

**LOCALIZATION OF RADIO SOURCES USING AUTONOMOUS
UNMANNED AERIAL VEHICLES FOR SEARCH
AND RESCUE APPLICATIONS**



M.Sc. THESIS

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Aeronautics and Astronautics Engineering Programme

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**ARAMA VE KURTARMA UYGULAMALARI İÇİN
OTONOM İNSANSIZ HAVA ARAÇLARI İLE RADYO KAYNAKLARININ
KONUMUNUN TESPİTİ**

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To my fiancée and my family,



FOREWORD

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ABBREVIATIONS

AOA	: Angle of Arrival
COTS	: Commercial-Off-the-Shelf
DOF	: Degrees of Freedom
EKF	: Extended Kalman Filter
FFT	: Fast Fourier Transform
GPS	: Global Positioning System
GUI	: Graphical User Interface
INS	: Inertial Navigation System
ISR	: Intelligence, Surveillance and Reconnaissance
KF	: Kalman Filter
LOS	: Line of Sight
NLOS	: Non-Line of Sight
PF	: Particle Filter
RC	: Remote Control
RF	: Radio Frequency
RSS	: Received Signal Strength
RSSI	: Received Signal Strength Indicator
SDR	: Software Defined Radio
SIL	: Software-In-the-Loop
TCP	: Transmission Control Protocol
TDOA	: Time Difference of Arrival
TOA	: Time of Arrival
TOF	: Time of Flight
UAV	: Unmanned Aerial Vehicle
UDP	: User Datagram Protocol
UHF	: Ultra High Frequency
UKF	: Unscented Kalman Filter



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LOCALIZATION OF RADIO SOURCES USING AUTONOMOUS UNMANNED AERIAL VEHICLES FOR SEARCH AND RESCUE APPLICATIONS

SUMMARY

In this thesis, the utilization of unmanned aerial vehicles (UAV) in the search and rescue operations is studied based on the radio frequency (RF) signal sources. Considering the significant improvements on the unmanned systems over the last twenty years, the usage of the UAVs can be convenient in terms of operational risks, cost and human resource requirements in the search and rescue operations. Particularly, the searching time of the target can be critically decreased with utilization of the UAVs. Taking advantages of the UAVs, an efficient and low-cost searching and localization algorithm is presented based upon the searching target emits the RF signals.

In the proposed solution to the search and rescue problem, each UAV is equipped with software defined radios (SDR) in order to receive the RF signal emitted from the RF signal source. Based on the conditions of the given problem, a frequency detection algorithm is presented using signal processing techniques to measure correct received signal strength (RSS) values in the propagation frequency of the RF source. In addition to that, free-space signal propagation model is modified with experimental signal strength measurements and it is utilized in the conversion from the signal strength to the approximated distance between the RF source and the UAVs for position estimation.

The estimation of the position of the RF source is performed by using recursive state estimation methods. At the beginning, deterministic localization methods are investigated. However, these techniques such as trilateration do not perform good localization results due to the RF signal noise. For this reason, an extended Kalman filter (EKF) based position estimation method is developed for multiple UAVs. Since this method requires multiple measurements from at least three UAVs, another position estimation method based on the particle filter (PF) is proposed for single UAV to make the elapsed time in the searching of the target more efficient.

In order to test the developed localization process, two software-in-the-loop (SIL) environments are developed with different specifications. These environments are supported with experimental tests and the models running in the environments are improved using the experimental tests to get more realistic simulation results.

At the end of the study, a genuine complete architecture of the system with hardware and software components is given to implement the proposed searching and localization methodology. In addition to the given hardware architecture which consists of completely commercial-off-the-shelf (COTS) devices, the developed software architecture proposes an efficient, easy to use solution to the search and rescue problem. Finally, the SIL test results are conducted in order to test the proposed methodology.



ARAMA VE KURTARMA UYGULAMALARI İÇİN OTONOM İNSANSIZ HAVA ARAÇLARI İLE RADYO KAYNAKLARININ KONUMUNUN TESPİTİ

ÖZET

Otonom sistemler konusunda gelişmeler ile birlikte insansız hava araçlarının kullanımı ciddi bir artış göstermektedir. Özellikle son 20 yıldaki gelişmeler dikkate alındığında, insansız hava araçları askeri uygulamalardan sivil uygulamalara çok geniş bir kullanım alanına yayılmıştır. Günümüzde uygun maliyetli ve çok çeşitli boyutta hava araçlarının üretimi ile birlikte, insansız hava araçları birçok noktada geleneksel hava araçlarına göre çok daha avantajlı hale gelmektedir.

Tarihte insansız hava araçlarının bilinen ilk kullanımı 19. yy. ın sonlarına dayanmaktadır. Başlangıçta askeri eğitimlerde hedef olarak kullanılan insansız hava araçları, özellikle İkinci Dünya Savaşı ile birlikte farklı bir önem kazanmıştır. 1950'lerin sonunda başlatılan programlarla birlikte insansız hava araçlarının istihbarat, gözetleme ve keşif görevleri için uygun hale getirilmesi planlanmıştır. Özellikle Soğuk Savaş döneminde, insan kaybı riski yerine insansız araçların tercihi hem daha güvenli hem de daha az maliyetli askeri operasyonları mümkün hale getirmiştir.

İnsansız hava araçlarının kullanımı, 21. yy. ın gelişi ile birlikte farklı bir boyuta ulaştı. Hem askeri alandaki insansız hava araçlarının silahlandırılması konusundaki çalışmalar hem de sivil alandaki yeni kullanım alanlarının oluşması insansız hava araçları üretiminin artmasına ve çok daha uygun maliyetli yeni tasarım ve sistemlerin çıkmasına yol açtı. Bu gelişmeler yüksek maliyete sahip olan, eğitilmiş insana ihtiyaç duyan ve insandan kaynaklanan hata ve risklere sahip arama-kurtarma operasyonlarının da seyrini değiştirdi. Bu durum, özellikle çoklu hava aracına sahip insansız hava araçları sistemlerinin arama-kurtarma operasyonlarında kullanılması konusunda yeni çalışmaların çıkmasına neden oldu.

Arama-kurtarma operasyonlarında en çok öne çıkan problemlerden birisi hedefin tespit edilmesidir. Genellikle arama bölgesi geniş mesafelere yayıldığında hedefin tespiti ciddi anlamda zorlaşmaktadır. Ayrıca, arama-kurtarma operasyonlarının genellikle zamana karşı yarışılan durumlar olması hedefin bir an önce bulunmasını daha önemli hale getirmektedir. Dolayısıyla hedefin tespiti ciddi ve çözülmesi gereken bir problem haline gelmektedir. Bu problemin çözümü olarak literatürde en çok sunulan yöntemlerden birisi görüntü üzerinden hedefin tespitini içeren yöntemlerdir. Bu yöntemlerde insansız hava araçlarındaki normal veya termal kameralar yardımıyla alan taranarak hedefin tespit edilmesi amaçlanmaktadır. Fakat, bu yöntem özellikle arama alanı geniş bir bölgeye yayıldığında verimsiz hale gelmektedir. Daha geniş bir bölgenin taranması amacıyla insansız hava araçlarının yüksek irtifada uçuşması gerekmektedir. Bu durum elde edilen görüntülerin çözünürlüğünün artırılması gerekliliğini ortaya çıkarmaktadır. Fakat, insansız hava araçlarının yük taşıma kapasiteleri ve uçuş süreleri göze alındığında, hava araçlarının üzerindeki kullanılan cihazların hesaplama yetenekleri kısıtlıdır. Buna alternatif olarak bazı çalışmalarda

elde edilen görüntü, yer istasyonuna gönderilerek burada hedef tespiti sunulmuş fakat bu çözüm de geniş alana yayılmış insansız hava araçları ile haberleşme problemi olduğunda verimsiz kalmaktadır. Bir başka alternatif olarak çok sayıda hava aracının kullanılması gerektiği ortaya çıksa da bu durum hem maliyet açısından hem de tasarlanacak sistemin kontrolünün karmaşıklığı açısından çok tercih edilebilir değildir.

Arama-kurtarma operasyonlarında hedefin tespiti konusunda önce çıkan bir diğer yöntem ise radyo sinyalleri kullanılarak hedefin konumunun belirlenmesini sağlayan yöntemlerdir. Arama-kurtarmada aranılan hedefin radyo sinyali yayabilecek bir cihaz taşıdığı (cep telefonu, telsiz vb.) kabul edilen bu tarz çalışmalarda, insansız hava araçlarına yerleştirilen ölçüm cihazları ile birlikte radyo sinyali üzerinden açı (yön), zaman ve mesafe gibi niceliklerinin hesaplanması ile çeşitli yöntemler geliştirilmiştir. Bu yöntemlerden zaman bazlı olanlar, GPS'in çalışma mantığına benzer olarak, sinyalin vericiden alıcıya varış zamanının kestirimine dayanmaktadır. Birden fazla referans noktasından zaman kestirimi kullanılarak hedefin konumunun kestirimi gerçekleştirilmektedir. Ayrıca bu tarz yöntemler, özellikle referans ölçüm noktalarının (insansız hava araçlarının) birbirleri senkronize olduğu kabulüne dayanmaktadır. Fakat, bu noktaların birbirlerinden uzak olduğu durumlarda senkronizasyonu sağlamak haberleşme açısından zor olduğu gibi radyo sinyalinin görüş alanının açık ve net olması gerekliliği, bu tarz yöntemler için bir diğer önemli kısıttır.

Hedefin konumunun tespiti konusunda öne çıkan bir diğer yöntem ise radyo sinyalinin yönünün tespit edilmesine dayanan çözümlerdir. Genellikle yönlü antenler kullanılarak ölçülen radyo sinyalinin yönü/açısı tespit edilerek, çeşitli geometrik ve yaklaşım yöntemleri ile radyo sinyal kaynağının tespiti amaçlanmaktadır. Sinyal açısına dayanan yöntemlerde göze çarpan en önemli problem, konum kestirim hatası mesafe arttıkça ciddi oranda artmaktadır. Bununla birlikte, tek bir açı kestirimi bile oldukça uzun zaman alabilmektedir. Bu durum, arama-kurtarma operasyonlardaki tespit süresinin önemi ile çelişmektedir.

