication technology structured on web browsers, eliminates voice echo problem and keeps the latency as short as GStreamer does. Therefore, our proposed system uses WebRTC technology to accomplish video chat process.

3.3.2 Face recognition module

In this section, the implemented face recognition algorithms are introduced.

All devices in the system have OpenCV [15] installed. While FPFRS and the mobile robot use Local Binary Points (LBP) based face detection algorithm [9] combined with Haar Cascades [40] to detect faces so that they can send captured images to domestic server that have real faces to make more accurate recognition later. Domestic server uses OpenFace face recognition algorithm [13] in addition to LBP-based face recognition algorithm. Since OpenFace needs libraries installed, which are not ported to RPi yet, and porting a library to a different platform is a time consuming job. Stability provided after these libraries to Raspian OS is not ensured. Therefore, none of the devices in the system are able to execute face recognition program that is based on OpenFace algorithm, except the domestic server.

3.3.2.1 Local binary pattern-based face recognition algorithm

Face detection is made using Haar Cascades [40] which makes use of different kinds of features regarding face objects such as eye, mouth, nose, profile face, frontal face. In our system, frontal face Haar Cascade is used to detect faces in images. After the face is detected, the detected region is cropped so that later face recognition algorithm can be processed on it. LBP-based face recognition algorithm [9] creates a model for

[4]VLC Player: `http://www.videolan.org/vlc/`
[5]GStreamer: `https://gstreamer.freedesktop.org/`
[6]WebRTC: `https://webrtc.org/`

each image set where the faces are detected. Image set consists of a person's images which are saved only in one session. A person can have many different image sets. Each set has its own unique label. LBP based face recognition system receives images and image set IDs as labels. After the training process, the system creates a model.

$$LBP(x_c, y_c) = \sum_{p=0}^{P-1} 2^p s(i_p - i_c) \tag{3.1}$$

LBP is calculated using the equation 3.1, where (x_c, y_c) is coordinates of central point with intensity i_c and neighbour of central pixel's intensity is presented as *in*. **s** sign function is given in equation 3.2.

$$s(x) = \begin{cases} 1, & \text{if} \quad x \geq 0 \\ 0, & \text{else} \end{cases} \tag{3.2}$$

For a central point (x_c, y_c), the position of the neighbor is (x_p, y_p), $p \in P$ can be calculated using equation 3.3. OpenCV implementation[7] does a bilinear interpolation to realize extended LBP as known as Circular LBP using equation 3.4.

$$\begin{aligned} x_p &= x_c + R\,cos(\frac{2\pi p}{P}) \\ y_p &= y_c - R\,sin(\frac{2\pi p}{P}) \end{aligned} \tag{3.3}$$

$$f(x,y) \approx [1-x \;\; x] \begin{bmatrix} f(0,0) & f(0,1) \\ f(1,0) & f(1,1) \end{bmatrix} \begin{bmatrix} 1-y \\ y \end{bmatrix} \tag{3.4}$$

During the recognition phase in Fig. 3.16, same face detection algorithm is run to find out the face to recognize. If the system detects a match based on the distance metric, it publishes the image set ID as a recognition result. According to this recognition result, the system uses a relational database to figure out whose image set it is by searching the image set ID and person ID. After the person ID information is obtained, the system uses relational database to retrieve user's full name. Finally the system returns who is recognized.

[7]Face Recognition with OpenCV:`http://docs.opencv.org/2.4/modules/contrib/doc/facerec/facerec_tutorial.html`

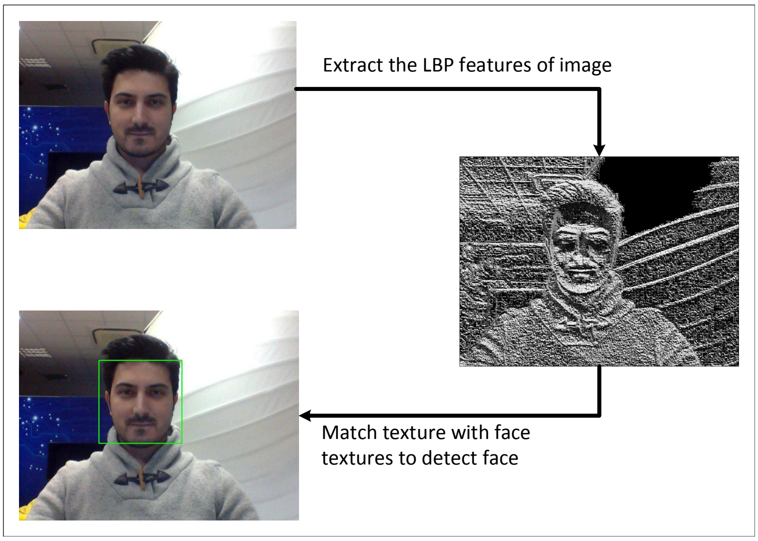


Figure 3.16 : Illustration of LBP-based face detection steps.

3.3.2.2 OpenFace face recognition algorithm

OpenFace algorithm [13] uses histograms of oriented gradients to detect faces. Then, this algorithm marks proper locations of the face. This process is called as *face landmarking* which gives information about pose that helps to warp images later in the alignment phase. Images are aligned according to the information taken from the main facial landmarks. These images are processed with the help of neural networks, which are adapted to the face features. These neural networks are trained on huge numbers of images. The system does not need to create a new neural network. The algorithm returns 128 features, which is a heuristically set number after passing an image through this neural network. Machine learning techniques are applied to determine whose features are closer to the features of that instantaneous image. Steps of Openface-based face recognition are illustrated in Fig. 3.17.

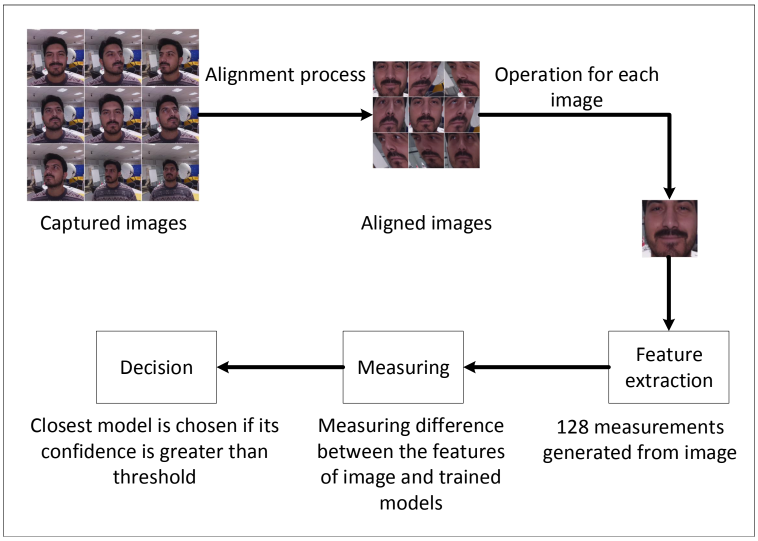


Figure 3.17 : Illustration of Openface-based face recognition steps.

3.3.3 Security module

In this section door lock mechanism and security management system are described in detail. In addition to the lock mechanism, video surveillance and motion-triggered video recording system bring the security to a higher level. This module works when it is specifically activated.

3.3.3.1 Lock system and management

FPFRS has an electronic lock system that can be triggered using a relay. This lock system is used to lock or open the door. When a visitor presses the button and user gets the notification, mobile application provides choices to the user. One of these choices is to open the door. If the user selects to open the door, the state of the door changes to "open". This is how the electronic lock system management is done.

3.3.3.2 Motion-triggered video surveillance

As a part of home automation system FPFRS has the ability to keep records of scenes where any motion or movement is detected. This motion sensor-triggered system records 5 seconds long videos. If the motion continues, consequent videos are recorded which can be played later. Using the mobile application, the camera of FPFRS can be activated any time desired.

3.3.4 Web interface

In this section both the front-end and the back-end of web interface are introduced. Also the web page and the associated web services are described in detail. Yii framework[8] is used to implement the web page using PHP. Yii framework has model view controller architectural pattern. This framework provides Gii module which is helpful to create codes. Using Gii module models, views and controllers can be created automatically when this module interacts with database. MySQL database is used to keep records of events, people, images etc.

Interface for Adding a Person to the System : This interface has form fields regarding the name, surname, e-mail, phone number. A user can add a person to the system using this interface. Activities such as deleting and updating a person are also integrated to the web interface.

Image Set Editor Interface : Captured face images are recorded to the database located at the domestic server. An image set of a person is captured to create model of him or her to be used later on for face recognition. Image set editor interface (Fig. 3.18) is intended to browse and modify image sets. This graphical user interface enables the user to delete arbitrary images from the set or delete the whole image set completely. When the user clicks on an image, this image is deleted from the image set.

Figure 3.18 : An image set acquired by the FPFRS after the button is pressed.

Interface for Assigning a Person to an Image Set : People and image sets are kept in a database. This interface (Fig. 3.19) is prepared to set a relation between

[8]http://www.yiiframework.com/

person and image sets. User can assign a person to an image set using this interface. Updating and deleting relation features are also available.

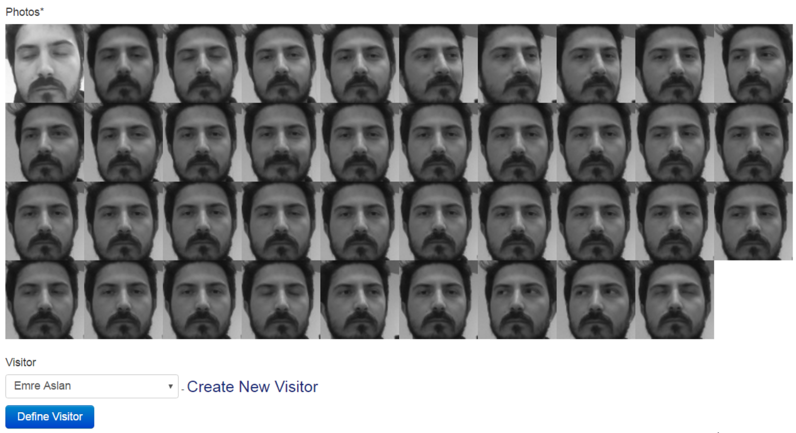


Figure 3.19 : Interface for assigning a person to an image set by either creating new visitor or assigning it to an existing visitor.

3.3.5 Mobile application

The mobile application starts with the user login screen. User enters login ID and password. Then these information are sent to the web service related to the verification. To protect personal information, the system uses tokenized security model, which creates a unique token per login to the system via mobile application. When the username and password are verified, a unique token is created and this token is saved to the database. Mobile application gets the token from the web service to use it later for verification. Web services provide information to the mobile application only using tokenized security. If the provided token is true, web services give information to mobile application as JavaScript Object Notation (JSON) objects. Otherwise web services only serve an empty JSON object or give error.

Mobile application gets IP information from the web server and checks if it is connected locally or over the internet. It checks the local network to login. If it is unable to login then it checks the internet to login. If it is unable to login either, it gives an error about connectivity or password.

All structures are based on Representational State Transfer (REST or RESTful) [41] in the mobile application. REST web services make data available to other platforms such as mobile phone, computer, embedded device to be used later on. REST is secure and even applicable to a running system. In this study, REST is used for information retrieval from databases hosted by servers. Requesting a proper URL to get information from a source is better than accessing a database directly, because accessing database from everywhere is not acceptable in terms of security. Moreover, each platform has its own style, convention, and tools to access to the database. To realize direct access the database from different platforms, each platform has to be implemented using proper methods since various platforms use different programming languages such as Java, C, C++, Python etc. to access a database. Instead of writing code to maintain a task for each platform, using REST to access information is practical and beneficial. As a result, REST saves time and energy.

Web services of domestic server are used to achieve information transfer between mobile application and database system.

Android application is implemented using Elipse IDE, Google Cloud Messaging (GCM) and web services.

Menu Screen : This screen (Fig. 3.20(a)) helps the user to go to the other screens. Icons are chosen according to the process to make the interface human friendly.

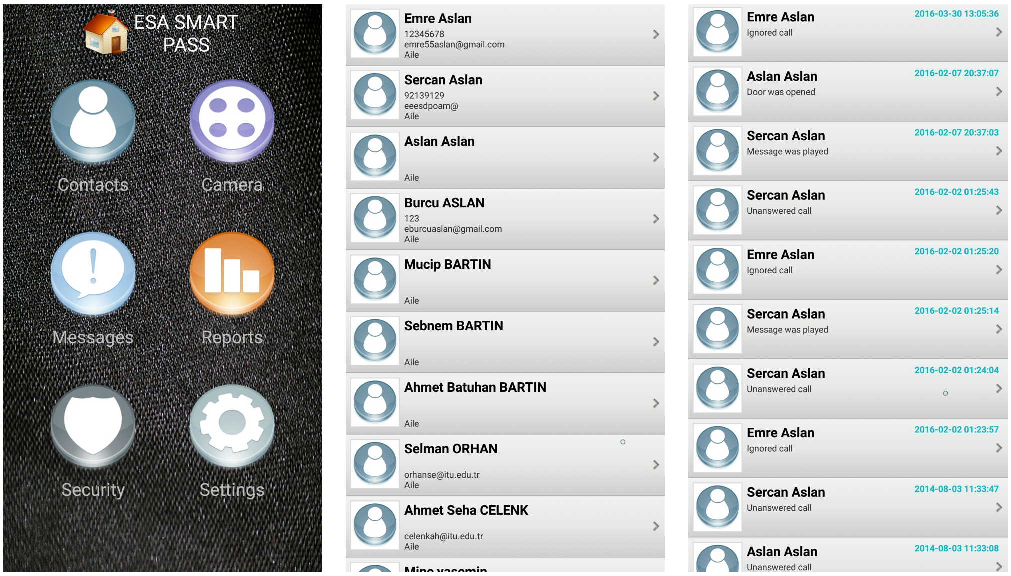
People Screen : User can see the list of the people who are recorded to the database. Moreover, the user can go though clicking an item to contact (via phone call and message) the person from another screen (Fig. 3.20(b)).