Radyo sinyallerinin kullanımı ile konum kestirimi konusunda çok tercih edilen bir diğer alternatif ise sinyal gücüne dayanan yöntemlerdir. Alıcı tarafta ölçülen sinyal gücünü kullanan bu yöntemler, sinyal yayılım modellerinin yardımıyla hedef ile alıcı/alıcılar arasındaki mesafenin kestirilmesi mantığına dayanır. Diğer yöntemlere göre karmaşık ölçüm sistemi veya senkronizasyon gerekliliği olmayan bu teknikteki en önemli problem sinyal yayılımının modellenmesinin zor olmasıdır. Radyo sinyali çevresel bir çok etkenden etkilenebileceği gibi, verici ve alıcı taraftaki kaynaklanan gürültüler de sinyal gücü üzerinde oldukça etkilidir. Gürültülü sinyaller üzerinden konum kestirimi başarısının artırımı amacıyla en çok tercih edilen yöntemler ise yinelemeli durum kestirim yöntemleridir. Özellikle bu alandaki Kalman filtrelerinin oldukça başarılı iş çıkarması, konum kestiriminde bu tarz filtrelere dayanan pek çok yöntemin ortaya çıkmasına neden olmuştur.

Bu tez çalışmasında, yukarıda bahsedilen arama-kurtarma problemlerinin çözümü amacıyla çoklu insansız hava aracı sistemi ve radyo sinyallerinin tespitinden yola çıkılarak etkili ve uygun maliyetli bir arama ve konum tespit yöntemi sunulmuştur. Sunulan çalışmada, insansız hava araçları sistemlerinin kalkıştan operasyonun sonuna dek tamamen otonom olarak hareket etmesiyle birlikte, geliştirilen yapı piyasadan hazır temin edilebilen malzeme donanım parçalarından ve özgün olarak geliştirilen yazılım parçalarından oluşmaktadır.

Çalışmada, öncelikle sinyal ölçümündeki belirsizlikler ve problemlerin çözümü amacıyla geliştirilen algoritmalar sunulmuştur. Temel alınan arama-kurtarma operasyonuna göre arama hedefinin bir el telsizi taşıdığı ve bu telsizden radyo sinyalleri yaydığı kabul edilmiştir. Buna göre, her insansız hava aracına radyo sinyalinin ölçümü amacıyla bir adet yazılım tabanlı radyo yerleştirilerek, bu radyolar hava araçlarına bulunan Raspberry Pi görev bilgisayarlarına bağlanmıştır. Hesaplama gerekliliği olarak verimli ve hafif olduğu için RTL-SDR V3 cihazı tercih edilmiştir. Bununla birlikte, RTL-SDR V3 farklı programlama dillerinde geliştirilmiş birçok açık kaynaklı yazılım tarafından desteklenmektedir. Yazılım tabanlı radyo alıcılar kullanılarak ölçülen radyo sinyalinden, Hızlı Fourier Dönüşümü gibi sinyal işleme teknikleri kullanılarak sinyal gücü hesaplanmaktadır. Ayrıca, kabul edilen arama-kurtarma senaryosuna göre sinyal kaynağının frekansı bilinmediği için frekans spektrum analizine dayanan bir radyo sinyali frekans tespit algoritması da geliştirilmiştir. Buna ek olarak bu çalışmada, konum kestiriminde kullanılması amacıyla elde edilen sinyal gücü değerlerinin mesafeye dönüştürülmesini sağlayan bir sinyal yayılım modeli sunulmuştur. Serbest uzay yayılım modeli baz alınarak geliştirilen bu yayılım modelinde, serbest yayılım modelinin içermediği radyo sinyali özelliklerini (yerden yansıma, gölgeleme etkisi vb.) dahil etmek amacıyla sinyal ölçüm testleri yapılmış ve sinyal modeli buna göre modifiye edilmiştir.

Sinyal gücü ölçümü kullanılarak radyo sinyal kaynağının konumunun kestirimi amacıyla, başlangıç olarak deterministik yöntemler denenmiş fakat bu tarz yöntemler sinyal gücündeki gürültünün çok fazla olması nedeniyle başarılı sonuç vermemiştir. Bu nedenle, konum kestirimi için Bayes filtre teorisine dayanan yinelemeli durum kestirim yöntemleri kullanılmıştır. Önerilen çözümde çoklu insansız hava aracının bulunması avantajından faydalanılarak, genişletilmiş Kalman filtresi yardımıyla ölçülen sinyal gücü değerleri, sinyal modeli ve her insansız hava aracının konum bilgisi kullanılarak konum kestirim yöntemi geliştirilmiştir. Geliştirilen bu çözüm en az üç insansız hava aracından, sinyal ölçümü alabilmesine dayanmaktadır. Fakat, sinyal ölçüm testlerinde farkedildiği üzere kullanılan yazılım tabanlı radyonun belirli mesafeler üzerinde sağlıklı sonuçlar vermemesi üzerine insansız hava araçlarının ölçümleri limitlenerek yanlış ölçümlerden kaynaklanan hatalarının önüne geçilmesi planlanmıştır. Bu kısıtlama konum kestirimi açısından başarıyı artırmasına rağmen tespit süresinin kritik olduğu arama-kurtarma operasyonlarına üç insansız hava aracının da sinyal menziline girmesini beklemek oldukça zaman alan bir süreçtir. Bu nedenle, tek bir insansız hava aracı ile sinyal konum tespitini mümkün kılmak ve diğer insansız hava araçları sinyal menziline girene kadar geçen süreyi verimli kullanmak amacıyla parçacık filtresi kullanılan bir diğer konum kestirim yöntemi geliştirilmiştir. Sonuç olarak, geliştirilen her iki konum kestiriminin ortak çalışabileceği ve hem tek insansız hava aracı hem de birden fazla insansız hava aracının sinyal menziline olduğu durumlar için geçerli bir arama ve lokalizasyon algoritması geliştirilmiştir.

Geliştirilen sistemin dış ortam uçuş testleri öncesinde test edilmesi ve uçuş testlerindeki ortaya çıkacak sorunların minimize edilmesi amacıyla farklı özelliklere sahip iki yazılımsal benzetim ortamı tasarlanmıştır. Tasarım sürecine X-Plane 10 uçuş simulatörü kullanılarak insansız hava araçlarının görselleştirilmesi sağlanan kompleks fakat görsel kalitesi yüksek bir benzetim ortamı ile başlanmıştır. Çalışmanın ilerleyen dönemlerinde, bu tasarımın en az üç yüksek sistem gereksinimlerine sahip bilgisayara ihtiyaç duyması ve test hazırlık sürecinin karmaşık ve uzun olması sebebiyle çok daha kompakt ikinci bir tasarıma gidilmiştir. Geliştirilen alternatif tasarımda, tek bir

Windows işletim sistemli bilgisayarda Ubuntu sanal makineler kullanılarak insansız hava araçlarının simüle edilmesi sağlanmış ve hem test başlatma zamanı hem de donanımsal gereklilik açısından ilk versiyondan daha verimli bir yazılımsal benzetim ortamı elde edilmiştir.

Bu tez çalışmasında, yazılımsal benzetim ortamlarına ek olarak, geliştirilen arama ve konum belirleme algoritmasını gerçeklemek için tasarlanan donanımsal mimari verilmiştir. Donanımsal mimari, hemen hemen bütün parçaları piyasadan hazır olarak temin edilebilen aviyonik tasarıma sahiptir. Bununla birlikte kullanılan donanımsal mimari üzerinde çalışan özgün bir yazılımsal mimari de sunulmuştur. Yazılımsal mimari, geliştirilen sinyal ölçümü ve tespiti ile tüm süreci otomatize hale getiren arama ve konum belirleme algoritmasının gerçeklemesini de içermektedir. Ayrıca, istenilen insansız hava aracından canlı görüntü almak amacıyla görüntü aktarım ve alım yazılımları da geliştirilerek bütün sistemin yer istasyonunda yine özgün olan bir kullanıcı arayüzü tarafından takibi amaçlanmıştır. Çalışmanın sonunda, geliştirilen algoritmaların tasarlanan yazılımsal benzetim ortamındaki test sonuçları verilmiştir.

1. INTRODUCTION

With the development of autonomous systems, the autonomous vehicles that can localize itself in an environment become more important. In addition to that, not only the localization of an autonomous vehicle but also the environmental awareness of the vehicle is essential in order to survive in an unknown environment or to accomplish searching missions. As a part of unmanned systems, unmanned aerial vehicles or drones have more advantage than other types of unmanned vehicles in terms of having more sensing range and freedom of movement. On the other hand, unmanned aerial vehicles have important drawbacks such as flight (mission) time and payload insufficiency. In order to cope with these handicaps, there are a lot of studies from efficient aircraft designs to optimized flight path plannings in order to increase flight time and payload capacity or diversity. Based on these improvements, UAVs have been gaining significant popularity in various application areas.

From the beginning of the 1900s to 1950s, UAVs were generally used as shooting decoy in military personnel training. After World War II, the U.S. Air Force started a new program with intent to use unmanned aircraft in Intelligence, Surveillance and Reconnaissance (ISR) missions [5]. Despite having high loss rate and limited survivability according to most manned aircrafts, the unmanned aircrafts were actively used in the ISR missions since they are cost efficient. Also, taking the risk of losing an unmanned aircraft is more acceptable than losing pilot with manned aircraft in terms of both cost and losing trained personnel.

The 21st century has been brought more application areas to unmanned aircraft world. At the beginning of the 2000s, UAVs are weaponized and used to strike critical enemy targets in military operations [6]. Currently, armed unmanned aerial vehicles have been used actively in service by some countries such as the USA, China, Turkey and being developed by many others [7].

With the beginning of the 2000s, another massive development of the unmanned aerial systems is civil and commercial applications. Particularly, the innovations on UAVs

bring new aspects of usage and the technological developments make cost-efficient and reliable UAVs or drones possible. As a result of research and development studies on UAVs, many utilization opportunities show up from logistics to aerial photography [8]. Therefore new solutions are developed with the utilization of the UAVs and proposed in order to solve some generic problems such as search and rescue problems by adding more sensing capabilities to UAVs [9], [10] or wildlife tracking problems [11], [12], [13].

1.1 Motivation

Currently, the search and rescue operations are mostly performed using airplanes and helicopters. However, the utilization of the human controlled aircrafts has some operational risks and significant cost [14]. For this reason, the UAVs can be utilized particularly in the searching stage of the search and rescue operations. Since they require less operational cost than the human controlled aircrafts, it is possible to perform more cost efficient searching operations. Also, they have more acceptable operation risks and they are more preferable in the bad weather conditions with proper UAV type instead of risking a human controlled aircraft. The work presented in this thesis contains the utilization of the UAVs in the search and rescue operations.

One of the main objectives of the search and rescue operations is the localization of the searching target. Based on the sensing and payload capability of unmanned aircraft, many methods are developed with utilization of the related hardware equipment. One of the most preferred methods is vision-based methods by using onboard visual or thermal cameras (e.g., IR cameras) [15], [16], [17]. However, the vision-based methods become infeasible in the perspective of computational cost and searching time particularly when the searching area is large. In such a scenario, the searched area must be maximized in a short time period due to the flight time of the UAVs.

Another approach in the localization of the searching target is using RF signals as the RF signals can be propagated to kilometers away. The systems relies on RF the signal, have two main sides such as transmitter and receiver. In these systems, the searching target or signal source usually represents the transmitter and UAVs receives this RF signal with onboard RF measurement units.

1.2 Literature Review

In the RF-based localization, current approaches are separated from each other in terms of some key aspects such as the utilization of the RF signal and the preferred techniques to estimate the position of the RF source. One of the most important key points in the RF-based localization is the obtainment of the raw signal data based on the preferred type of sensor. The first option is the measurement of the arrival time of the RF signal using time measurement sensors. Using the time measurements, time-based methods are proposed to locate the RF signal. These methods have similar working principle as the Global Positioning System (GPS). Since the radio waves propagate at the speed of light, the distance between receiver and transmitter can be estimated using the time information of the RF signal arrival. Based on this concept, one of the leading techniques is the Time of Arrival (ToA) localization technique which relies on the arrival time of the RF signal which travels from the RF source to at least 3 reference receiver points [18]. Although the TOA technique offers highly accurate localization results in theory, it is hard to ensure the time synchronization between the source and the receivers in the real world applications. To overcome this drawback, the Time Difference of Arrival (TDoA) technique, which is similar to ToA, is presented. This technique uses the time differences between the detection of the RF signal at the synchronized receivers [18]. Also, the source doesn't have to be synchronized with the receivers which makes TDoA more feasible than ToA in the real world applications. Based on this technique, there are some studies about the RF-based localization in both indoor [19] and outdoor applications [20]. However, the synchronization requirement between the receivers becomes a very important issue particularly in the long-range UAV applications where there are communication constraints between them. Also, the line-of-sight (LOS) condition between the source and the receivers has another important effect on the TDoA localization results [19].

Another option is the estimation of the bearing angle or the direction of the RF signal. The localization of the RF sources with direction based approach is highly popular both indoor [21], [22] and outdoor applications [11], [13]. This concept is also called as direction finding problem which can be considered from different perspectives. Preferred direction finding technique is generally correlated with the used hardware equipment mounted on the UAV. Using a group of mounted antennas and the phase

difference of the received signal, a common direction finding technique is called as pseudo-Doppler direction finding is presented. This technique is implemented on UAVs with a constellation of four rapidly switched onboard antennas to measure the line of bearing [23]. In addition to that, it is possible to estimate the bearing angle using the polarization property of the directional antennas. As the antenna gain is higher in the direction, where the antenna is pointing at, the received signal strength will also be higher in that direction. Therefore, change on the received signal strength can be used in the bearing estimation. This technique is applied on both ground [21], [24] and aerial robot applications [25], [26]. Realization of the bearing estimation is generally performed using multiple antennas. Furthermore, some researchers have studied about the estimation of the bearing angle using yaw control of a quadrotor [22]. In this case, the quadrotor keeps rotating at a constant altitude and estimates bearing angle using signal strength measurements from a directional antenna. The constant rotation of the quadrotor removes the requirement of using a gimbal mechanism to rotate the antenna. However, this makes the control loops more complicated and limits the translational movement and range of the quadrotor.

The most important drawback on the direction based approaches is the error becomes bigger when the distance between the RF source and the UAVs are large if the direction finding system has lower precision [27]. Also, some works showed that long time might be required to make a single bearing estimation [13]. This makes the mission planning and the flight time of the UAVs more important in the search and rescue applications. Therefore, the optimization of the searching path planning is also another addressed problem in the literature [11], [28], [29], [30].

Received signal strength is used not only to estimate bearing angle, but also to estimate the distance between the RF source and the UAVs. In theory, the distance can be calculated using the RF propagation principles with knowledge of some parameters such as signal frequency, transmitter power etc. However, the RF propagation is a complex phenomenon and highly affected by the environmental conditions [2], [28]. Further, this complexity makes the modeling of the RF signal propagation harder if the environment is complex. In order to cope with the hardness of the modeling issues, a base path-loss or propagation model is utilized and improved with generally experimental measurements [31]. The irregularities of the RF signal propagation can

be added to the model as additive noise in Gaussian, Rayleigh or Rician distribution [32]. Also, the optimization of the measurement hardware is another addressed issue to get unique signal strength measurements from corresponding distances [33].

On the other hand, some researchers prefer signal strength mapping technique instead of using strength modeling in the literature. This technique is also called as scene analysis or RSS fingerprinting and consist of two main stages such as the offline and the online phase. In the offline phase, the RSS values are measured from known distance or positions and a database is generated based on these measurements. These values are compared to new RSS measurements in the online phase and each new measurement is assigned to the closest known distance or positions. Some examples of this technique can be found in outdoor GSM applications [34].

In the RF-based localization, the most common challenge is noisy measurements. Independent from the preferred RF sensing technique, the RF signal measurements are mainly suffered from the environment and the process noise. This reality makes the usage of the conventional geolocation techniques such as trilateration infeasible to locate the RF source due to huge localization errors [3]. Therefore, the filtering techniques have an important role in the proposed localization studies to minimize the localization error with proper sensing models. In the literature, Bayesian filters are the most popular filtering/estimation technique to perform the localization. There are many presented works that use Kalman filter (KF) [35], extended Kalman filter (EKF) [36], [37], unscented Kalman filter (UKF) [31], [36] and particle filter (PF) [22], [25], [12].

1.3 Thesis Contribution

In previous works of the author, some solutions are presented on the basis of different search and rescue problem conditions. The first work was about the localization of the RF emitting targets using multiple UAVs in the case of the transmitter power of the RF signal is an unknown parameter [3]. Trilateration results for a set of possible transmitter powers were analyzed based on the RSS measurements obtained from three UAVs. Then a neural network model was used in order to classify the transmitter power of the RF emitting target. Using this info, the position of the RF emitting target was estimated with a combined solution consist of the trilateration and the

EKF. In another work, the localization of an RF source was performed using only one UAV and PF. The measurement model of RF signal strength is improved using experimental measurement tests. Also, an antenna model is developed to get more realistic simulation results [2].

This thesis concentrates the conceptual approach behind the proposed solution tested in the previous work to solve the searching and localization problem [1]. Before performing the localization, the RF signal strength measurement technique is described in detail. Based on the RF signal strength, PF and EKF based position estimation methods are used together for single and multi-UAV cases. Also, from the localization algorithm to complete hardware and software architectures are given more detailed. With intent to perform realistic simulation tests, the SIL system is improved and its more generalized version is also presented with the development process. Algorithms and components of the whole localization system is discussed and reconsidered in the perspective of the search and rescue problem. This thesis does not include the testing of the algorithm since the experimental testing has already given in the previous work [1]. Except that, only SIL tests are performed and the results are given in order to provide the verification of the presented architecture.

The proposed work in this thesis has a hardware architecture which consists of completely commercial-off-the-shelf (COTS) devices and it is supported with distinctive software architecture. As a result, an efficient, easy to use searching and localization solution to solve search and rescue problems with UAVs is proposed in this thesis.

1.4 Problem Assumptions

The problem discussed in this thesis is defined under some assumptions and the solution is presented with considering defined problem. First of all, the searching environment is $n \times n \text{ km}^2$ area with flat terrain ($0 < n < 10$). Therefore, the target and the UAVs have always clear LOS. The searching target is stationary and emits the RF signal using a handheld radio. Although the exact propagation frequency is unknown, the lower and upper bounds of propagation frequency band is known and the propagation band is in the Very High Frequency (VHF) band (30–300 MHz). This is the only knowledge about the searching target. Also, it is known that there is no

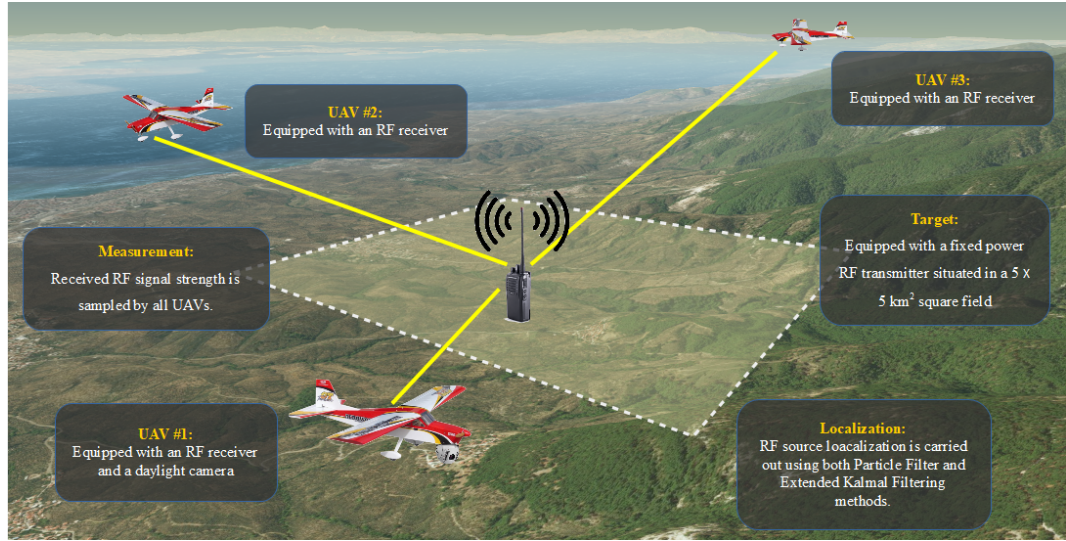


Figure 1.1 : Visual representation of the defined problem.

other active RF source at VHF band in the searching area. In addition to that, the autonomous UAV system consists of three fixed wing UAVs and each UAV can only gather the RF signal strength by onboard measurement sensor. However, the onboard sensors have predefined measurement range. The visual representation of the problem is given in Figure 1.1.