Reports Screen : This screen (Fig. 3.20(c)) is shown when a visitor comes to the door and a notification is sent to the user to select an action. In addition, these selected actions are also illustrated on this screen.

3.3.6 Audiovisual human tracking on a mobile robot

Proposed distributed system includes a mobile robot. This mobile robot has various sensors such as microphone array, depth sensor and camera to track human.

Bayram et al. have proposed audio-vision-based single human [34] and multi-person [35] tracking for active robot perception. In this study, human tracking system is based on these researches. The mobile robot uses multiple signal classification structured on generalized eigenvalue decomposition method for sound source localization in the audition modality and a method combining feature-based and color-based face



(a) Menu Screen (b) People Screen (c) Reports Screen

Figure 3.20 : Mobile Application Screens.

detection and tracking methods in vision modality to cope with issues affecting the detection and tracking in a real-world environment.

3.4 Activation Modes for Human Identification

Proposed distributed system includes two kinds of interaction devices. One is FPFRS and the other one is a mobile robot. In this section the activation modes of the FPFRS are described in detail accompanied with their exemplary usage scenarios.

3.4.1 Button triggered human identification

This mode is active when a visitor arrives at a door having FPFRS, for example when household is not at home. The visitor presses the button, which is used as a door bell, in the front cover of the FPFRS. After the camera is activated to capture images, the domestic server simultaneously activates the mobile robot to detect the person and to capture images. These images are processed by the face recognition algorithms in the domestic server. Recognition output is given via smart phone notification to the user.

3.4.2 Motion triggered human identification

People need to keep burglars away from private property. Video surveillance systems have been developed to address this issue. However, it is not easy to track human generated actions within the records. The motivation for creating this mode is to detect anomalies in the environment automatically.

As a proposed solution to tracing actions, smart video recording is implemented. FPFRS for recording video in this mode only runs when motion sensor is triggered. Suppose a visitor approaches to a place where FPFRS is located. Motion sensor in FPFRS detects the motion and triggers the camera to capture images. Mobile robot is also activated by the domestic server as described in Section 3.4.1. Captured images are processed by the face recognition algorithms in the domestic server. Recognition output is transmitted to the user via smart phone notification to user.

3.5 Behaviours of the Mobile Robot

In the proposed system, mobile robot waits for an instruction and behaves accordingly indirectly triggered by FPFRS and sent by the domestic server. The mobile robot is located at a place and ready to serve when invoked.

All behaviours described below are about to capture facial image of a person. We make use of the fact that the person finds the mobile robot interesting, thus wakes the attention of the person. However, some people may not find the mobile robot attractive and do not look towards the robot, which makes the face recognition more difficult using the images taken by the robot.

If the mobile robot can not attract attention of the person at first sight, the mobile robot has to actively approach to the person. Therefore, rotational motion, displacement, audiovisual human tracking and dialog-based approaches are established for observing the environment and detecting and recognizing a human.

3.5.1 Human identification using rotational motion

Movements of the visitor's face makes capturing facial images of the visitor difficult. To solve this problem, a camera integrated to the mobile robot having the ability to catch face images will be useful. In this mode, the mobile robot, which is located at the close vicinity of the door moves around itself. Robot is triggered using the instruction from the domestic server.

3.5.2 Human identification using displacement

Sometimes a visitor not only looks around but also walks and moves around. In this situation to identify a human, camera has to catch the person to capture his/her face image. In this mode, mobile robot moves around and approaches to the person if the face is detected. Domestic server activates the mobile robot, which autonomously determines where to go.

3.5.3 Human identification using audiovisual human tracking

It is sometimes difficult to detect a person in some situations, mostly due to the position of the human in relation to the FPFRS and mobile robot's placements. Vision may not be useful, when target is too close or far from the camera. To address this issue, a microphone array is used for sensing the audio in the environment.

In this mode, the mobile robot listens to the environment and makes decisions to localize the audio source. Audition, which is a complementary modality, helps the robot to get close to the audio source. After all, it approaches to the person if the face is detected. The robot keeps tracking the person if the person is in the visible area. Domestic server triggers the mobile robot to go into this mode.

3.5.4 Human identification using robot-initiated dialog

In this behaviour scheme, the mobile robot welcomes the visitor, after a person is detected in the designated area. The mobile robot talks to attract to attention of the visitor. Aim of this interaction is guiding the person to look towards the camera of the mobile robot. This interaction not only provides capturing facial images with a natural approach in this way, but also makes the visitor more relaxed by accompanying to him/her.

4. EXPERIMENTS AND RESULTS

In this section experimental conditions, evaluation criteria are introduced. Results, and discussion are introduced.

4.1 Experimental Conditions

Firstly, a stress test was applied to the video talk feature of mobile application to evaluate the load performance of the system.

The experiments regarding the face recognition performance were divided into two parts; 1)laboratory experiments, which were rather restricted and 2)real world experiments, which were rather open for improvision in terms of human robot interaction. In the laboratory experiments, facial images of people were collected using the FPFRS and the Kinect sensor on the robot. Face recognition analysis was done using these gathered facial images. However, in the real world experiments, FPFRS was fixed on a location near the door as in Fig. 4.1 and the mobile robot was used to help the recognition. In the latter experiment face recognition process based on the collected images from the running distributed system was evaluated.

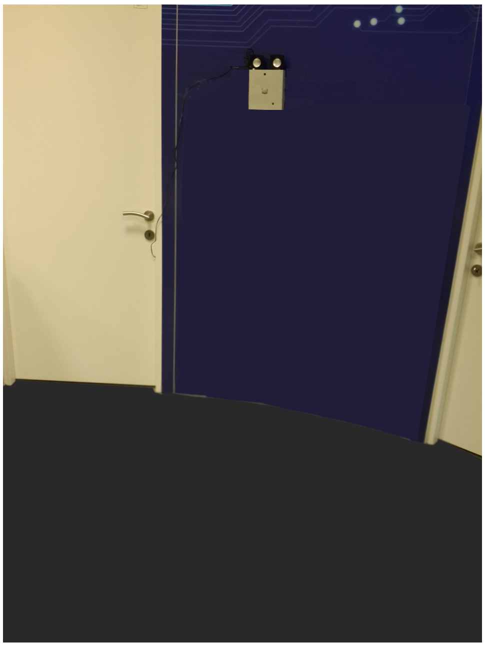


Figure 4.1 : Experiment stage.

All experiments were carried out in an indoor environment. The experiment stage is illustrated in Fig. 4.1 and the environment of the real world experiments is given in Fig. 4.2. FPFRS was fixed to the wall at the height of 160 cm (Fig. 4.1). The mobile robot was modified and rised to the height of 150 cm (Fig. 3.14). FPFRS built on Raspberry Pi 3, was used to perform real world experiments. Technical specifications of RPi 3 is given in Table 4.1. Technical specifications of the robot [42] is given in Table 4.2.

Table 4.1 : Raspberry Pi 3 Technical Specifications.

A 1.2GHz 64-bit quad-core ARMv8 CPU
802.11n Wireless LAN
Bluetooth 4.1
Bluetooth Low Energy (BLE)
1GB RAM
4 USB ports
40 GPIO pins
Full HDMI port
Ethernet port
Combined 3.5mm audio jack and composite video
Camera interface (CSI)
Display interface (DSI)
Micro SD card slot
VideoCore IV 3D graphics core

Table 4.2 : TurtleBot Technical Specifications.

Dimensions	354 x 354 x 420 mm
Weight	6.3 kg
Max payload	5 kg
Max speed	0.65 m/s
Obstacle clearance	15 mm
Drivers and APIs	ROS

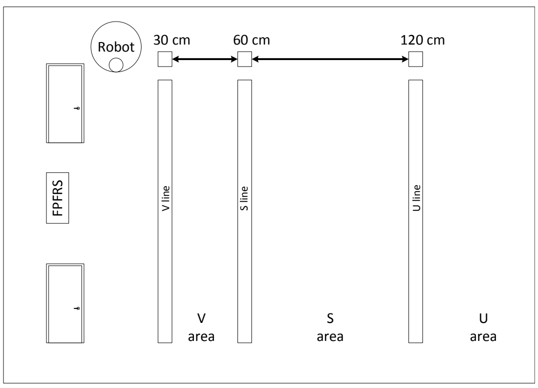


Figure 4.2 : Environment of the real world experiments in a realistic room setup.

The proposed distributed system was tested in three real world experiments. The first investigation was based on a visitor who came to the door and rang the doorbell. The second test was conducted to simulate someone suspicious who was looking and walking around the door. The third test was structured on an unrelated person who was far away from the door. During the second and the third experiments, the motion sensor activated face recognition system whereas in the first experiment, the system has activated by the button. During the experiments, the results of the face recognition were investigated in different time intervals such as 10 seconds, 20 seconds, and 30 seconds.

The location of the participants were planned according to the three real world experiments described above. Participants were positioned at 30 cm to 60 cm distance away from the door for the visitor scenario, whereas they were located at 60 cm to 120 cm far away for suspicious person scenario, and 120 cm or farther away for the unrelated person scenario. Distances were illustrated to the participants using a white tape stuck on the floor. In addition, names of lines were written on the tapes to orient the participants. The names of the lines were given as "V Line", "S Line", and "U Line" where V denotes visitor, S stands for suspicious person, and U presents unrelated person. Observation area was divided into three districts. The region between the V Line and S Line was called *V Area*, the region between S Line and U Line was named *S Area*, and the region beyond the U Line was entitled *U Area*.

Mobile robot had four behaviours to help identification of a human. In each experiment the mobile robot performed all behaviours such as rotational motion, displacement, audiovisual human tracking and dialog based interaction.

Scenarios and role of the participants were told before investigation. They were located in the designated area and to play scenario they acted like a visitor, a suspicious person, and an unrelated person. Participants played their role for each fictive scenario. As a visitor, they were positioned at *V Area*, did not make displacement movements, and they only looked around. As a suspicious person, they were located at *S Area*, walked inside *S Area*, behaved as if they were patrolling and watching out to be sure no one could see them. As an unrelated person, they were told to do everything they wanted except harming the hardware. They were able to show interest in FPFRS and the mobile robot depending on their desire. No pressure was applied to the participants to participate in the experiments. The interaction was left to the participants choice.

Training data were collected from FPFRS only in the real world experiments. Images were collected from participants in the designated areas such as *V Area*, *S Area*, and *U Area*. 20 images were captured from a participant for each region to gather balanced instances of images.

Analysis of the distributed system was investigated in terms of the passed time to recognize a person, the impact of role of the participant to the face recognition, the distance of the participant to the FPFRS, and the effect of the mobile robot's behaviours.

Participants, who attended to the experiments, also participated in the Post-Study System Usability Questionnaire (PSSUQ), which consists of 19 questions and rating from 1 to 7 for each question about the prototype, the proposed distributed face recognition system and its underlying applications including the mobile application.

4.2 Research Questions

In this study, we are particularly interested in the effects of the platform, distance, human-robot interaction, and training database size on the recognition performance of the proposed distributed face recognition system.

- ***Effect of the platform:***The proposed distributed system has two activation modes and four robot behaviours to identify human. These different methods were evaluated using different platforms in terms of recognition score and confidence in real world experiments. The difference between triggering the system manually to capture images (button triggered human identification) and capturing an image when the distributed system was triggered automatically (motion triggered human identification) was investigated. The relation between confidence which is an output of the face recognition and the proposed distributed system's activation modes and behaviours were revealed.
- ***Effect of the distance:***Collected results in real world experiments were analyzed in terms of distance. *V line*, *S line* and *U line* were specified as different distances.

- ***Effect of the human-robot interaction:***The impact of the mobile robot on humans was observed, while the mobile robot not only was capturing images, but also talking to human.

- ***Effect of the data size:***Face recognition results of the distributed system in terms of the data size was also analysed. This criterium was intended to assess the effect of collected data in time intervals to recognize people.

4.3 Evaluation Criteria

The proposed distributed system was evaluated using various metrics on different scenarios.