1.5 Organization of Thesis

The rest of the thesis is organized as follows.

Chapter 2 presents the RF signal strength measurement technique with the frequency detection algorithm and signal measurement hardware. Also, the modified signal propagation model which is developed based on the free-space propagation model and the experimental tests, is given.

Chapter 3 introduces the position estimation methods attempted in this thesis. In addition to that, the complete localization algorithm to solve search and localization problem is presented.

Chapter 4 describes the developed SIL environments to test the localization algorithm with detailed software models.

Chapter 5 presents complete architecture to perform proposed localization algorithm. The hardware and software architecture is given with the preferred UAV platform.

Chapter 6 concludes the thesis and gives the insight about future work.



2. MEASUREMENT OF THE RF SIGNAL

Measurement of the RF signal propagated by the RF source is one of the most crucial stages in the localization. Since the RF signal does not carry extra information and it is assumed that the UAVs can only gather the raw RF signal, the transformation of this raw signal to more convenient information is highly important. Also, the definition of the search and rescue problem brings the requirement of a frequency detection system. In this chapter of the thesis, developed frequency detection and RSS measurement technique is presented with hardware details. Furthermore, conversion between the measured RSS and the distance between the UAVs and the RF source is explained.

2.1 RF Measurement Hardware

RF signal measurements are performed using commercial-off-the-shelf (COTS) software defined radios (SDR). Although there are many commercially available SDRs, RTL-SDR V3 is used to measure signal strength due to its low-cost (<\$ 25 USD) and lightweight (< 50 g) advantages. Also, there are some open-source libraries available written in C and Python programming languages which makes this device easy to use. RTL-SDR devices have the RTL2832U chipset which originally designed as a Digital Video Broadcasting-Terrestrial (DVB-T) module.



Figure 2.1 : RTL-SDR v3.

In addition to the chipset, it is possible to access raw I/Q (in-phase and quadrature) data by a proper tuner. RTL-SDR devices have different tuner options which change some specifications of the device such as frequency range. The RTL-SDR V3 has Rafael Micro R820T tuner dongle and 24 - 1766 MHz operating frequency range. Although it provides maximum 3.2 MS/s (mega samples per second) sample rate, in other meaning 3.2 MHz scanning bandwidth, the device has instability issues after 2.4 MHz bandwidth [38].

In order to measure RF signal strengths, each of the UAVs was equipped with an RTL-SDR V3 connected a Raspberry Pi 3 B+ via USB connection. An omnidirectional antenna is connected to each RTL-SDR V3 devices via their SMA connector. An example of the RTL-SDR V3 is shown in Figure 2.1.

2.2 Frequency Detection Algorithm

The RTL-SDR V3 provides raw I/Q data which is a complex signal consists of an I signal in cosine waveform and Q signal in sine waveform. These two signals have the same frequency but they have 90° phase difference between each other. Since it is already a complex sinusoid, its sine and cosine components that have opposite signs will cancel each other in the frequency domain. Therefore, Fast Fourier Transform (FFT) of measured I/Q data will have one peak in the frequency domain. Using the FFT, a searching method is developed based on the frequency spectrum analysis with overlapping searching intervals in the lower and upper bound frequencies of the propagation band.

At the beginning of the frequency detection, the propagation band is split into small ($<2\text{MHz}$) sub-bands. While passing from the previous sub-band to the next one, the center frequency of the sub-band is shifted by half of the sub-band size. Thus, it is ensured that the measurement of the signal is performed twice by shifting with half of the sub-band size in sequential scanning. At each searching sub-band, the FFT is used to get the frequency response of the measured raw RF data and the maximum amplitude with its corresponding frequency bin is saved in a list. At the end of the searching process, if the found frequencies that belong to the largest two amplitudes are the same, it is decided that the frequency of the RF emitting target is found and the

Algorithm 1 Frequency Detection

```
1: procedure FREQSCAN
2:   initialize()
3:   repeat
4:     windows[]  $\leftarrow$  divide(frequencyBand)
5:     for i = 1 to length(windows[]) do
6:       spectrum  $\leftarrow$  abs(fft(windows[i]))
7:       rss  $\leftarrow$  max(spectrum)
8:       freq  $\leftarrow$  frequencyof(rss)
9:       list(Freq,RSS)  $\leftarrow$  freq,rss
10:      sortHighestAtEnd(list.RSS)
11:   until list.RSS(end).Freq  $\neq$  list.RSS(end-1).Freq
12:   return list.RSS(end).Freq
```

Figure 2.2 : The algorithmic representation of the frequency detection process [1].

frequency scanning process is terminated. The detection process is given in the Figure 2.2.

Figure 2.3 depicts an illustration belongs to a frequency detection test. In this test, the frequency of the RF signal is assumed in 136-155 MHz frequency band. This propagation frequency band is divided into sub-bands and the bandwidth of the sub-bands is set as 2 MHz based on the stability issues of the RTL-SDR V3 in bandwidth over 2 MHz. The frequency response of each sub-band is shown as different colors and the maximum amplitudes belong to each sub-band is also shown. As it can be seen in Figure 2.3, the frequency of the RF signal has the highest amplitude and it is detected twice by the result of the frequency scanning algorithm.

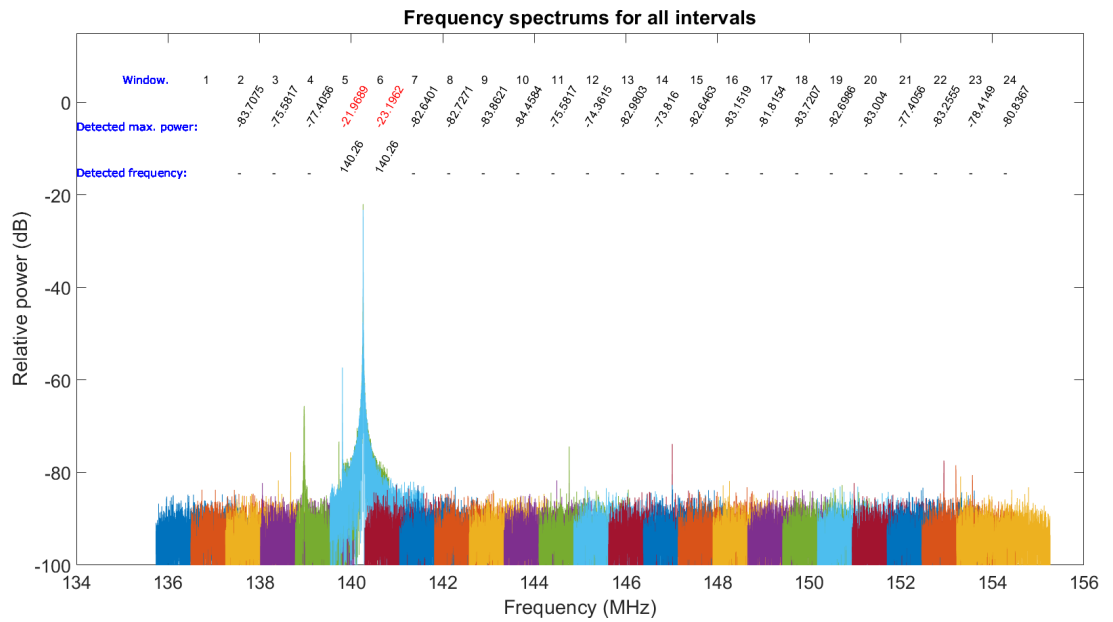


Figure 2.3 : An illustration of a frequency detection test.

2.3 Signal Strength Calculation with Detected Frequency

The RTL-SDR V3 provides raw I/Q data which is not an appropriate data type to use in RF-based localization. For this reason, the preprocessing on the measured RF signal data is required before using it. As it is described in Section 2.2, the amplitudes of the frequency spectrum can be calculated via FFT. On the contrary of the frequency detection process, the measurement bandwidth of the RTL-SDR is selected as a narrower band to eliminate the signal interferences and harmonic effects of the RF signal.

At the beginning of signal strength measurement, the center frequency of the RTL-SDR is set as the detected frequency from the frequency detection. At each measurement, the amplitude values of the frequency response are converted to log scale. Also, the amplitude of the sample in the middle of the frequency spectrum is compared with a threshold which is determined based on experimental RF measurement tests to identify whether the received signal is under the noise floor or above. If the amplitude value is higher than the threshold, the value of the maximum amplitude and its neighbors are averaged to get rid of the effects of centered frequency sampling errors. If the amplitude value is greater than the threshold, this amplitude value is defined as an acceptable one. Otherwise, the obtained signal strength values are marked as noise floor values of the spectrum. The aim of this decision process is gathering reliable signal strength measurement to use in position estimation. The spectrums of RF measurement tests when the RF signal source is active or passive are shown in Figure 2.4.