- ***Confidence:***Face recognition confidence is a measurement metric to evaluate the results of the tests. Distances between the image and each model are calculated by (Equation 4.1) where i is an image to be processed to identify person, m is a model being trained using OpenFace, x_i is a feature of the image tested, x_m is a feature of a model. Since an image is represented using 128 features thanks to OpenFace, all difference between each specific feature is calculated to find out distance in Equation 4.1.

$$d(i,m) = \sqrt{(x_{i1} - x_{m1})^2 + (x_{i2} - x_{m2})^2 + \ldots + (x_{i128} - x_{m128})^2} \tag{4.1}$$

  Then, a decision is made by face recognition system to predict a model or not, according to the distances. For an image, the more closer to the trained class ($dmin$) means the more likely to be a member of that class. If distance is small, confidence will be high. Confidence is calculated by Equation 4.1.

$$confidence = 1 - \frac{|d_{max} - d_{min}|}{d_{max}} \tag{4.2}$$

  Since normalization process in done by dividing the difference between maximum and minimum distance to the maximum distance, confidence value is always represented in 0-1 interval. In real world experiments confidence threshold is determined as 0.30 heuristically to achieve high f-score. The aim of threshold is to figure out unknown people, besides, applying a threshold before prediction ensures that decision is made by more consciously.

- ***True Positive:***For an experiment, the number of correctly identified person being experimented gives True Positive(TP) result. This metric can be used in evaluation, besides, it is used to calculate recall, precision, and f-score.

- ***True Negative:***For an experiment, the number of correctly identified person of not being experimented gives True Negative(TN) result.

- ***False Negative:***For an experiment, it is the number of identification about the actual person, but identification result turns out to be incorrect. This metric can be used in evaluation, besides, it is used to calculate f-score.

- ***False Positive:***For an experiment, the number of identification of a person who is identified as the actual person incorrectly. This metric can be used in evaluation, besides, it is used to calculate f-score.

- ***Precision:***It is also named as positive predicted value. For an experiment, precision is calculated by the number of a correctly identified person(TP) divided by the number of positive prediction including incorrect identification of the person(FP) and TP. It is calculated by Equation 4.3.

$$Precision = (\frac{TP}{TP + FP}) \tag{4.3}$$

- ***Recall:***It is also named as hit rate, sensitivity, or true positive rate. For an experiment, recall is calculated by the number of the correct identification of a person(TP) divided by summation of the number of incorrect, missed identification of the person(FN) and TP. It is calculated by Equation 4.4.

$$Recall = (\frac{TP}{TP + FN}) \tag{4.4}$$

- ***F-score :***It is also named as F-measure. It is a measure of the test's accuracy. It is harmonic mean of precision and recall. It is calculated by Equation 4.5.

$$\begin{aligned} F - score &= 2\,\frac{1}{\frac{1}{recall} + \frac{1}{precision}} \\ F - score &= 2\,\frac{precision\ .\ recall}{precision\ +\ recall} \\ F - score &= 2\,\frac{2TP}{2TP + FP + FN} \end{aligned} \tag{4.5}$$

4.4 Results

In this section video talk delay performance of the proposed system, results of the laboratory experiments and results of real world experiments, and subjective evaluation results are introduced.

4.4.1 Video talk delay performance

WebRTC based video conference system is tested for overloaded attenders. In the initial applied stress test on video conference system, observed results have that expectation for an efficient and suitable conference quality, maximum delay must be at most 2 seconds.

Experiment was done with an internet speed of 20 Mbps. Video resolution has been determined as 640x480 pixel. The server had a processor with 2 GHz one core processor and a RAM of 3 GB. Due to the fact that using gigabit internet connection, there was no constraint bandwidth limit regarding.

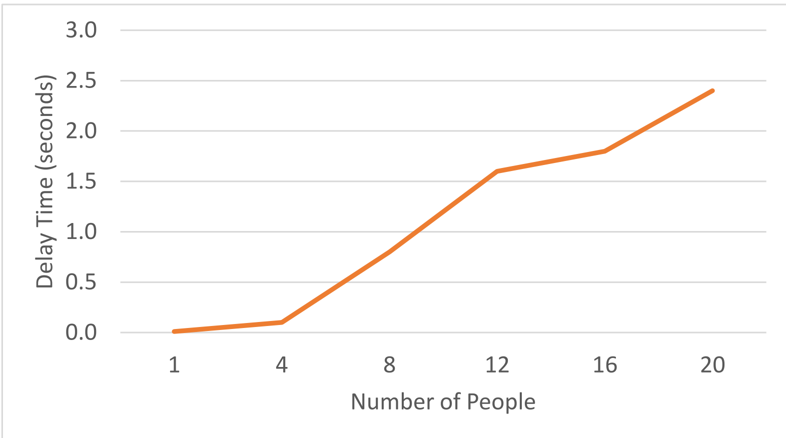


Figure 4.3 : WebRTC stress test.

The results of this test showed that the video chat system is able to support high quality service up to 16 people. Therefore, it can be used in various places, where people need a guide, such as hotels, museums, and meetings.

4.4.2 Results of the laboratory experiments

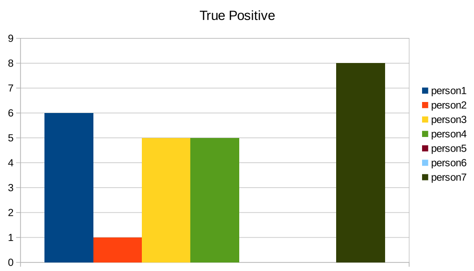
In this section, the performance of the face recognition with FPFRS, TurtleBot and a confidence based fusion approach are given. These experiments are based on collected data, which are not created in real experiment scenarios.

4.4.2.1 Recognition scores using FPFRS

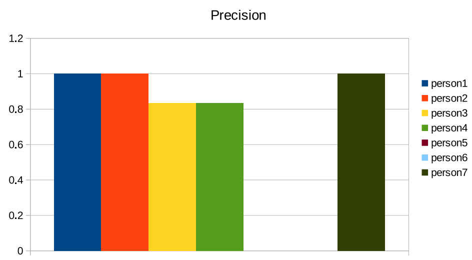
FPFRS uses Haar Cascades to detect frontal faces in the photos. The image set consists of the images of a person and these images are preprocessed by OpenCV based face detection algorithm. This preprocessing operations contain cropping photo that sometimes decreases performance of face recognition. In this part neither alignment process, nor warping process is applied to the photos.

In this experiment, we collected 196 images, which belong to 7 people, from *V area*. These images are divided into two groups as training and test set. Training set consists of 20 photos per person. In total, there are 140 images for the training set. Test set has 8 images per person and there are 56 images to test.

In this experiment, OpenFace face recognition algorithm [13] is used. As a result, faces are detected in 31 images, and recognized in 25 images correctly. In average, recall is 0.446, precision is 0.806, average confidence for each prediction is 0.644, and f-score is 0.574.



(a) True Positive



(b) Precision

(c) Recall

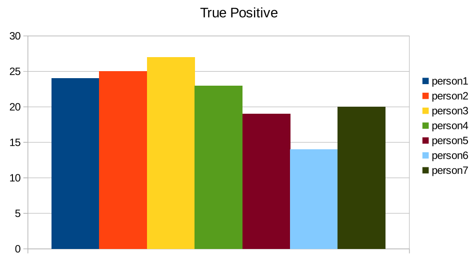
Figure 4.4 : Recognition scores using FPFRS.

4.4.2.2 Recognition scores using the mobile robot

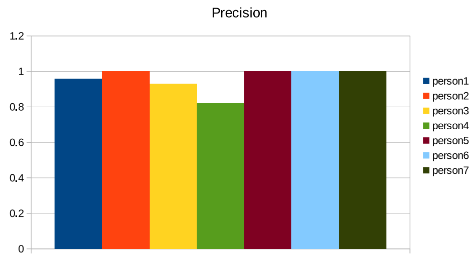
In this experiment no preprocessing is done except Openface pipeline [13]. In this pipeline, face detection and alignment operations are applied to the images. Finally, with the help of deep neural network and a large model trained before, Openface exports the corresponding features to a Comma Separated Value (CSV) file.

Face dataset in this experiment consists of 700 images, which belong to 7 people. 490 images are used in the training stage, 210 photos are used in the test stage.

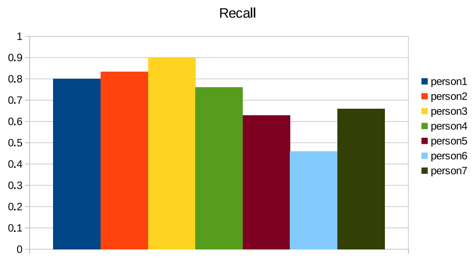
As a result faces are detected in 160 images, and recognized in 152 images correctly. In average, recall is 0.724, precision is 0.91 and average confidence for each prediction is 0.870, and f-score is 0.806.



(a) True Positive



(b) Precision



(c) Recall

Figure 4.5 : Recognition scores using the mobile robot.

4.4.2.3 Distributed recognition scores using highest confidence

Images taken from FPFRS and the mobile robot were using the confidence of face recognition algorithm's prediction. In face recognition algorithm each prediction gets image as input and results label and confidence as outputs. In this experiment, 60 face images of 6 people were used in total. One half of the images were taken from FPFRS and the other half of the images were taken from the mobile robot.

As a result choosing highest confidence rate for each prediction improved accuracy rate of face recognition system up to 95%.

4.4.2.4 Recognition scores using machine learning

Same image set as in Section 4.4.2.3 was used as the collected images. Three popular machine learning algorithms were used for fusion such as Decision Tree (DT) [43], Random Forest Tree (RFT) [44], and Linear Support Vector Machine (SVM) [45] were used to increase the accuracy of the face recognition. These machine learning methods were applied using predicted label and confidence to find the real label.

The tests were done applying k fold cross validation where k was taken 10. Accuracy of DT was 88%, Linear SVM was 95%, and RFT was 95%.

4.4.3 Results of the real world experiments

Each participant attended 12 different experiments, (Fig. 4.6) which have different parameters such as the distance between the participants and FPFRS, namely the role of the participants, and the activation mode of the hybrid system, as well as the behaviour of the mobile robot. Duration of each experiment was 60 seconds and each participants had in total 12 minutes to test the proposed system.

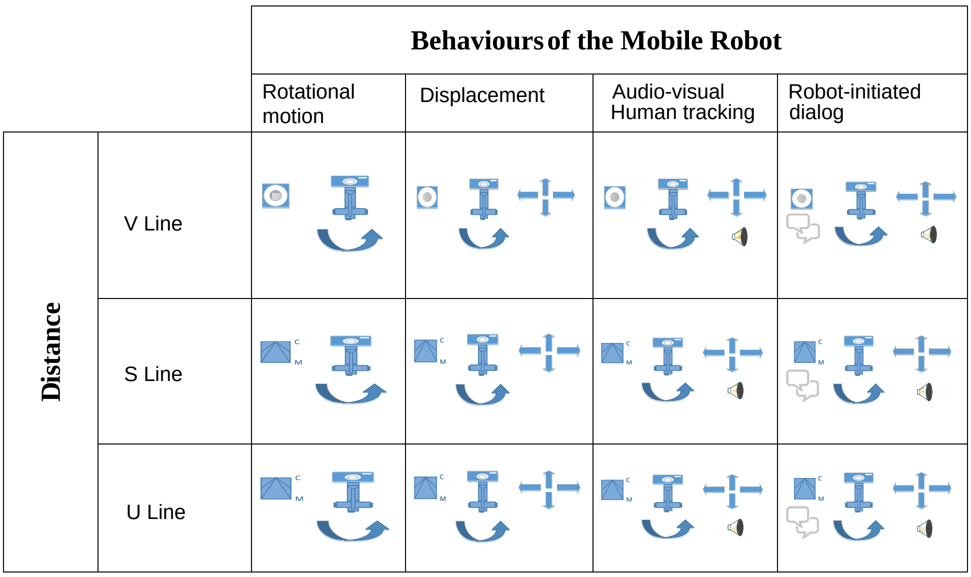


Figure 4.6 : Features of the experimental framework.

The performance of the distributed face recognition system, based on OpenFace library, was evaluated using the metrics given in Section 4.3. Altogether 25 people participated in the experiments. All participant's images are used in the training phase. 10 of the 25 participants attended to the test of real world scenario based experiments.

4.4.3.1 Results on the effect of the activation mode and robot behaviour

In this part, the role of activation modes of the FPFRS and behaviours of the mobile robot are investigated. Activation modes of FPFRS consist of button-triggered and motion-triggered modes. Behaviours of the mobile robot consist of rotational, displacement, audiovisual, and robot-initiated dialog based audiovisual tracking behaviours.

Confusion matrices showing the actual and predicted people in all these modes and behaviours are given in Table 4.3 - 4.8. In these tables P1 - P10 indicate the person identification number. U is used for unknown people and O is used for others.

Table 4.3 : Confusion matrix of the results obtained from only button-triggered FPFRS.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**23**	-	-	-	-	-	-	-	-	-	2	-
	P2	-	**16**	-	-	1	-	1	-	-	-	-	4
	P3	-	-	5	-	-	1	-	-	-	-	**28**	2
	P4	-	-	-	**15**	-	-	-	-	-	-	-	1
	P5	-	-	-	-	**15**	4	-	-	-	-	1	1
	P6	-	-	-	-	-	**12**	-	-	-	-	1	3
	P7	-	-	-	4	-	-	**14**	-	-	-	2	1
	P8	-	-	-	-	-	-	-	**22**	-	-	3	2
	P9	-	-	-	-	1	-	-	-	**12**	-	2	-
	P10	-	-	-	1	1	-	-	-	-	**13**	1	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.4 : Confusion matrix of the results obtained from only motion-triggered FPFRS.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**20**	12	-	-	1	-	-	-	-	2	7	2
	P2	-	7	-	4	-	1	-	-	-	2	**18**	3
	P3	-	1	4	-	-	3	-	-	-	2	**11**	6
	P4	-	-	-	**38**	-	-	-	-	-	-	1	-
	P5	-	-	-	-	**15**	2	-	-	-	1	3	1
	P6	-	-	-	1	-	**33**	-	-	1	-	2	5
	P7	-	-	-	8	-	-	**20**	-	-	-	1	2
	P8	-	-	-	-	-	-	-	**28**	-	-	3	2
	P9	-	-	-	-	-	-	-	-	**4**	-	2	-
	P10	-	-	-	2	2	-	-	-	-	**16**	4	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.5 : Confusion matrix of the results obtained from only rotational tracking behaviour of the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**21**	1	-	-	-	-	-	-	-	-	2	-
	P2	-	**19**	-	-	-	-	-	-	-	-	3	-
	P3	-	3	**8**	-	-	1	-	-	-	-	3	1
	P4	-	-	-	**15**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**9**	-	-	-	-	-	1	1
	P6	-	-	-	-	-	**21**	-	-	-	-	-	1
	P7	-	1	-	-	-	-	**20**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**22**	-	-	-	5
	P9	-	-	-	-	-	-	-	-	**11**	-	-	-
	P10	-	-	-	-	1	-	-	-	-	**22**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.6 : Confusion matrix of the results obtained from only displacement tracking behaviour of the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**28**	-	-	-	-	-	-	-	-	-	-	-
	P2	-	**24**	-	-	-	-	-	-	-	-	1	-
	P3	-	-	**14**	-	-	-	-	-	-	-	2	1
	P4	-	-	-	**14**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**12**	-	-	-	-	-	1	2
	P6	-	-	-	-	-	**24**	-	-	-	-	-	-
	P7	-	-	-	-	-	-	**19**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**16**	-	-	3	5
	P9	-	-	-	-	-	-	-	-	**7**	-	1	-
	P10	-	-	-	-	-	-	-	-	-	**22**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.7 : Confusion matrix of the results obtained from only audiovisual tracking behaviour of the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**22**	-	-	-	-	-	-	-	-	-	1	-
	P2	-	**8**	-	-	-	-	-	-	-	-	-	1
	P3	-	1	**7**	-	-	-	-	-	-	-	2	-
	P4	-	-	-	**8**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**7**	-	-	-	-	-	-	-
	P6	-	-	-	-	-	**19**	-	-	-	-	-	-
	P7	-	-	-	-	-	-	**20**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**11**	-	-	-	4
	P9	-	-	-	-	-	-	-	-	**5**	-	1	-
	P10	-	-	-	-	-	-	-	-	-	**18**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.8 : Confusion matrix of the results obtained from only interaction with audiovisual tracking behaviour of the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**26**	-	-	-	-	-	-	-	-	-	-	-
	P2	-	**21**	-	-	-	-	-	-	-	-	2	-
	P3	-	-	**11**	-	-	-	-	-	-	-	3	1
	P4	-	-	-	**9**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**9**	-	-	-	-	-	-	1
	P6	-	-	-	-	-	**19**	-	-	-	-	-	-
	P7	-	-	-	-	-	-	**28**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**13**	-	-	-	7
	P9	-	-	-	-	-	-	-	-	**11**	-	-	-
	P10	-	-	-	-	-	-	-	-	-	**22**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.9- 4.14 show the precision, recall, f-score and support results obtained from these confusion matrices.

Table 4.9 : Precision, recall, f-score and support results obtained from only button-triggered FPFRS.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.92	0.96	25
P2	1.00	0.73	0.84	22
P3	1.00	0.14	0.24	36
P4	0.75	0.94	0.83	16
P5	0.83	0.71	0.77	21
P6	0.71	0.75	0.73	16
P7	0.93	0.67	0.78	21
P8	1.00	0.81	0.90	27
P9	1.00	0.80	0.89	15
P10	1.00	0.76	0.87	17
U	-	-	-	-
O	-	-	-	-
Average/Total	0.94	0.68	0.75	216

Table 4.10 : Precision, recall, f-score and support results obtained from only motion-triggered FPFRS.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.45	0.62	44
P2	0.35	0.20	0.25	35
P3	1.00	0.15	0.26	27
P4	0.72	0.97	0.83	39
P5	0.83	0.68	0.75	22
P6	0.85	0.79	0.81	42
P7	1.00	0.65	0.78	31
P8	1.00	0.85	0.92	33
P9	0.80	0.67	0.73	6
P10	0.70	0.64	0.67	25
U	-	-	-	-
O	-	-	-	-
Average/Total	0.83	0.61	0.66	304

Table 4.11 : Precision, recall, f-score and support results obtained from only rotational tracking behaviour of the mobile robot.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.88	0.93	24
P2	0.79	0.86	0.83	22
P3	1.00	0.50	0.67	16
P4	1.00	1.00	1.00	15
P5	0.90	0.82	0.86	11
P6	0.95	0.95	0.95	22
P7	1.00	0.95	0.98	21
P8	1.00	0.81	0.90	27
P9	1.00	1.00	1.00	11
P10	1.00	0.96	0.98	23
U	-	-	-	-
O	-	-	-	-
Average/Total	0.97	0.88	0.91	192

Table 4.12 : Precision, recall, f-score and support results obtained from only displacement tracking behaviour of the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	1.00	1.00	28
P2	1.00	0.96	0.98	25
P3	1.00	0.82	0.90	17
P4	1.00	1.00	1.00	14
P5	1.00	0.80	0.89	15
P6	1.00	1.00	1.00	24
P7	1.00	1.00	1.00	19
P8	1.00	0.67	0.80	24
P9	1.00	0.88	0.93	8
P10	1.00	1.00	1.00	22
U	-	-	-	-
O	-	-	-	-
Average/Total	1.00	0.92	0.95	196

Table 4.13 : Precision, recall, f-score and support results obtained from only audiovisual tracking behaviour of the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.96	0.98	23
P2	0.89	0.89	0.89	9
P3	1.00	0.70	0.82	10
P4	1.00	1.00	1.00	8
P5	1.00	1.00	1.00	7
P6	1.00	1.00	1.00	19
P7	1.00	1.00	1.00	20
P8	1.00	0.73	0.85	15
P9	1.00	0.83	0.91	6
P10	1.00	1.00	1.00	18
U	-	-	-	-
O	-	-	-	-
Average/Total	0.99	0.93	0.95	135

Table 4.14 : Precision, recall, f-score and support results obtained from only interaction with audiovisual tracking behaviour of the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	1.00	1.00	26
P2	1.00	0.91	0.95	23
P3	1.00	0.73	0.85	15
P4	1.00	1.00	1.00	9
P5	1.00	0.90	0.95	10
P6	1.00	1.00	1.00	19
P7	1.00	1.00	1.00	28
P8	1.00	0.65	0.79	20
P9	1.00	1.00	1.00	11
P10	1.00	1.00	1.00	22
U	-	-	-	-
O	-	-	-	-
Average/Total	1.00	0.92	0.96	183

Figure 4.7 shows the comparison of the f-scores in one single for all modes and behaviours.

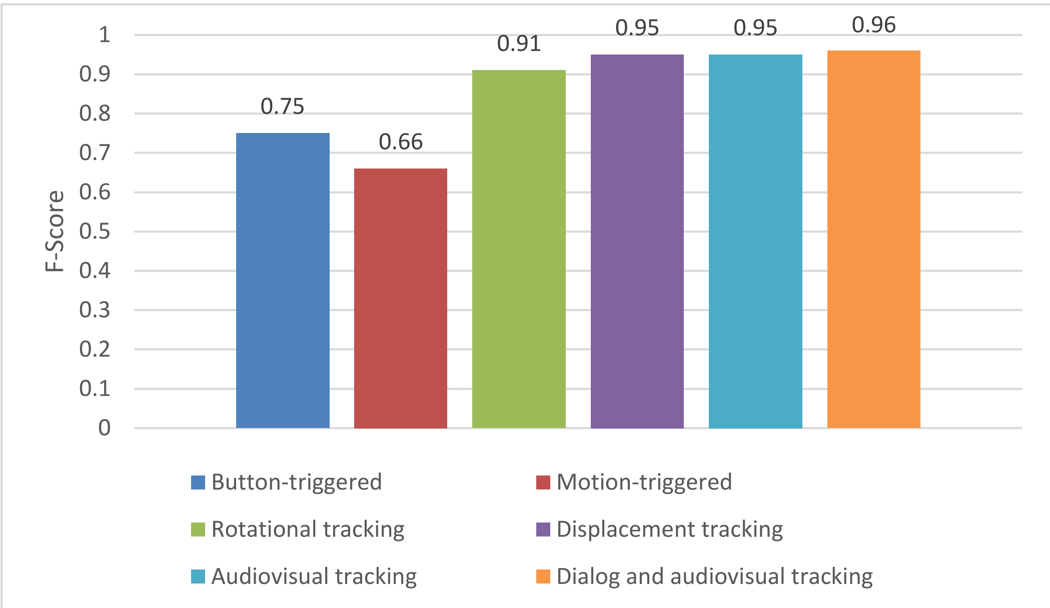


Figure 4.7 : F-scores from the experiments with different activation modes and behaviours.

Best results are obtained from robot-initiated dialog and audiovisual tracking behaviour. People found robot-initiated dialogs interesting and robot achieved to attract participants making them look into itself. Thus, facial images are captured more effectively in order to be used in face recognition. Even rotational motion of the mobile robot performed acceptable performance having the f-score 0.91. Best results of FPFRS are obtained from button-triggered action mode having the f-score 0.75. Motion-triggered activation mode of the FPFRS was the worst among all of the activation modes and robot behaviours. Since motion-triggered activation mode captures image only when a motion is detected and FPFRS was fixed, performance of this mode was not good.

Results of this test revealed that in the real world experiments tracking a person improves performance of the human identification.

4.4.3.2 Results on the effect of the distance and platform

In this part the role of distance is investigated. *V Line, S Line,* and *U Line* are determined as distance metrics. Platforms consist of the FPFRS and the mobile robot.

Confusion matrices showing the actual and predicted people in all these modes and behaviours are given in Table 4.15 - 4.20. In these tables P1 - P10 indicate the person identification number. U is used for unknown people and O is used for others.

Table 4.15 : Confusion matrix from the results obtained in V area using only the FPFRS.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**23**	-	-	-	-	-	-	-	-	-	2	-
	P2	-	**16**	-	-	1	-	1	-	-	-	-	4
	P3	-	-	5	-	-	1	-	-	-	-	**28**	2
	P4	-	-	-	**15**	-	-	-	-	-	-	-	1
	P5	-	-	-	-	**15**	4	-	-	-	-	1	1
	P6	-	-	-	-	-	**12**	-	-	-	-	1	3
	P7	-	-	-	4	-	-	**14**	-	-	-	2	1
	P8	-	-	-	-	-	-	-	**22**	-	-	3	2
	P9	-	-	-	-	1	-	-	-	**12**	-	2	-
	P10	-	-	-	1	1	-	-	-	-	**13**	1	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.16 : Confusion matrix from the results obtained in V area using only the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**35**	-	-	-	-	-	-	-	-	-	1	-
	P2	-	**20**	-	-	-	-	-	-	-	-	-	-
	P3	-	-	-	-	-	-	-	-	-	-	-	-
	P4	-	-	-	**8**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**15**	-	-	-	-	-	-	-
	P6	-	-	-	-	-	**24**	-	-	-	-	-	1
	P7	-	-	-	-	-	-	**30**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**19**	-	-	1	8
	P9	-	-	-	-	-	-	-	-	**17**	-	-	-
	P10	-	-	-	-	1	-	-	-	-	**26**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.17 : Confusion matrix from the results obtained in S area using only the FPFRS.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**13**	4	-	-	1	-	-	-	-	1	2	1
	P2	-	**5**	-	1	-	-	-	-	-	1	3	1
	P3	-	-	-	-	-	-	-	-	-	-	**1**	-
	P4	-	-	-	**9**	-	-	-	-	-	-	1	-
	P5	-	-	-	-	**8**	-	-	-	-	1	-	-
	P6	-	-	-	-	-	**10**	-	-	1	-	-	-
	P7	-	-	-	-	-	-	**6**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**9**	-	-	3	-
	P9	-	-	-	-	-	-	-	-	**2**	-	-	-
	P10	-	-	-	-	-	-	-	-	-	**6**	4	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.18 : Confusion matrix from the results obtained in S area using only the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**36**	1	-	-	-	-	-	-	-	-	-	-
	P2	-	**27**	-	-	-	-	-	-	-	-	2	-
	P3	-	2	**25**	-	-	1	-	-	-	-	4	-
	P4	-	-	-	**19**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**14**	-	-	-	-	-	1	1
	P6	-	-	-	-	-	**29**	-	-	-	-	-	-
	P7	-	1	-	-	-	-	**33**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**27**	-	-	-	5
	P9	-	-	-	-	-	-	-	-	**11**	-	2	-
	P10	-	-	-	-	-	-	-	-	-	**30**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.19 : Confusion matrix from the results obtained in U area using only the FPFRS.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	7	**8**	-	-	-	-	-	-	-	1	5	1
	P2	-	2	-	3	-	1	-	-	-	1	**15**	2
	P3	-	1	4	-	-	3	-	-	-	2	**10**	6
	P4	-	-	-	**29**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**7**	2	-	-	-	-	3	1
	P6	-	-	-	1	-	**23**	-	-	-	-	2	5
	P7	-	-	-	8	-	-	**14**	-	-	-	1	2
	P8	-	-	-	-	-	-	-	**19**	-	-	-	2
	P9	-	-	-	-	-	-	-	-	**2**	-	2	-
	P10	-	-	-	2	2	-	-	-	-	**10**	-	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.20 : Confusion matrix from the results obtained in U area using only the FPFRS mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**26**	-	-	-	-	-	-	-	-	-	2	-
	P2	-	**25**	-	-	-	-	-	-	-	-	4	1
	P3	-	2	**15**	-	-	-	-	-	-	-	6	3
	P4	-	-	-	**19**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**8**	-	-	-	-	-	1	3
	P6	-	-	-	-	-	**30**	-	-	-	-	-	-
	P7	-	-	-	-	-	-	**24**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**16**	-	-	2	8
	P9	-	-	-	-	-	-	-	-	**6**	-	-	-
	P10	-	-	-	-	-	-	-	-	-	**28**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.21- 4.26 show the precision, recall, f-score and support results obtained from these confusion matrices.