2.4 Obtaining Distance from RF Signal Strength

RF signal strengths can be converted to the distances between the RF source and the UAVs using signal propagation models. In theory, the path loss of the RF signal while traveling from the transmitter to the receiver can be calculated based on some parameters such as transmitter power, propagation frequency, distance etc. Using the free space path loss model, the mathematical representation of the received power at

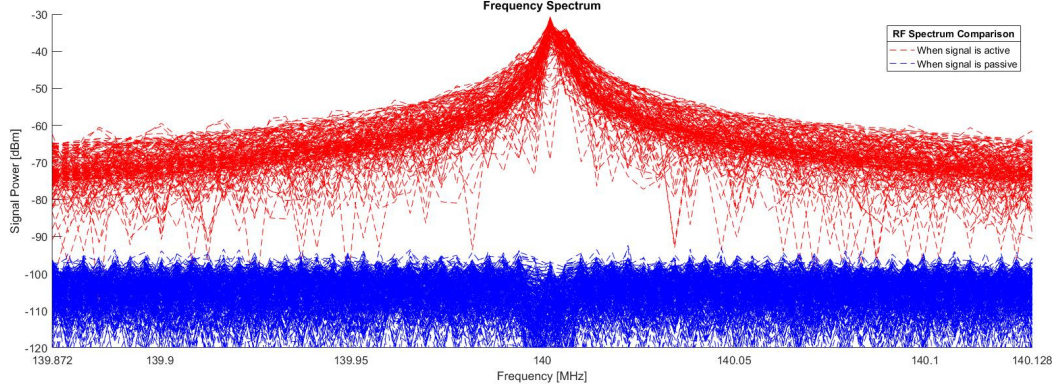


Figure 2.4 : Frequency spectrum of measured RF signal for 500 measurement steps whether RF source is propagating (red) and not propagating (blue).

the receiver antenna can be described as follows [39]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{4\pi^2 d^2} \quad (2.1)$$

where d is the distance between the receiver and the transmitter, P_t is the transmitter power, P_r is the received power, λ is wavelength, G_t and G_r are the transmitter and the receiver antenna gains. Using Equation 2.1 (also called as Friis Transmission Equation [39]), the distance between the receiver and the transmitter can be found as follows:

$$d = \sqrt{\frac{P_t G_t G_r \lambda^2}{4\pi^2 P_r}} \quad (2.2)$$

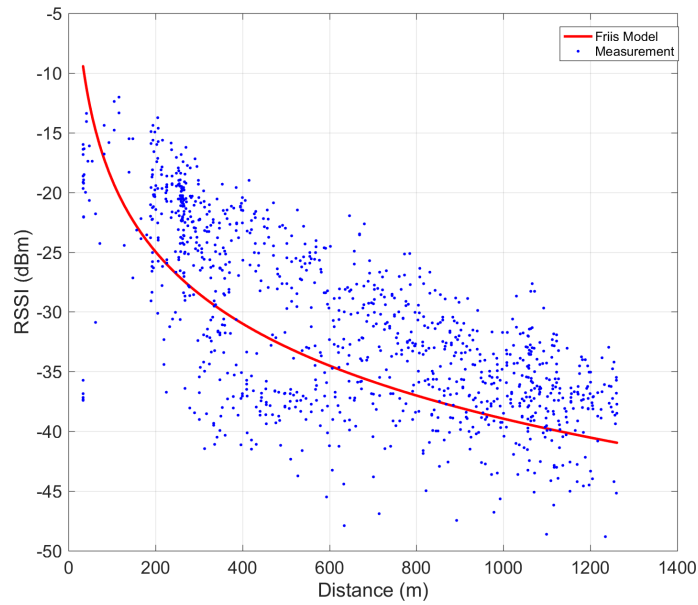


Figure 2.5 : Comparison of received signal strength values from experimental results and theoretical free-space model with respect to distances [2].

However, the free space path loss model assumes that the environment is a free space environment and does not consider some effects such as multipath fading, shadowing or ground reflections [40].

As described in Section 1.4, the searching environment is assumed as flat terrain and have a clear LOS. In addition to that, the previous works show that the problems and complexity of RF propagation modeling [28], [2], the free space path loss model is selected as a base model, then it is modified with experimental RF measurement tests and the modified version is given as follows:

$$P_r(d, M_1, M_2) = \frac{P_t G_t G_r \lambda^2}{4\pi^2 d^2} M_1 + M_2 \quad (2.3)$$

where M_1 and M_2 are modification factors.

3. SEARCHING AND LOCALIZATION OF THE RF SOURCE

Depends on the RF measurement technique, the position of the RF target can be found using geolocation techniques such as trilateration, triangulation etc., with multiple measurements from reference points. However, these deterministic methods are not sufficient to locate the RF source due to noise characteristics [2], [28]. In this chapter of the thesis, starting from trilateration which is one of the deterministic methods, developed approaches depending on the number of the UAVs are given using recursive state estimation techniques such as EKF and PF. Finally, the four-stage searching and localization algorithm is presented including the searching of the area with offline generated trajectory, the PF and the EKF based estimation stages.

3.1 Deterministic Localization Using Trilateration

Using geometry, the position of an object can be calculated with some known information. Trilateration is an old geometric method and relies on the relationship between 3 or more known reference points and their distances to the target object. Normally, 3-dimensional trilateration requires at least 4 measurements [41]. Nevertheless, the restricted version of the trilateration method was used in the early stage of this thesis. To simplify the problem, it was assumed that the UAVs are flying at the same constant altitude and the target is positioned on a 2-dimensional surface. This assumption allows finding position of the target with 3 distinct measurements [42]. This methodology is depicted in Figure 3.1 with the temporary cartesian coordinate system. The origin of the new coordinate system defined at the position of the first UAV and the second UAV is positioned on the x -axis.

Based on these modifications, a set of formulas is given as follows to find the position of the target:

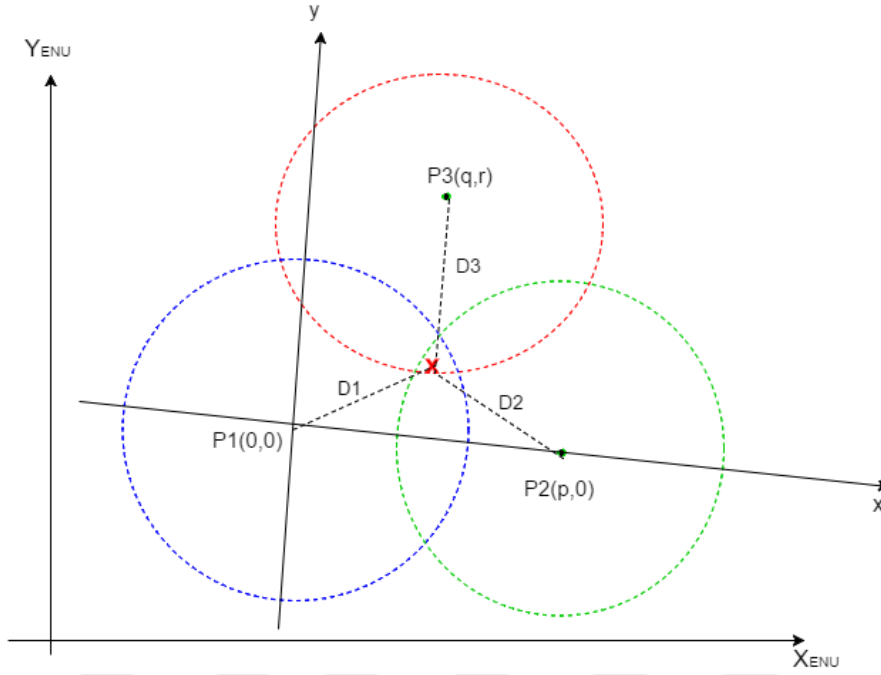


Figure 3.1 : Applying trilateration method with modified axes [3].

$$\mathbf{e}_x = (\mathbf{P}_2 - \mathbf{P}_1) / \|\mathbf{P}_2 - \mathbf{P}_1\|, \quad (3.1)$$

$$a = \mathbf{e}_x(\mathbf{P}_3 - \mathbf{P}_1), \quad (3.2)$$

$$\mathbf{e}_y = (\mathbf{P}_3 - \mathbf{P}_1 - a\mathbf{e}_x) / \|\mathbf{P}_3 - \mathbf{P}_1 - a\mathbf{e}_x\|, \quad (3.3)$$

$$\mathbf{e}_z = \mathbf{e}_x \times \mathbf{e}_y, \quad (3.4)$$

$$d = \|\mathbf{P}_2 - \mathbf{P}_1\|, \quad (3.5)$$

$$b = \mathbf{e}_y(\mathbf{P}_3 - \mathbf{P}_1), \quad (3.6)$$

$$x_{new} = (D_1^2 - D_2^2 + d^2) / 2d, \quad (3.7)$$

$$y_{new} = [(D_1^2 - D_3^2 + a^2 + b^2) / 2b] - (ax_{new} / b), \quad (3.8)$$

$$z_{new} = \sqrt{|D_1^2 - x_{new}^2 - y_{new}^2|}, \quad (3.9)$$

$$\mathbf{P}_{target} = \mathbf{P}_1 + x_{new}\mathbf{e}_x + y_{new}\mathbf{e}_y + z_{new}\mathbf{e}_z, \quad (3.10)$$

where $\mathbf{P}_k$ is the position vector of UAV_k and D_k is distance between the target and UAV_k where $k = 1, 2, 3$, $\mathbf{e}_x$, $\mathbf{e}_y$ and $\mathbf{e}_z$ are the basis unit vectors.

The trilateration technique is implemented on simulation with 3 UAVs following their predefined paths. Based on the measurement test, additive Gaussian white noise (AWGN) is applied to the signal strength measurements.

One of the simulation results is given in Figure 3.2 where blue points represent consecutive positions of the UAVs at each simulation step, red points represent trilateration results and the green point shows the real position of the target.

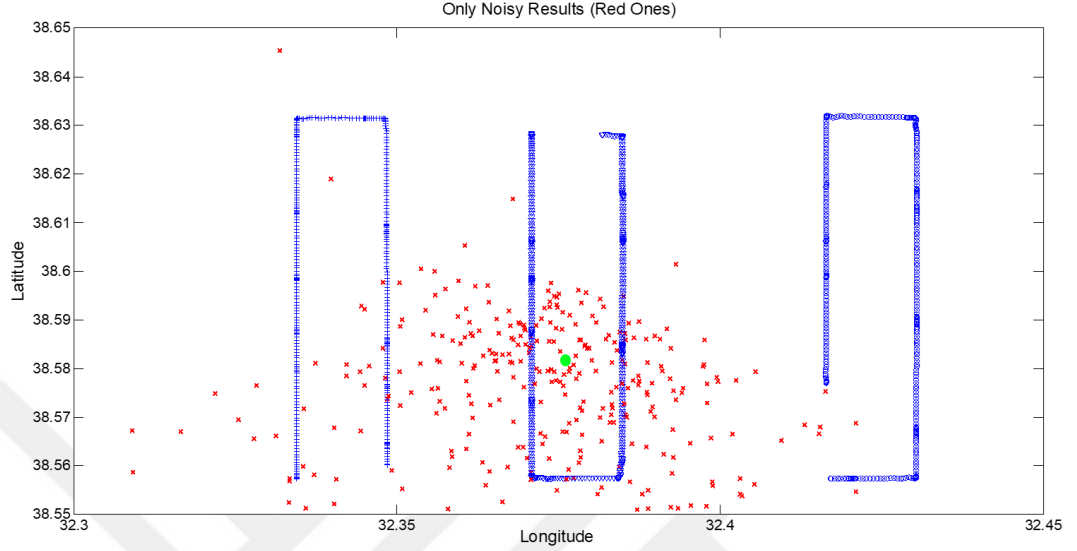


Figure 3.2 : Effect of high magnitude noise on trilateration.