Table 4.21 : Precision, recall, f-score and support results of scenario 1 - V Area only FPFRS.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.92	0.96	25
P2	1.00	0.73	0.84	22
P3	1.00	0.14	0.24	36
P4	1.00	0.14	0.24	36
P5	0.83	0.71	0.77	21
P6	0.71	0.75	0.73	16
P7	0.93	0.67	0.78	21
P8	1.00	0.81	0.90	27
P9	1.00	0.80	0.89	15
P10	1.00	0.76	0.87	17
U	-	-	-	-
O	-	-	-	-
Average/Total	0.94	0.68	0.75	216

Table 4.22 : Precision, recall, f-score and support results of scenario 1 - V Area only the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.97	0.99	36
P2	1.00	1.00	1.00	20
P3	-	-	-	-
P4	1.00	1.00	1.00	8
P5	0.94	1.00	0.97	15
P6	1.00	0.96	0.98	25
P7	1.00	1.00	1.00	30
P8	1.00	0.68	0.81	28
P9	1.00	1.00	1.00	17
P10	1.00	0.96	0.98	27
U	-	-	-	-
O	-	-	-	-
Average/Total	1.00	0.94	0.96	206

Table 4.23 : Precision, recall, f-score and support results of scenario 2 - S Area only the FPFRS.

	Precision	Recall	F-Score	Support
P1	1.00	0.59	0.74	22
P2	0.56	0.45	0.50	11
P3	-	-	-	1
P4	0.90	0.90	0.90	10
P5	0.89	0.89	0.89	9
P6	1.00	0.91	0.95	11
P7	1.00	1.00	1.00	6
P8	1.00	0.75	0.86	12
P9	0.67	1.00	0.80	2
P10	0.67	0.60	0.63	10
U	-	-	-	-
O	-	-	-	-
Average/Total	0.87	0.72	0.78	94

Table 4.24 : Precision, recall, f-score and support results of scenario 2 - S Area only the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.97	0.99	37
P2	0.87	0.93	0.90	29
P3	1.00	0.78	0.88	32
P4	1.00	1.00	1.00	19
P5	1.00	0.88	0.93	16
P6	0.97	1.00	0.98	29
P7	1.00	0.97	0.99	34
P8	1.00	0.84	0.92	32
P9	1.00	0.85	0.92	13
P10	1.00	1.00	1.00	30
U	-	-	-	-
O	-	-	-	-
Average/Total	0.98	0.93	0.95	271

Table 4.25 : Precision, recall, f-score and support results of scenario 3 - U Area only the FPFRS.

	Precision	Recall	F-Score	Support
P1	1.00	0.32	0.48	22
P2	0.18	0.08	0.11	24
P3	1.00	0.15	0.27	26
P4	0.67	1.00	0.81	29
P5	0.78	0.54	0.64	13
P6	0.79	0.74	0.77	31
P7	1.00	0.56	0.72	25
P8	1.00	0.90	0.95	21
P9	1.00	0.50	0.67	4
P10	0.71	0.67	0.69	15
U	-	-	-	-
O	-	-	-	-
Average/Total	0.80	0.56	0.60	210

Table 4.26 : Precision, recall, f-score and support results of scenario 3 - U Area only the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.93	0.96	28
P2	0.93	0.83	0.88	30
P3	1.00	0.58	0.73	26
P4	1.00	1.00	1.00	19
P5	1.00	0.67	0.80	12
P6	1.00	1.00	1.00	30
P7	1.00	1.00	1.00	24
P8	1.00	0.62	0.76	26
P9	1.00	1.00	1.00	6
P10	1.00	1.00	1.00	28
U	-	-	-	-
O	-	-	-	-
Average/Total	0.99	0.86	0.91	229

Figure 4.8 shows the comparison of the f-scores in one single for all modes and behaviours.

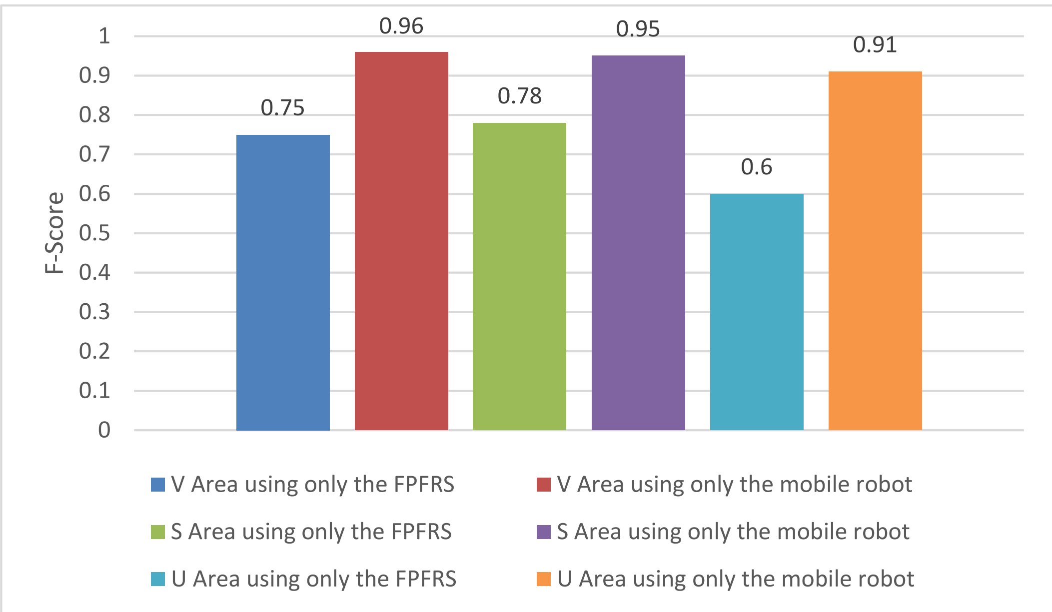


Figure 4.8 : F-scores from the experiments with different distances and platforms.

The mobile robot achieved to high f-scores in all areas, whereas the FPFRS could not achieved high f-score in the experiment done at *U Area*. The f-score results of the mobile robot were between the 0.91 - 0.96, but the f-score results of the FPFRS were changing from 0.6 to 0.78.

On one hand this test revealed that the distance matters when experiment is done using the FPFRS. On the other hand f-score performance of the mobile robot is independent from the distance.

4.4.3.3 Results on the effect of the duration of interaction

This experiment was intended to investigate the effect of the time-lapse on the proposed distributed approach. Images captured by FPFRS and the mobile robot were evaluated within their time intervals, which were set as 10 seconds and its multiples. Since the mobile robot and the participants could not take part in long tests due to possibility of the participants' distraction, maximum duration of tests' was set to periods of 60 seconds for each experiment.

Four time-lapse (70 sec, 140 sec, 210 sec, 260 sec) are determined to show the role of time interval to gather more images and improve the recognize performance.

Confusion matrices showing the actual and predicted people in four time-lapse in Table 4.27 - 4.30. In these tables P1 - P10 indicate the person identification number. U is used for unknown people and O is used for others.

Table 4.27 : Confusion matrix obtained from 70 seconds long recordings using FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**40**	3	-	-	-	-	-	-	-	-	8	1
	P2	-	**28**	-	-	-	-	-	-	-	-	7	4
	P3	-	4	13	-	-	2	-	-	-	-	**18**	2
	P4	-	-	-	**27**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**83**	18	-	-	-	-	33	18
	P6	-	-	-	1	-	**34**	-	-	1	-	-	3
	P7	-	1	-	2	-	-	**36**	-	-	-	-	1
	P8	-	-	-	-	-	-	-	**44**	-	-	2	6
	P9	-	-	-	-	-	-	-	-	**21**	-	3	-
	P10	-	-	-	-	1	-	-	-	-	**34**	1	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.28 : Confusion matrix obtained from 140 seconds long recordings using FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
	P1	**78**	7	-	-	-	-	-	-	-	-	10	1
	P2	-	**76**	-	4	-	-	-	-	-	1	25	5
	P3	-	4	**29**	-	-	2	-	-	-	1	28	6
	P4	-	-	-	**62**	-	-	-	-	-	-	-	1
	P5	-	-	-	-	**43**	4	-	-	-	-	6	5
Actual	**P6**	-	-	-	1	-	**68**	-	-	1	-	1	8
	P7	0	1	-	7	-	-	**62**	-	-	-	2	2
	P8	0	-	-	-	-	-	-	**68**	-	-	6	12
	P9	-	-	-	-	1	-	-	-	**33**	-	4	-
	P10	0	-	-	1	3	-	-	-	-	**61**	2	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.29 : Confusion matrix obtained from 210 seconds long recordings using FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
	P1	**113**	10	-	-	1	-	-	-	-	2	12	2
	P2	-	**76**	-	3	1	-	1	-	-	2	20	8
	P3	-	5	**39**	-	-	4	-	-	-	1	38	9
	P4	-	-	-	**83**	-	-	-	-	-	-	1	1
	P5	-	-	-	-	**59**	5	-	-	-	1	6	5
Actual	**P6**	-	-	-	1	-	**101**	-	-	1	-	2	9
	P7	-	1	-	10	-	-	**92**	-	-	-	2	3
	P8	-	-	-	-	-	-	-	**96**	-	-	9	17
	P9	-	-	-	-	1	-	-	-	**39**	-	6	-
	P10	-	-	-	3	4	-	-	-	-	**89**	3	2
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.30 : Confusion matrix obtained from 260 seconds long recordings using FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**140**	13	-	-	1	-	-	-	-	2	12	2
	P2	-	**95**	-	4	1	1	1	-	-	2	24	8
	P3	-	5	**49**	-	-	5	-	-	-	2	49	11
	P4	-	-	-	**99**	-	-	-	-	-	-	1	1
	P5	-	-	-	-	**67**	6	-	-	-	1	6	6
	P6	-	-	-	1	-	**128**	-	-	1	-	3	9
	P7	-	1	-	12	-	-	**121**	-	-	-	3	3
	P8	-	-	-	-	-	-	-	**112**	-	-	9	25
	P9	-	-	-	-	1	-	-	-	**50**	-	6	-
	P10	-	-	-	3	4	-	-	-	-	**113**	5	2
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.31- 4.34 show the precision, recall, f-score and support results obtained from these confusion matrices.

Table 4.31 : Precision, recall, f-score and support results of 70 seconds long recording using FPFRS and the mobile robot.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.77	0.87	52
P2	0.78	0.72	0.75	39
P3	1.00	0.33	0.50	39
P4	0.90	1.00	0.95	27
P5	0.99	0.55	0.70	152
P6	0.63	0.87	0.73	39
P7	1.00	0.90	0.95	40
P8	1.00	0.85	0.92	52
P9	0.95	0.88	0.91	24
P10	1.00	0.92	0.96	37
U	-	-	-	-
O	-	-	-	-
Average/Total	0.94	0.72	0.79	501

Table 4.32 : Precision, recall, f-score and support results of 140 seconds long recordings using FPFRS and the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.81	0.90	96
P2	0.86	0.68	0.76	111
P3	1.00	0.41	0.59	70
P4	0.83	0.98	0.90	63
P5	0.91	0.74	0.82	58
P6	0.92	0.86	0.89	79
P7	1.00	0.84	0.91	74
P8	1.00	0.79	0.88	86
P9	0.97	0.87	0.92	38
P10	0.97	0.90	0.93	68
U	-	-	-	-
O	-	-	-	-
Average/Total	0.95	0.78	0.84	743

Table 4.33 : Precision, recall, f-score and support results of 210 seconds long recordings using FPFRS and the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.81	0.89	140
P2	0.83	0.68	0.75	111
P3	1.00	0.41	0.58	96
P4	0.83	0.98	0.90	85
P5	0.89	0.78	0.83	76
P6	0.92	0.89	0.90	114
P7	0.99	0.85	0.92	108
P8	1.00	0.79	0.88	122
P9	0.97	0.85	0.91	46
P10	0.94	0.88	0.91	101
U	-	-	-	-
O	-	-	-	-
Average/Total	0.94	0.79	0.85	999

Table 4.34 : Precision, recall, f-score and support results of 260 seconds long recordings using FPFRS and the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.82	0.90	170
P2	0.83	0.70	0.76	136
P3	1.00	0.40	0.58	121
P4	0.83	0.98	0.90	101
P5	0.91	0.78	0.84	86
P6	0.91	0.90	0.91	142
P7	0.99	0.86	0.92	140
P8	1.00	0.77	0.87	146
P9	0.98	0.88	0.93	57
P10	0.94	0.89	0.91	127
U	-	-	-	-
O	-	-	-	-
Average/Total	0.94	0.79	0.85	1226

Figure 4.9 shows the comparison of the f-scores in one single for all modes and behaviours.

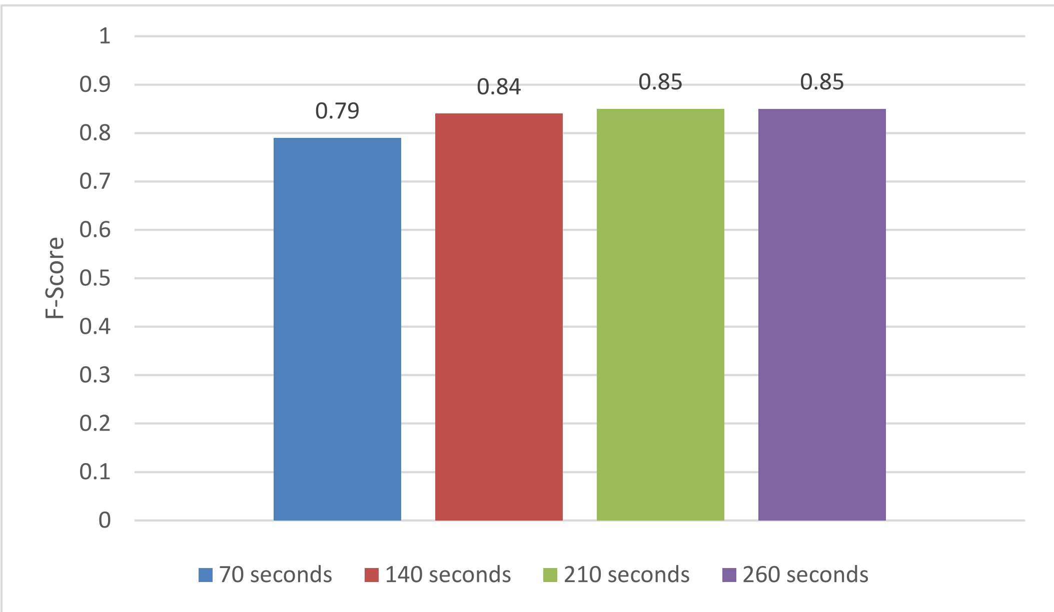


Figure 4.9 : F-scores of the experiments with different durations.

This test showed correlation between the number of the captured images and its improvements on human identification. After certain data are collected, performance of the distributed recognition system states stable. For this experiment, after 140 seconds long duration, it is observed that f-score of the system have been changed only 0.1, which can be ignored and can not be taken into account as an improvement.

4.4.3.4 Results of face recognition in relation to the individual platform

FPFRS and the mobile robot have different advantages and disadvantages. When the mobile robot encounters a face, it tracks and keeps capturing images to be used later on in the recognition. On the contrary, FPFRS is fixed to the wall and catches static facial images. However, FPFRS has button-triggered activation mode which makes the participant come close to its camera to enable capturing clear, high quality and well adjusted facial images.

Confusion matrices showing the actual and predicted people in relation to the individual platform in Table 4.35 - 4.36. In these tables P1 - P10 indicate the person identification number. U is used for unknown people and O is used for others.

Table 4.35 : Confusion matrix obtained from using only FPFRS.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**43**	12	-	-	1	-	-	-	-	2	9	2
	P2	-	**23**	-	4	1	1	1	-	-	2	18	7
	P3	-	1	9	-	-	4	-	-	-	2	**39**	8
	P4	-	-	-	**53**	-	-	-	-	-	-	1	1
	P5	-	-	-	-	**30**	6	-	-	-	1	4	2
	P6	-	-	-	1	-	**45**	-	-	1	-	3	8
	P7	-	-	-	12	-	-	**34**	-	-	-	3	3
	P8	-	-	-	-	-	-	-	**50**	-	-	6	4
	P9	-	-	-	-	1	-	-	-	**16**	-	4	-
	P10	-	-	-	3	3	-	-	-	-	**29**	5	2
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.36 : Confusion matrix obtained from using only the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
	P1	**97**	1	-	-	-	-	-	-	-	-	3	-
	P2	-	**72**	-	-	-	-	-	-	-	-	6	1
	P3	-	4	**40**	-	-	1	-	-	-	-	10	3
	P4	-	-	-	**46**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**37**	-	-	-	-	-	2	4
Actual	**P6**	-	-	-	-	-	**83**	-	-	-	-	-	1
	P7	-	1	-	-	-	-	**87**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**62**	-	-	3	21
	P9	-	-	-	-	-	-	-	-	**34**	-	2	-
	P10	-	-	-	-	1	-	-	-	-	**84**	-	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.37- 4.37 show the precision, recall, f-score and support results obtained from these confusion matrices.

Table 4.37 : Precision, recall, f-score and support results of only FPFRS.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.62	0.77	69
P2	0.64	0.40	0.49	57
P3	1.00	0.14	0.25	63
P4	0.73	0.96	0.83	55
P5	0.83	0.70	0.76	43
P6	0.80	0.78	0.79	58
P7	0.97	0.65	0.78	52
P8	1.00	0.83	0.91	60
P9	0.94	0.76	0.84	21
P10	0.81	0.69	0.74	42
U	-	-	-	-
O	-	-	-	-
Average/Total	0.87	0.64	0.70	520

Table 4.38 : Precision, recall, f-score and support results of only the mobile robot.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.96	0.98	101
P2	0.92	0.91	0.92	79
P3	1.00	0.69	0.82	58
P4	1.00	1.00	1.00	46
P5	0.97	0.86	0.91	43
P6	0.99	0.99	0.99	84
P7	1.00	0.99	0.99	88
P8	1.00	0.72	0.84	86
P9	1.00	0.94	0.97	36
P10	1.00	0.99	0.99	85
U	-	-	-	-
O	-	-	-	-
Average/Total	0.99	0.91	0.94	706

Figure 4.10 shows the comparison of the f-scores in relation to the individual platform.

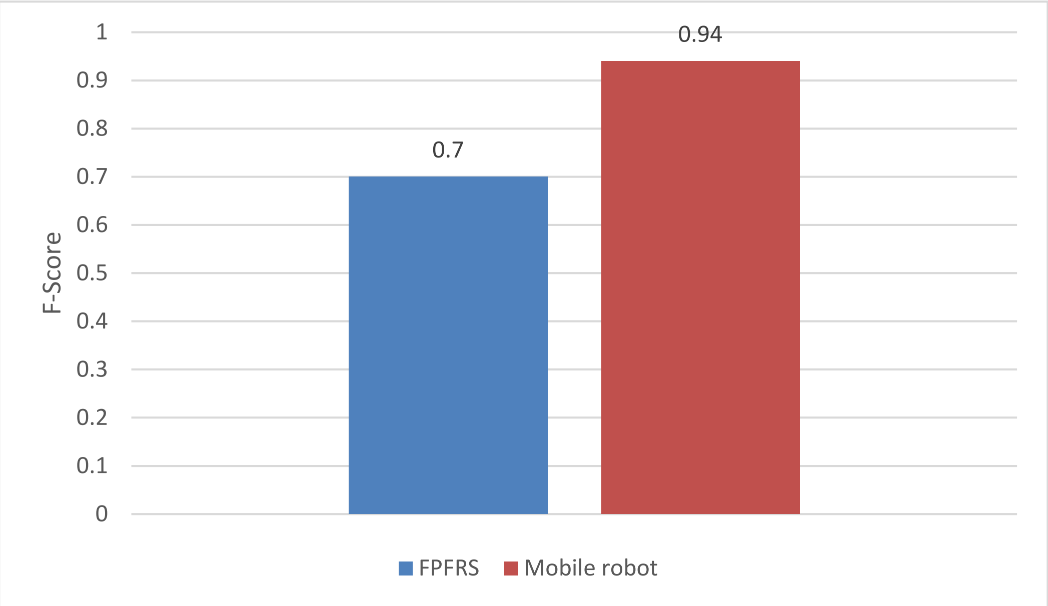


Figure 4.10 : F-scores from the experiments with different platform.

Regarding the different distances, interactions of the participants, and illumination in the indoor environment the f-score of the FPFRS was acceptable since due to fixed position of the camera. The f-score result of the FPFRS was lower than the mobile robot as expected. This test revealed that the tracking ability of the mobile robot made a difference in a good manner.

4.4.3.5 Results of the distributed system in relation to the distance

Test environment was divided into three regions according to the distance between the participants and FPFRS. This test came up with the aim of inspecting the role of the distance on the proposed distributed system.

Confusion matrix showing the actual and predicted people in relation to the distance in Table 4.39 - 4.41. In these tables P1 - P10 indicate the person identification number. U is used for unknown people and O is used for others.

Table 4.39 : Confusion matrix of scenario 1 - V Area FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**58**	-	-	-	-	-	-	-	-	-	3	-
	P2	-	**36**	-	-	1	-	1	-	-	-	-	4
	P3	-	-	5	-	-	1	-	-	-	-	**28**	2
	P4	-	-	-	**23**	-	-	-	-	-	-	-	1
	P5	-	-	-	-	**30**	4	-	-	-	-	1	1
	P6	-	-	-	-	-	**36**	-	-	-	-	1	4
	P7	-	-	-	4	-	-	**44**	-	-	-	2	1
	P8	-	-	-	-	-	-	-	**41**	-	-	4	10
	P9	-	-	-	-	1	-	-	-	**29**	-	2	-
	P10	-	-	-	1	2	-	-	-	-	**39**	1	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.40 : Confusion matrix of scenario 2 - S Area FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**49**	5	-	-	1	-	-	-	-	1	2	1
	P2	-	**32**	-	1	-	-	-	-	-	1	5	1
	P3	-	2	**25**	-	-	1	-	-	-	-	5	-
	P4	-	-	-	**28**	-	-	-	-	-	-	1	-
	P5	-	-	-	-	**22**	-	-	-	-	1	1	1
	P6	-	-	-	-	-	**39**	-	-	1	-	-	-
	P7	-	1	-	-	-	-	**39**	-	-	-	-	-
	P8	-	-	-	-	-	-	-	**36**	-	-	3	5
	P9	-	-	-	-	-	-	-	-	**13**	-	2	-
	P10	-	-	-	-	-	-	-	-	-	**36**	4	-
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.41 : Confusion matrix of scenario 3 - U Area FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**33**	8	-	-	-	-	-	-	-	1	7	1
	P2	-	**27**	-	3	-	1	-	-	-	1	19	3
	P3	-	3	**19**	-	-	3	-	-	-	2	16	9
	P4	-	-	-	**48**	-	-	-	-	-	-	-	-
	P5	-	-	-	-	**15**	2	-	-	-	-	4	4
	P6	-	-	-	1	-	**53**	-	-	-	-	2	5
	P7	-	-	-	8	-	-	**38**	-	-	-	1	2
	P8	-	-	-	-	-	-	-	**35**	-	-	2	10
	P9	-	-	-	-	-	-	-	-	**8**	-	2	-
	P10	-	-	-	2	2	-	-	-	-	**38**	-	1
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.42- 4.44 show the precision, recall, f-score and support results obtained from these confusion matrices.

Table 4.42 : Precision, recall, f-score and support results of scenario 1 - V Area FPFRS and the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.95	0.97	61
P2	1.00	0.86	0.92	42
P3	1.00	0.14	0.24	36
P4	0.82	0.96	0.88	24
P5	0.88	0.83	0.86	36
P6	0.88	0.88	0.88	41
P7	0.98	0.86	0.92	51
P8	1.00	0.75	0.85	55
P9	1.00	0.91	0.95	32
P10	1.00	0.89	0.94	44
U	-	-	-	-
O	-	-	-	-
Average/Total	0.97	0.81	0.85	422

Table 4.43 : Precision, recall, f-score and support results of scenario 2 - S Area FPFRS and the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.83	0.91	59
P2	0.80	0.80	0.80	40
P3	1.00	0.76	0.86	33
P4	0.97	0.97	0.97	29
P5	0.96	0.88	0.92	25
P6	0.97	0.97	0.97	40
P7	1.00	0.97	0.99	40
P8	1.00	0.82	0.90	44
P9	0.93	0.87	0.90	15
P10	0.92	0.90	0.91	40
U	-	-	-	-
O	-	-	-	-
Average/Total	0.96	0.87	0.91	365

Table 4.44 : Precision, recall, f-score and support results of scenario 3 - U Area FPFRS and the mobile robot.

	Precision	Recall	F-Score	Support
P1	1.00	0.66	0.80	50
P2	0.71	0.50	0.59	54
P3	1.00	0.37	0.54	52
P4	0.77	1.00	0.87	48
P5	0.88	0.60	0.71	25
P6	0.90	0.87	0.88	61
P7	1.00	0.78	0.87	49
P8	1.00	0.74	0.85	47
P9	1.00	0.80	0.89	10
P10	0.90	0.88	0.89	43
U	-	-	-	-
O	-	-	-	-
Average/Total	0.91	0.72	0.78	439

Figure 4.11 shows the comparison of the f-scores in relation to the distance.