Figure 3.2 depicts that the noise effect on the trilateration results. Since trilateration is a pure geometric method, it is highly sensitive to dramatic changes on measurements. In this example, the localization error can reach 5-6 km at some simulation steps for a 10×10 km simulation area. Therefore, using trilateration alone is not enough to locate the RF target effectively.

3.2 Localization Using Recursive State Estimation

The results of early works in this thesis and some works in the literature indicate the necessity of state estimation methods with proper system models. The main idea behind these methods is the estimation of the state variables from the data. Based on the probability theory, the state estimation algorithms compute belief distributions which are the posterior probabilities over state variables conditioned on the available data. Belief over a state variable x_t can be denoted as [4];

$$bel(x_t) = p(x_t | z_{1:t}, u_{1:t}) \quad (3.11)$$

where $z_{1:t}$ is the past measurements and $u_{1:t}$ is the past control inputs.

3.2.1 Bayes Filter Algorithm

Bayes filter algorithm is the most generic algorithm to calculate belief distribution and consists of two main stages. In the first stage, the state is predicted at time t from the previous state posterior, before incorporating the measurement at time t . This stage is generally called as the prediction stage. The second stage of the Bayes filter algorithm includes calculation of the final belief at time t using the current measurement and this stage is also called as the correction or the measurement stage. These two stages take part in most of the state estimation algorithms generated from the Bayes filter algorithm such as Kalman filters. The pseudo-algorithmic form of the Bayes filter algorithm is given in Figure 3.3.

Algorithm 2 Bayes filter.

```

1: procedure BAYESFILTER
2:   for all  $x_t$  do
3:      $\overline{bel}(x_t) = \int p(x_t | u_t, x_{t-1}) \text{bel}(x_{t-1}) dx$ 
4:      $\text{bel}(x_t) = \eta p(z_t | x_t) \overline{bel}(x_t)$ 
5:   end for
6:   return  $\text{bel}(x_t)$ 

```

Figure 3.3 : The algorithmic representation of the Bayes filter algorithm [4].

3.2.2 Position Estimation Based on Extended Kalman Filter

In the literature, the Kalman filter is one of the most studied Bayes filter implementations and represents belief distribution by the mean and the covariance for Gaussian systems [4]. Since the measurement model is not a linear model, extended version of the Kalman filter which is called as extended Kalman filter is used for this nonlinear problem with Gaussian assumption on RF signal uncertainty [3]. As the target is assumed as a stationary target, the filter states consist of the position of the target:

$$X_{k+1} = f_k(X_k) = AX_k, \quad (3.12)$$

where X_k represents the state of the filter $X_k = [x_k, y_k, z_k]$, and the position of the target is in cartesian coordinates. The measurement model gives the distance between UAVs and the RF emitting target. The location of UAV is obtained from onboard inertial

navigation system (INS) in practical implementation of this method.

$$r_k = \sqrt{(x_{uk} - x_k)^2 + (y_{uk} - y_k)^2 + (z_{uk} - z_k)^2}, \quad (3.13)$$

where x_{uk}, y_{uk}, z_{uk} are position of k th UAV and r_k is distance between the RF source and k th UAV. The Jacobian matrix can be calculated from this distance equation:

$$H_k = \begin{bmatrix} \frac{\partial r_1}{\partial x} & \frac{\partial r_1}{\partial y} & \frac{\partial r_1}{\partial z} \\ \frac{\partial r_2}{\partial x} & \frac{\partial r_2}{\partial y} & \frac{\partial r_2}{\partial z} \\ \frac{\partial r_3}{\partial x} & \frac{\partial r_3}{\partial y} & \frac{\partial r_3}{\partial z} \end{bmatrix} = \begin{bmatrix} -\frac{(x_{u1}-x)}{r_1} & -\frac{(y_{u1}-y)}{r_1} & -\frac{(z_{u1}-z)}{r_1} \\ -\frac{(x_{u2}-x)}{r_2} & -\frac{(y_{u2}-y)}{r_2} & -\frac{(z_{u2}-z)}{r_2} \\ -\frac{(x_{u3}-x)}{r_3} & -\frac{(y_{u3}-y)}{r_3} & -\frac{(z_{u3}-z)}{r_3} \end{bmatrix} \quad (3.14)$$

$$Z_{k+1} = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} \quad (3.15)$$

Measurement matrix Z_{k+1} includes the distance values D_1, D_2, D_3 for each of UAVs are calculated with the distance equation. The EKF update equation is given as:

$$X_{k+1} = X_k + K_{k+1}[Z_{k+1} - H_{k+1}], \quad (3.16)$$

$$R_k = \begin{bmatrix} \sigma_{D_1}^2 & 0 & 0 \\ 0 & \sigma_{D_2}^2 & 0 \\ 0 & 0 & \sigma_{D_3}^2 \end{bmatrix} \quad (3.17)$$

Where K_{k+1} is the gain matrix and R_k is the covariance matrix of the measurement noise computed by $\sigma_{D_{uk}}^2$ which represents precalculated variances of each distance. It is important to note that these variances of each distance values are modeled with the outdoor flight data [1].

In the previous work [3], EKF was initialized with the result of the trilateration method. However, as the trilateration results are too noisy and faulty, the convergence of the EKF algorithm was a little bit problematic. Therefore, the initialization of the EKF algorithm is supported by another estimation algorithm based on the particle filter for single UAV.

3.2.3 Position Estimation Based on Particle Filter

The EKF algorithm given in the previous section (Section 3.2.2) requires three measurements from three UAVs. However, it is important to make the time-efficient until all UAVs enter the RF signal range. Therefore, a position estimation algorithm was proposed based on the particle filter in the previous work [2].

PF is an alternative non-parametric implementation of the Bayes filter. The posterior is represented by a set of random state samples drawn from this posterior. The samples of a posterior distribution are called particles in particle filters.

The procedure of the position estimation using PF is given as follows in detail [2].

1. At the beginning of the estimation, all the particles x_t are uniformly distributed into the field in front of the UAV according to its heading angle and their initial weights are equal to each other.

$$w_0^{[n]} = 1/N_p, n = 1, 2, \dots, N_p \quad (3.18)$$

where n -th particle at time t is shown by $x_t^{[n]}$, and its weight is shown by $w_t^{[n]}$. Also, N_p represents the total number of the particles which is equal to 2500 in this application. This number of particles do not cause too much work load for the processor. It is needed to be 2500 or more in order to keep the density of particles high enough for operating in such a large area.

2. Iterations for $0 < t < T_{\text{arrival}}, t \in \mathbb{Z}$ where T_{arrival} represents the time when all UAVs receive RF signal.

- (a) Sample the particles $x_t^{[n]}$ from the proposal distribution $q(x_t^{[n]}|x_{t-1}^{[n]}, u_t)$, where u_t is the control input which is zero because of stationary RF emitting target.
- (b) Update weights $w_t^{[n]}$,

$$w_t^n \propto w_{t-1}^{[n]} \frac{p(z_t|x_t^{[n]})p(x_t^{[n]}|x_{t-1}^{[n]})}{q(x_t^{[n]}|x_{t-1}^{[n]}, z_t)} \quad (3.19)$$

where z_t is the measured signal strength value at time t . For proper weighting, the standard deviation of noise (σ_{rss}) on signal strength sensor should be converted properly to the standard deviation of distance (σ_d) by using the signal propagation model as described in Section 2.4. Moreover, to make estimation more realistic, the measured signal strength values gathered from outdoor flight tests are used to model and find exact standard deviation of noise.

- (c) Normalize the weights:

$$w_t^{[n]} = w_t^{[n]} / \sum_{n=1}^{N_p} w_t^{[n]} \quad (3.20)$$

- (d) Resample all particles uniformly according to the weights and replace the $w_t^{[n]} = 0$ particles with the new particles derived from weighted particles.
- (e) Obtain the result of the particle filter given by,

$$x_t = \sum_{n=1}^{N_p} w_t^{[n]} x_t \quad (3.21)$$

3.3 Four Stage Searching and Localization Algorithm

The searching and localization algorithm proposed in this thesis includes four consecutive stages which involve elapsed time between takeoff and landing. The whole process is executed fully autonomous and the flowchart of the process is given in Figure 3.4.

3.3.1 Stage 1: Tracking Offline Generated Searching Trajectory

The first stage is tracking offline path to ensure that at least one UAV enters the RF signal range. Based on the Figure 2.4, the signal measurement equipment has a limited range which does not contain all the searching area. Thus, the receiving signal strength values are limited and only the measured signal strengths above some threshold are defined as acceptable signal strength. The threshold is specified using experimental measurement tests. As the searching area is much bigger than this measurement range, a trajectory is generated offline based on the parameters of the environment such and the range threshold of the measurement equipment. After generating these trajectories for three UAVs, the UAVs start to tracking this trajectory until at least one UAV enters the RF signal range. In addition to that, if a UAV that can receive the signal in acceptable limits exits the RF signal range, all UAVs are guided to the last maximum signal strength receiving location. During this process all UAVs scan the whole frequency band since the exact propagation frequency is unknown.

3.3.2 Stage 2: First Signal Measurement and the Particle Filter Estimation Initialization

After the first signal measurement above the acceptable limits, the frequency of the received signal is detected and this process is repeated several times to ensure correct detection. Using the detected frequency, the signal strength measurement is started and

PF based position estimation is initialized based on the heading angle of the UAV as mentioned in Section 3.2.3. This stage is the shortest stage in terms of elapsed time during the stage.