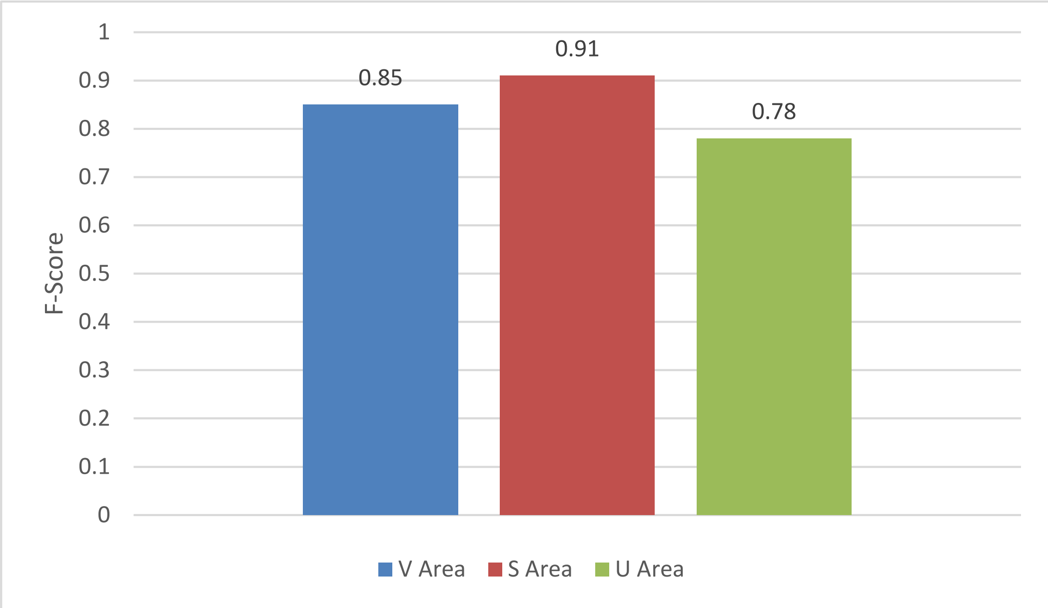


Figure 4.11 : F-scores from the experiments with different distances.

This test revealed that the distance metric matters on the distributed human identification system. Although the mobile robot decreases the effect of distance by taking advantage of mobility (explained in Section 4.4.3.4), the effects of the distance on the FPFRS was quite deadly (explained in Section 4.4.3.4). F-score results of the *V Area* and the *S Area* areas were acceptable. However, f-score result of the *U Area* showed that bad performance of the FPFRS affected overall result in a bad manner, even the mobile robot could not saved the f-score result.

4.4.3.6 Overall results of the distributed system

In this part overall achievement of all scenarios from different distances based on all platforms is investigated.

Confusion matrix showing the actual and predicted people for overall results of the distributed system in Table 4.45. In these tables P1 - P10 indicate the person identification number. U is used for unknown people and O is used for others.

Table 4.45 : Confusion matrix of combination of FPFRS and the mobile robot.

		Predicted											
		P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**U**	**O**
Actual	**P1**	**140**	13	-	-	1	-	-	-	-	2	12	2
	P2	-	**95**	-	4	1	1	1	-	-	2	24	8
	P3	-	5	**49**	-	-	5	-	-	-	2	49	11
	P4	-	-	-	**99**	-	-	-	-	-	-	1	1
	P5	-	-	-	-	**67**	6	-	-	-	1	6	6
	P6	-	-	-	1	-	**128**	-	-	1	-	3	9
	P7	-	1	-	12	-	-	**121**	-	-	-	3	3
	P8	-	-	-	-	-	-	-	**112**	-	-	9	25
	P9	-	-	-	-	1	-	-	-	**50**	-	6	-
	P10	-	-	-	3	4	-	-	-	-	**113**	5	2
	U	-	-	-	-	-	-	-	-	-	-	-	-
	O	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.46 show the precision, recall, f-score and support results obtained from the confusion matrix.

Table 4.46 : Precision, recall, f-score and support results of distributed system.

	Precision	**Recall**	**F-Score**	**Support**
P1	1.00	0.82	0.90	170
P2	0.83	0.70	0.76	136
P3	1.00	0.40	0.58	121
P4	0.83	0.98	0.90	101
P5	0.91	0.78	0.84	86
P6	0.91	0.90	0.91	142
P7	0.99	0.86	0.92	140
P8	1.00	0.77	0.87	146
P9	0.98	0.88	0.93	57
P10	0.94	0.89	0.91	127
U	-	-	-	-
O	-	-	-	-
Average/Total	0.94	0.79	0.85	1226

This test revealed that the proposed distributed human identification system achieved high f-score overall. In total 1226 images were captured from 10 participants using a FPFRS and a mobile robot within the 4 minutes for each experiments. F-score was acceptable in order to apply the distributed human identification approach to the other systems.

Since distributed human identification system have ability to take advantage of more than one platforms and devices to improve performance, the results of this experiment would be more likely to have higher f-scores if multiple mobile robots were used.

4.4.4 Results of the subjective evaluation

Participants evaluated the prototype, the proposed hybrid system and its applications including the mobile application demo. They learned the usage of system and completed the tasks easily. The button and the camera looked very similar, in the first sight this revealed that the interface of the prototype could be designed better and needs improvements in order to provide more user friendly interface. The participants found the mobile application very useful to handle tasks. In addition, they noticed that feedback of both mobile application and FPFRS were not enough when an error or unexpected action happened. PSSUQ results of the mobile application and FPFRS are given in Fig. 4.12, Fig. 4.13, Fig. 4.14, Fig. 4.15.

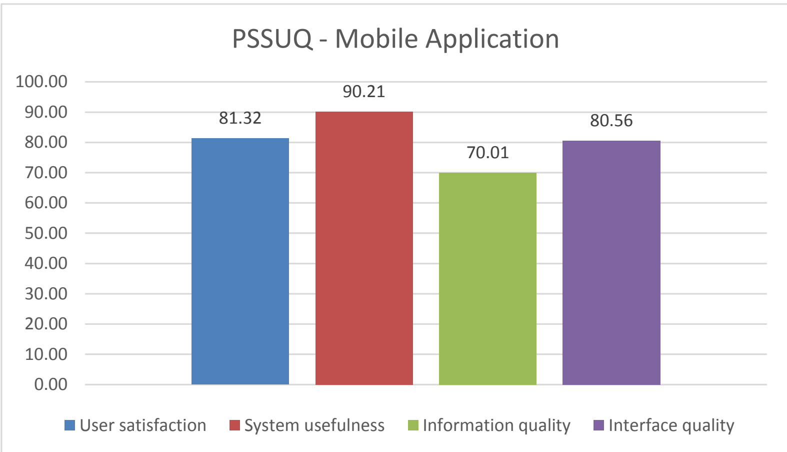


Figure 4.12 : Average PSSUQ results of the mobile application.

4.5 Discussion

Laboratory and real world experiments revealed that the more the person interacts with the distributed system, the more the distributed system will recognize the person with higher confidence. Performed experiments showed that best results are obtained from button triggered activation mode. Because the participants were so close to the camera and their role was acting like a visitor who came to visit. Thus, they did not move around and only looked at the camera in front of themselves.

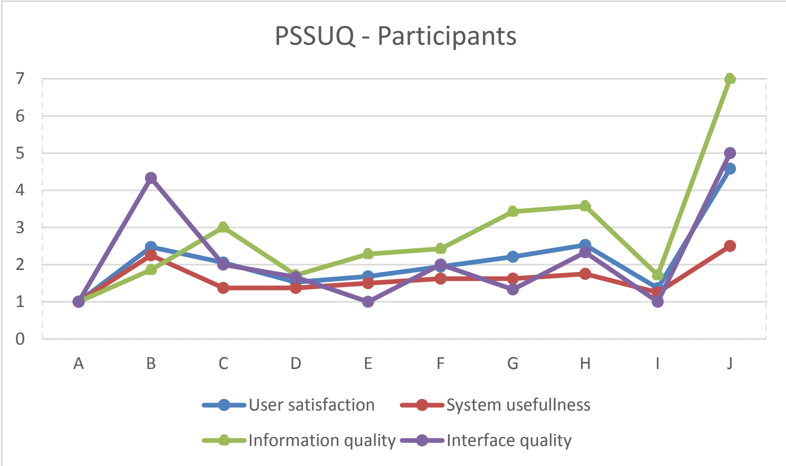


Figure 4.13 : Individual PSSUQ results regarding the mobile application.

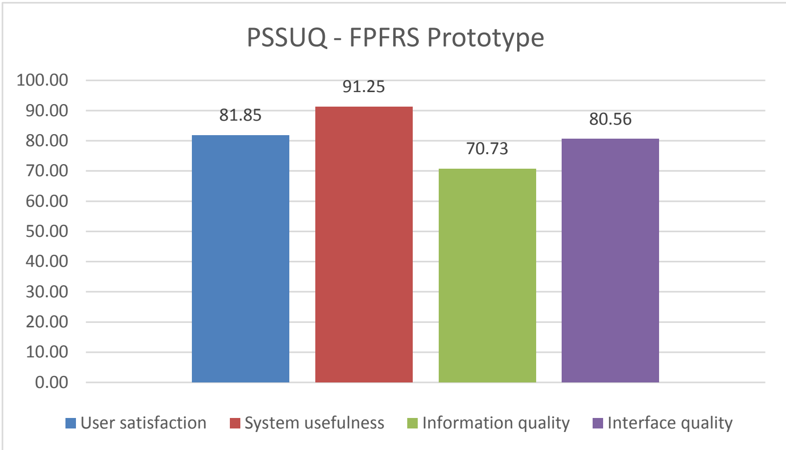


Figure 4.14 : Average PSSUQ Results of the FPFRS.

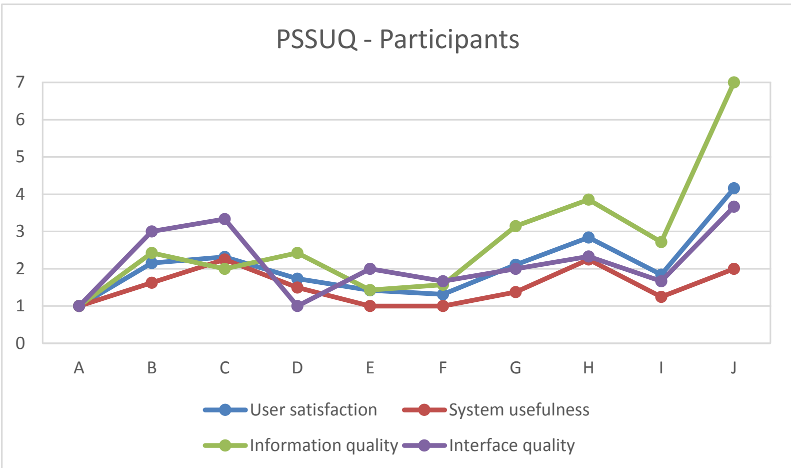


Figure 4.15 : Individual PSSUQ results reqarding the FPFRS.

Illumination effects the performance of the proposed system in the real world experiments. Additional light sources should be used to reduce the effect of the illumination.

Humans are a social beings. Mobile robot without interaction with the participant performed well. However, when the sociality and interaction were included to the mobile robot, most things such as the interactions of the participants, care of the participants and face recognition score all improved. Human-robot interaction was another striking side of the proposed hybrid system when the hybrid system was evaluated in terms of the contribution of the mobile robot. Robot-initiated dialog was intended to take a response from the participants. While interacting with the participants, the mobile robot also tracks their face. The participants gave different reactions to the robot, since they were attracted from robot's various behaviours. At the end of this experience, most of the participants stated that they would like to have new features such as an improved AI in the robot in order to speak and act more consciously, increasing capability of manoeuvre, and a moving head.

Nowadays using and carrying smart mobile phones instead of computers is more common among the people. So, the performance, capability of handling tasks, and interface of mobile application is very important. According to the PSSUQ, the participants were satisfied with the features of mobile application. However, it is not acceptable for the interface in terms of the responsive design. Yet, the results of PSSUQ and comments of the participants showed that the system could be improved to be more user friendly as well as handling more tasks.

5. CONCLUSIONS AND RECOMMENDATIONS

In this section main conclusions, practical applications of this study and future works are introduced in detail.

5.1 Main Conclusions

This study proved that face recognition with hybrid autonomous approach can be done practically. Many devices can be used to get information for face recognition in different ways. Robots patrol to detect human, FPFRS devices use camera and motion sensors to detect human. Both devices transfer informations to a server to make decisions for scenarios.

This study also showed that state of art techniques in face recognition can be applied to systems very easily. Improved OpenFace face recognition algorithm is nearly two times better than LBP face recognition algorithm according to precision.

In this study remote control of door and cameras are implemented as mobile application with tokenized security. Internet of things is new concept of making things smarter. However it causes security leaks. Therefore in this study a crypted unique token is created for each session. This is necessary to keep hackers out of system.

TurtleBot robot provided different kind of informations about environment. For example different poses of people that improved face recognition. So hybrid autonomous approach solved hard problems of face recognition.

5.2 Practical Applications of This Study

In this part real world examples of system are introduced as short scenarios and applications.

5.2.1 Smart home automation

System is very suitable for being a part of home automation. It has ability to lock door, view cameras etc. In addition it sends notifications to mobile phones.