3.3.3 Stage 3: Particle Filter Based Position Estimation

The first correct measurement of the RF signal triggers the other UAVs to cancel their searching trajectory and fly over the location of the measurement. At the same time, the UAV entered the RF signal range is carry out the PF based position estimation. At each estimation followed by measurement, the waypoint of the UAV is updated with some delay based on the estimation result. The reason of delayed guidance is the prevention of the effects of the unstable estimation results. With the delayed update, the system act as a low pass temporary filter for the target position. Thus, reasonable target changes, which is suitable for smooth trajectories, can be obtained. As a consequence, the localization duration is extended with this delay. However, insistent measurements towards a wrong temporary target while flying a smooth trajectory makes the particle filter to eliminate the particles causing that wrong estimation. Smooth trajectories meet the long sampling time requirement which eliminates the effect of noise.

The PF based estimation stage continues until all UAVs enter the RF signal range. In order to make the elapsed time before the arrival of the third UAV more efficient, two UAVs work together in the PF based estimation.

3.3.4 Stage 4: Extended Kalman Filter Based Position Estimation

When all UAVs enter the RF signal range, the EKF based position estimation is initialized using the last estimation performed by the PF. At each measurement, the EKF estimates the RF source location and all UAVs follow a circular trajectory around the estimated target position. The main idea behind the circular trajectory is to guarantee that the UAVs don't interfere with the signal strength measurements of other UAVs. Also, this trajectory locates each UAV after the target location in the different angles at different altitudes, thus the collision between the UAVs can be avoided and operation is performed safely.

The main reason of using PF and EKF together, make the elapsed time more efficient until all UAVs enter the signal range. After that obtaining better estimation results

using EKF from multiple UAVs since each of them fly in three different angles of the RF source. Therefore, interference on the signal strength measurements can be prevented. The flowchart of the proposed localization algorithm is depicted in Figure 3.4.

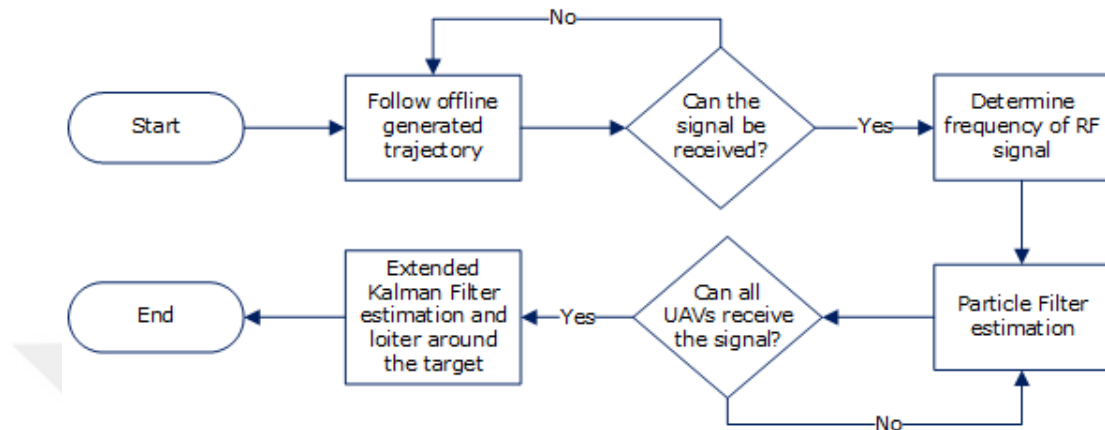


Figure 3.4 : The flowchart of the proposed localization algorithm.



4. SOFTWARE-IN-THE-LOOP ENVIRONMENT

The creation of a software simulation environment is one of the most important development phases not only to minimize possible errors in outdoor flight tests, but also to test the software modules to be used in the outdoor flight tests. Therefore, it is important to develop a simulation system including software modules and the software/virtual models of the hardware equipment. For this reason, two different versions of software-in-the-loop (SIL) environment are created based on the visualization type and hardware requirement. These SIL environments are used in the development of the localization algorithm given in Chapter 3. In this chapter of the thesis, the developed SIL environments are explained in detail.

4.1 SIL System Version I

Early tests of the localization algorithm were performed using MATLAB/SIMULINK. However, that simulations were not realistic in terms of both the visualization and operational reality of the localization system. Since it is planned to control the UAVs with ArduPlane autopilot in the outdoor flight tests, the SIL system was designed based on the ArduPlane autopilot [43].

In this SIL system, the UAVs are visualized using X-Plane 10 Simulator and each UAV runs on different computers. Each simulator runs a UAV model and communicates with ArduPlane SIL autopilot via Transmission Control Protocol (TCP). The connection between the autopilot and the ground station is provided by a UAV guidance and communication script was written in Python. In addition to that, this script emulates the measured RF signal strength using the free space propagation model with the addition of high magnitude Gaussian noise. All UAVs (PCs) communicate with the ground station computer via User Datagram Protocol (UDP) and they are guided by Mission Planning Software based on the localization results. The architecture of this SIL system is given in Figure 4.1.

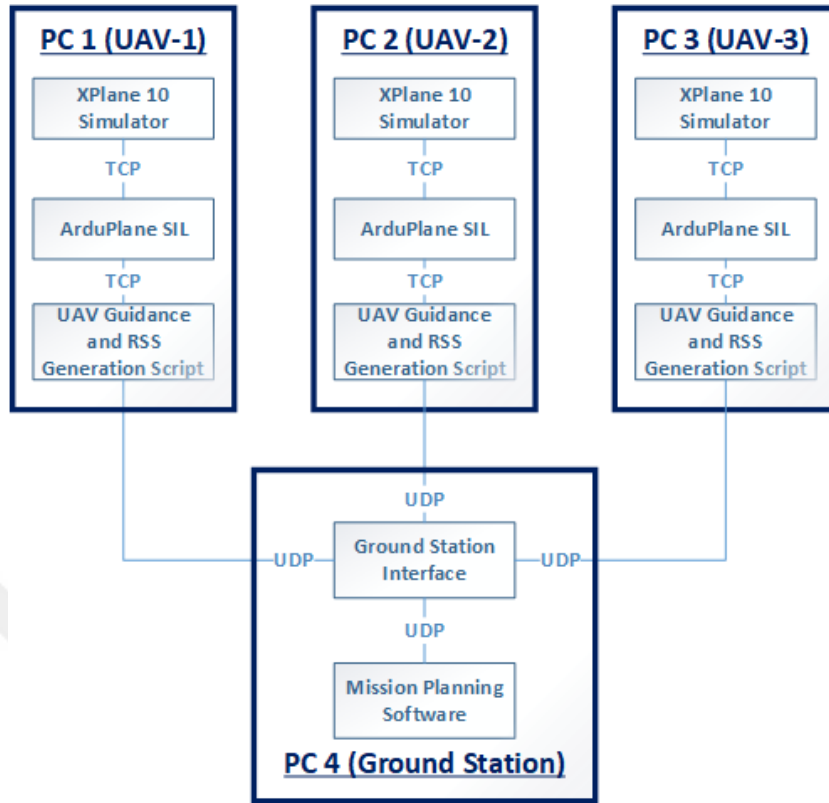


Figure 4.1 : The architecture of the SIL Version I.

4.1.1 UAV Model, Control and Visualization

In the SIL System Version I, the UAVs are visualized using X-Plane 10 simulation game [44]. X-Plane 10 includes many detailed aircraft models and allows realistic simulations with different environmental conditions. In addition to that, the aircraft flies on the X-Plane 10 can be controlled via both a remote controller (RC) and an autopilot via TCP/UDP. On the other hand, ArduPlane SIL software is compatible with X-Plane 10 simulator and this combination promises more realistic simulation tests.

As can be seen in the Figure 4.1, a UAV instance has three main modules. The first module of the UAV instance is a UAV model runs on the X-Plane 10. In this module, the HiLStar UAV model is preferred because of it is a lightweight UAV model which is given in the Figure 4.2. In order to control the UAV model runs on X-Plane 10, ArduPlane autopilot is connected via TCP connection. The last module of the UAV instance is guidance and RF signal strength generation script written in Python programming language. The first task of this module is communication with the autopilot via TCP and execution of the path planning outputs coming from the

ground station via UDP. Execution of commands and data transaction is performed using Dronekit module which is a Python wrapper for MAVLink message formats [45]. Another main task of the guidance module is the generation of the signal strength measurements based on the Free Space Propagation Model given in Section 2.4 using the real location of the simulated target and the location of the UAV runs on X-Plane 10. To get more realistic measurements, additive Gaussian white noise is added on the generated signal strength value based on the experimental RF measurements. In this system, each of the UAV instances is running on different computers due to compatibility and hardware requirement reasons.



Figure 4.2 : HiLStar UAV model flies on the X-Plane 10 simulator.

4.1.2 Ground Station Model

In addition to three computers represent UAVs, a fourth computer is utilized as the ground station to gather all data coming from the UAVs and guide the UAVs using the localization results. The ground station model has two main sub-modules developed on MATLAB. First module, a ground station interface is developed in order to visualize the location information coming from the UAVs on a map. This module collects the signal strength values with the location information of the UAVs and shares them with mission planning software which is the second module of the ground station and runs the localization algorithm given in Section 3.3.

An image of the SIL System Version I was taken from one of the SIL tests is given in Figure 4.3. Three UAVs run on three different computers and the coming information

from the UAVs is visualized both on a map and on Windows consoles in the ground station computer.



Figure 4.3 : An image of the SIL System Version I during a SIL test.

4.2 SIL System Version II

The previous SIL system given in Section 4.1 allows the more realistic simulations in terms of the visualization and communication. However, this system requires at least three different computers with high system requirements. In addition to that, the SIL System Version I requires some preparation time and this makes SIL testing time inefficient. For these reasons, a second SIL system was developed considering performance requirements. The main idea of this developing process was the creation of a SIL system can run single PC and simulates at least 3 UAVs. This idea realized using three virtual machines running on a host computer.