5.2.2 Face recognition based pass systems

Generally in factories employee use cards to record their start time to work. They login to system with their cards. As a result of this thesis study, they can look a camera to login system instead of card usage. Someone can login other person's card which is not wanted by employer. If this system applied in this kind of places as a second level security, it will be much better.

5.2.3 Location detection and customer recognition in markets

Devices can be placed in special regions. Each device in special region suggests specific products according to customer's shopping behaviour. This study can be improved to recognize customers and can be applied to markets.

5.2.4 Serving as an autonomous patrolling security guard

Robot can be used to patrol in a route. FPFRS can be located at specific places and they can serve video surveillance with smart video record when motion sensor catches action.

5.2.5 Assistance and adaptations to security systems

Security guards have a route to patrol on determined time intervals. Some logger devices are located on the route to keep log of check in time of the security personnel. To realize this process the guard carries another device, which interacts with logger device. FPFRS can be used to keep logs of the security personnel and log information can be tracked via smart mobile phones. This provides more security when compared to old fashioned systems, because another person can pretend as security guard using device to cheat logger devices. In addition application of proposed system is easier than old systems in the perspective of tracking records and logs of the security guards.

5.2.6 Disabled people, elder people and babies tracking at home systems

People work for earn a living and sometimes they have to leave a relative, who is in need of care, alone. When people are at work or somewhere else, they are worried about that is everything okay at home. Proposed hybrid recognition system can be applied to reflect what is happening at home to property-owners' smart mobile phone.

House is divided into designated areas preferably rooms. FPFRS is planted to for each room. If FPFRS senses any motion, it begins to identification process. After person is recognized, location of the person in the room is estimated and this state is kept as state logs in a database.

If FPFRS could not sense any motion in a long time, mobile robot is called to aid to person.

5.3 Future Works

More kind of devices can be adapted to system. Their communication can be improved using Message Queuing Telemetry Transport (MQTT) [1] protocol. Near field communication (NFC) technology can be applied to system to transfer person's identification information for people who don't want to share facial photos with system. Applying If This Then That (IFTTT) [2] applets, which are triggered based on conditional statements of other platforms such as Weather Underground, Dropbox, Google, Nest, Spotify, Facebook, Hue etc., to proposed system means control of many things and data flow between many platforms. Therefore, IFTTT can be adapted to the prototype to make system more useful.

[1] http://mqtt.org

[2] https://ifttt.com

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APPENDICES

APPENDIX A.1

PREPARATION OF SYSTEM

In this section creating micro sd card for Raspberry Pi and installing required libraries and tools are introduced.

Setting Raspberry Pi Card

Raspbian Jessie is downloaded from official website of RPiF. File is unzipped to get operating system image file. That image file is written to micro sd card. Windows users can use Win32DiskImager program to handle writing process.

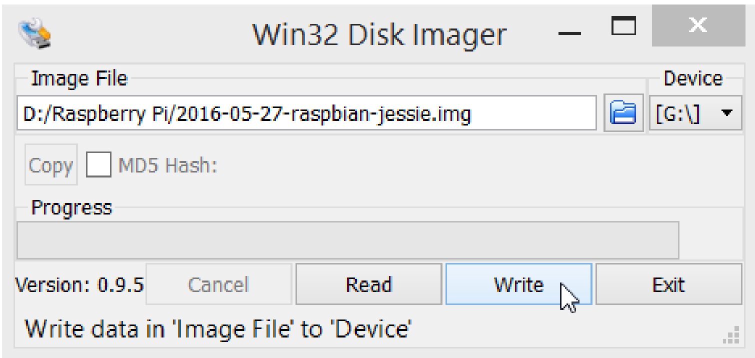

Figure A.1 : Win32DiskImager.

Connecting To Raspberry Pi

Raspbian Jessie loaded sd card is inserted to RPi. Screen and keyboard can be used here to apply settings. However for headless (without screen) RPi devices remote control systems are available. Device should be connected to internet. Ip address information of device should have known to connect. Windows users can use ip scanner tools or programs. RPi can be connected via SSH where login user is pi and password is raspberry. Windows users can use PuTTY program to connect. Connection is verified and device is ready to installing other tools.

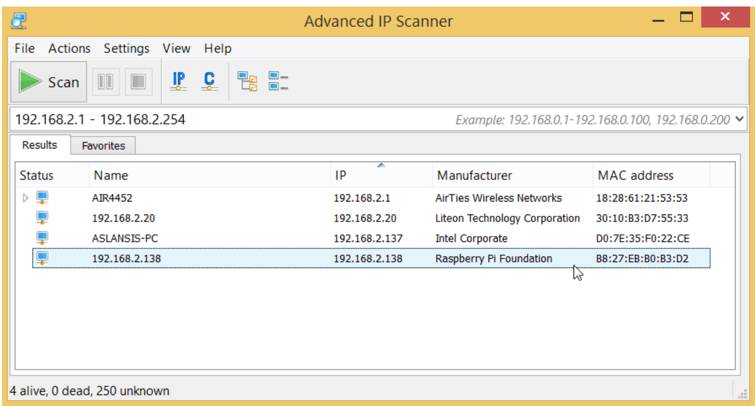

Figure A.2 : Advanced Ip Scanner.

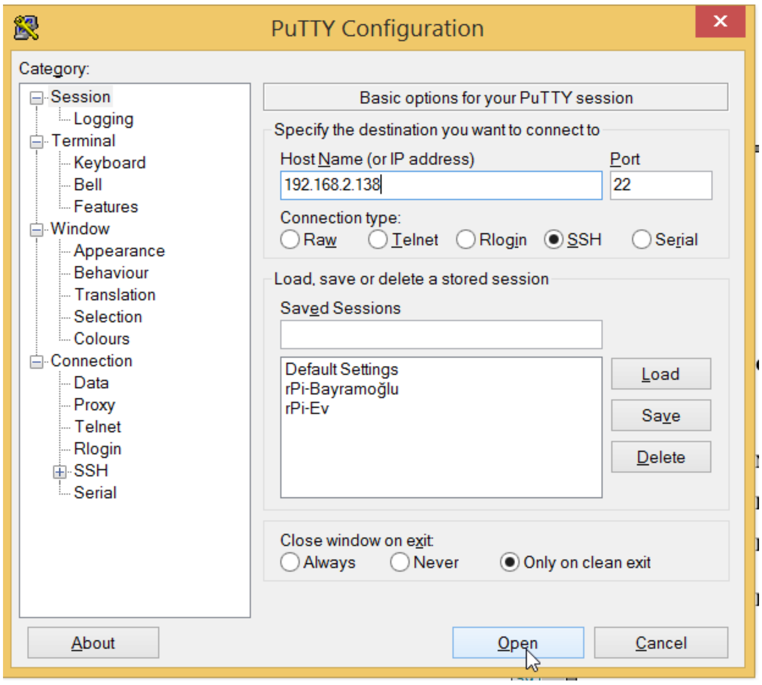

Figure A.3 : PuTTY.

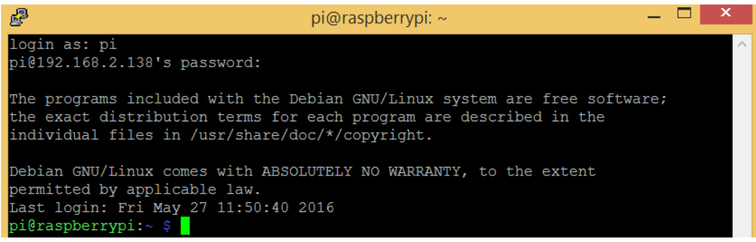

Figure A.4 : SSH Login.

Install Graphical Remote Control

XRDP is a graphical desktop sharing system which provides using screen as headless RPi screen. It uses tightvncserver and configures all things about connection.

```
sudo apt-get install xrdp
```

Network Settings

Connecting to local network and internet is very important for this system. To connect modem with password automatically, Raspberry Pi needs modification on network settings. This is done by following commands.

```
sudo nano /etc/network/interfaces
sudo nano /etc/wpa_supplicant/wpa_supplicant.conf
```

Web Server Installation

Web server is used to communicate devices thanks to web services. Each device including Raspberry Pi, TurtleBot robot and Linux Server Pc need web server in this system.

Apache Web Server Installation

System needs PHP web server. Apache is suitable to devices in this system. Therefore Apache is chosen to be used.

```
sudo apt-get install apache2 -y
sudo apt-get install mysql-server -y
sudo apt-get install php5 -y
sudo apt-get install php5-mysql -y
```

Phpmyadmin Setup

```
sudo bash
apt-get install phpmyadmin
nano /etc/apache2/apache2.conf
```

Include /etc/phpmyadmin/apache.conf

```
/etc/init.d/apache2 restart
mysqladmin -u root password 'pass'
```

Yii Settings

```
sudo chmod -R 777 /var/www/esasp/protected/runtime
sudo chmod -R 777 /var/www/esasp/assets
```

Mod Settings

```
sudo a2enmod rewrite
sudo nano /etc/apache2/sites-enabled/000-default
```

CHANGE - OLD Options Indexes FollowSymLinks MultiViews AllowOverride None
CHANGE - NEW Options Indexes FollowSymLinks MultiViews AllowOverride All

```
sudo service apache2 restart
```

Apache System Command Settings

```
sudo pkexec visudo
www-data ALL=(/var/www/) NOPASSWD: ALL
```

Python and OpenCV Setup

```
sudo apt-get install build-essential cmake pkg-config
sudo apt-get install libjpeg8-dev libtiff4-dev
libjasper-dev libpng12-dev
sudo apt-get install libgtk2.0-dev
sudo apt-get install libavcodec-dev libavformat-dev
sudo apt-get install libswscale-dev libv4l-dev
sudo apt-get install libatlas-base-dev gfortran
wget https://bootstrap.pypa.io/get-pip.py
sudo python get-pip.py
sudo pip install virtualenv virtualenvwrapper
sudo rm -rf ~/.cache/pip
```

Then, update /.profile file to include the following lines:

```
# virtualenv and virtualenvwrapper
export WORKON_HOME=$HOME/.virtualenvs
source /usr/local/bin/virtualenvwrapper.sh
```

Reload .profile file:

```
source ~/.profile
mkvirtualenv cv

sudo apt-get install python2.7-dev
pip install numpy

wget -O opencv-2.4.10.zip
http://sourceforge.net/projects/opencvlibrary/
files/opencv-unix/2.4.10/opencv-2.4.10.zip/download
unzip opencv-2.4.10.zip
cd opencv-2.4.10

mkdir build
cd build
cmake -D CMAKE_BUILD_TYPE=RELEASE -D
 CMAKE_INSTALL_PREFIX=/usr/local -D
 BUILD_NEW_PYTHON_SUPPORT=ON -D INSTALL_C_EXAMPLES=ON -D
 INSTALL_PYTHON_EXAMPLES=ON  -D BUILD_EXAMPLES=ON ..

make

sudo make install
sudo ldconfig
```

Find where the cv2.so is, for example /usr/local/lib/python2.7/dist-packages, then add this into /.bashrc by doing:

```
sudo gedit ~/.bashrc
```

and add

```
export
PYTHONPATH=/usr/local/lib/python2.7/dist-packages:$PYTHONPATH
```

in the last line. And then remember to open another terminal, this can work.

```
cd ~/.virtualenvs/cv/lib/python2.7/site-packages/
ln -s /usr/local/lib/python2.7/site-packages/cv2.so cv2.so
ln -s /usr/local/lib/python2.7/site-packages/cv.py cv.py
```

```
workon cv
python
>>> import cv2
>>> cv2.__version__
'2.4.10'
```

Dlib Install

```
sudo apt-get install cmake
sudo apt-get install libboost-python-dev
wget http://dlib.net/files/dlib-19.2.tar.bz2
tar jxf dlib-19.2.tar.bz2
cd dlib*
sudo python setup.py install
pip install dlib
```

APPENDIX A.2

Post Study System Usability Questionnaire (PSSUQ)

1. Overall, I am satisfied with how easy it is to use this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

2. It was simple to use this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

3. I could effectively complete the tasks and scenarios using this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

4. I was able to complete the tasks and scenarios quickly using this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

5. I was able to efficiently complete the tasks and scenarios using this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

6. I felt comfortable using this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

7. It was easy to learn to use this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

8. I believe I could become productive quickly using this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

9. The system gave error messages that clearly told me how to fix problems.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

10. Whenever I made a mistake using the system, I could recover easily and quickly.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

11. The information (such as on-line help, on-screen messages and other documentation) provided with this system was clear.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

12. It was easy to find the information I needed.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

13. The information provided for the system was easy to understand.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

14. The information was effective in helping me complete the tasks and scenarios.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

15. The organization of information on the system screens was clear.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

16. The interface of this system was pleasant.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

17. I liked using the interface of this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

18. This system has all the functions and capabilities I expect it to have.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

19. Overall, I am satisfied with this system.

a. Prototype of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**
b. Mobile Application of FPFRS	**Strongly Agree**	1	2	3	4	5	6	7	**Strongly Disagree**

Comments:

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Aslan, E. S., Özdemir, Ö. F., Hacıoğlu, A., & İnce, G. (2016, May). Smart pass automation system. In *Signal Processing and Communication Application Conference (SIU), 2016 24th* (pp. 225-228). IEEE.