The SIL System Version II consists of a Windows 10 host computer and three Ubuntu 14.04 virtual machines represent the UAVs. In the experimental flight tests, it is planned to use Raspberry Pi 3 B+ mounted and connected to Pixhawk autopilot in the UAV. Therefore, Ubuntu is selected to keep environment similarity as it is a version of Linux operating systems like Raspbian OS that runs on the Raspberry Pi. Also, each virtual machine is designed to have ArduPlane SIL connected to Mission Planner ground station software for 2-dimensional visualization [46]. In addition to that, the UAV Guidance Script and RF Measurement Model completes all sub-modules of a

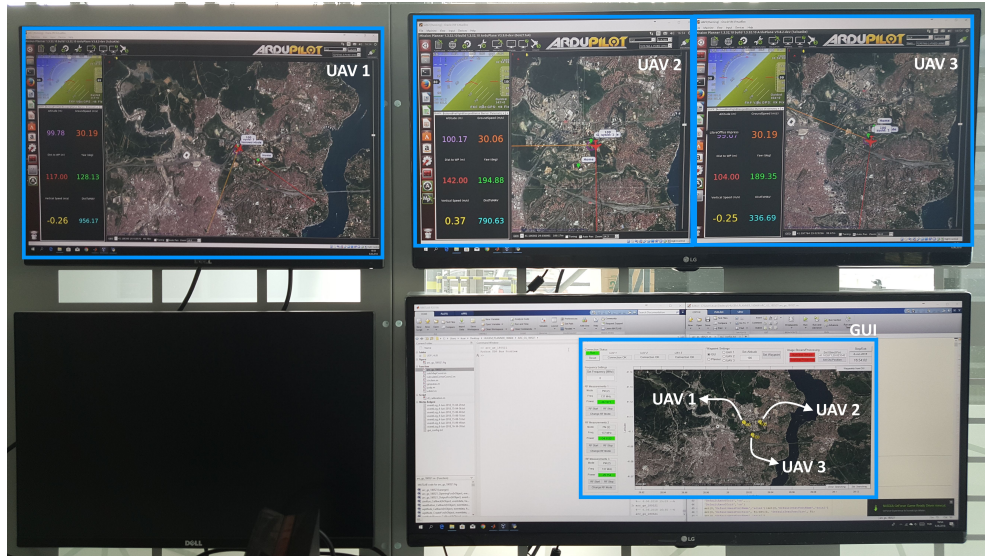


Figure 4.4 : An image of the SIL System Version II during a SIL test.

virtual machine. On the other hand, the host machine has Message Proxy Software to organize communication between the ground station and the UAVs, Graphical User Interface (GUI) and Mission Planning Software. The communication between the host and the virtual machines is provided via UDP communication with port forwarding technique using network adapter. The whole structure of the SIL System Version II is depicted in the Figure 4.5. In the Figure 4.4, an image of the SIL System Version II was taken from one of the SIL tests is given.

One of the most important advantages of the SIL System Version II is modularity as each UAVs runs on own virtual system. In other meaning, each component of the SIL environment is isolated from each other. Therefore, this SIL system allows hybrid flight tests that the real and the virtual UAVs can be tested together. Also, it has much shorter preparation time than the previous version.

4.2.1 UAV Model, Control and Guidance

A six degrees-of-freedom (6-DOF) RC aircraft model is used as the UAV model and it is controlled with ArduPlane autopilot. Similar to the SIL Version I, a Python script is used to provide communication between the UAV and the ground station. Instead of the X-Plane 10, the ArduPlane SIL is connected to the Mission Planner ground station software and 2-dimensional visualization of the UAV is performed. Also, Mission Planner shows many parameters of the UAV in the screen.

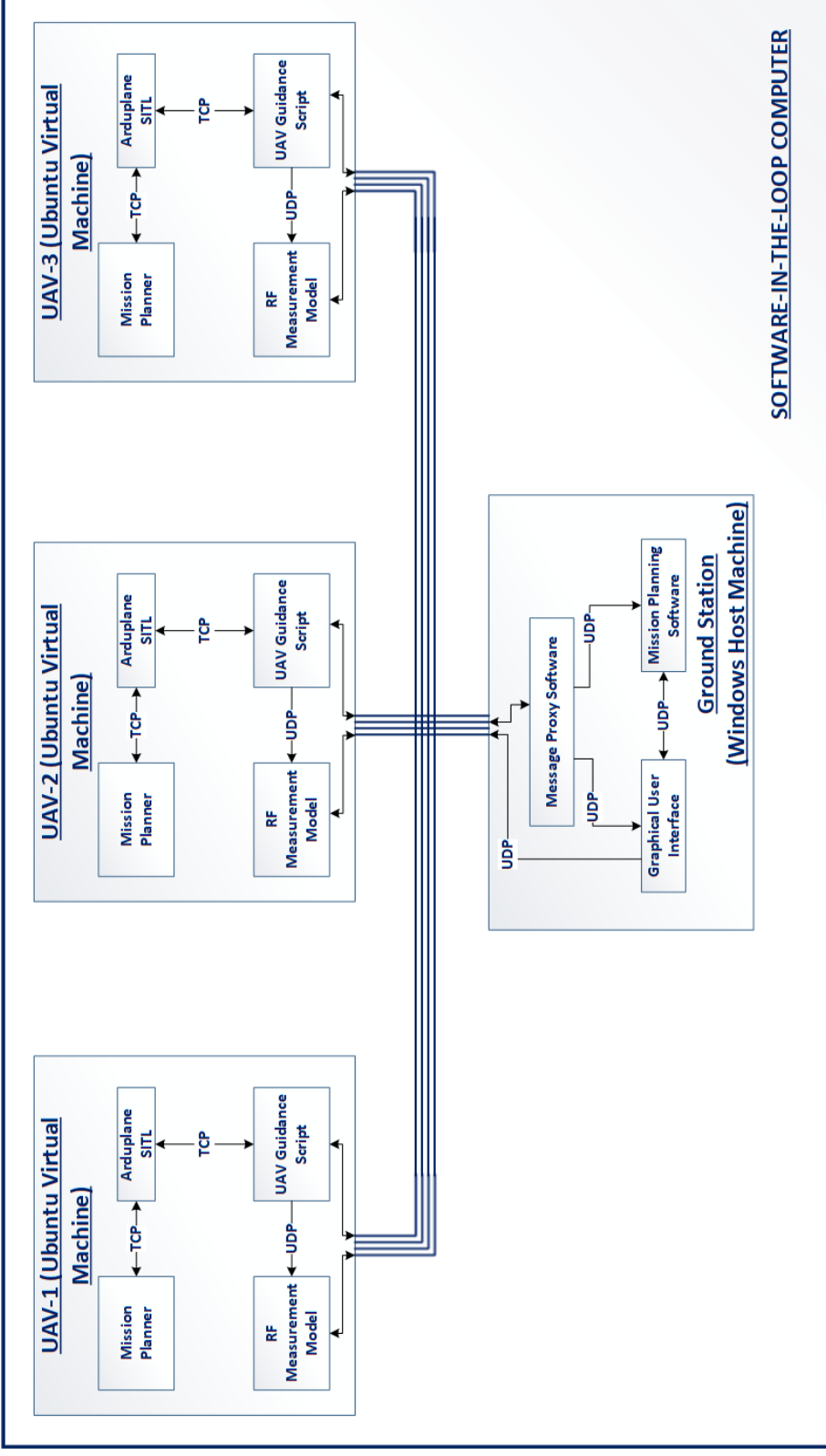


Figure 4.5 : The architecture of the SIL System Version II.

4.2.2 RF Measurement Model

In addition to the visualization difference from the previous version, one of the most important changes in this version is more realistic RF measurement and signal generation model. Since the emulation of the frequency detection requires the generation of the whole spectrum, the RF Measurement Model doesn't include the frequency detection stage. In order to emulate the RF signal strength, the modified propagation model given in Section 2.4 is used. To get more realistic measurement including RF noisy effects, additive white Gaussian noise (AWGN) is added to the calculated signal strength with covariance R which is adjusted based on the RF measurement test results given in Figure 2.5. The generated final signal strength value can be shown as follows,

$$RSS_n = RSS_{modifiedmodel} + \mathcal{N}(0, R). \quad (4.1)$$

In RF signal propagation, antenna gains is also important in addition to the RF signal noise. During the flight, the angle between the UAV and the source is continuously changing, thus the propagation and receiving gains of antennas will be affected. In addition to the assumption of the all components have omnidirectional monopole antennas in the proposed system, it is also assumed that antenna mounted on UAV is oriented towards the direction of the gravity and the antenna of the RF source is oriented towards perpendicular to the ground. Practically, the antenna orientation changes while UAV is in pitch or roll motion. However, it is assumed that the antenna orientations don't change depends on the motion of the UAV.

The modeling of the antennas is performed using MATLAB Antenna Toolbox. The gain of a monopole antenna is calculated as a function of azimuth and elevation angles of the UAV depending on the RF source antenna based on the physical characteristics of the antennas used on the experimental tests. Although the gain is not affected by the azimuth angle, the elevation angle has an effect on it since the antenna is omni-directional. This relation between the elevation angle and antenna gain is non-linear. So, this relation is discretized and simplified as a look-up-table

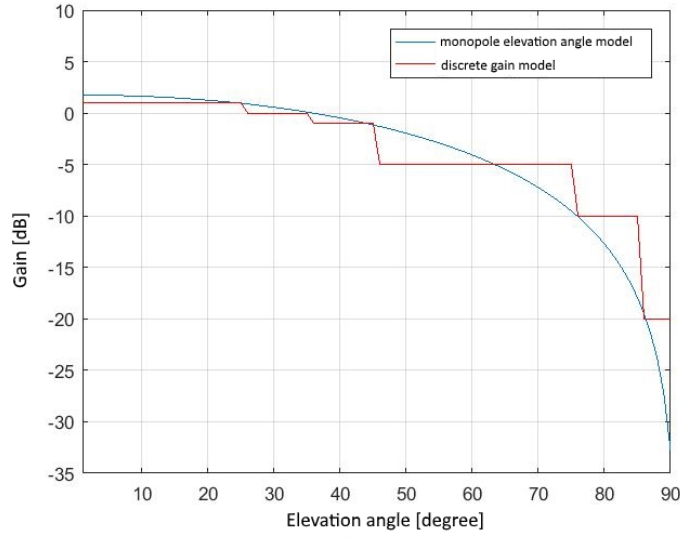


Figure 4.6 : Relation between elevation angle and antenna gain [2].

function in the simulation stage. The modeled non-linear function and its discretized approximation are depicted in the Figure 4.6.

4.2.3 Communication Model

The communication between the ground station and the UAVs is provided with a wireless communication network established using Wi-Fi modems in the real system. To emulate this communication, a local area network (LAN) is established between the virtual machines and the host machine using a virtual wireless network adapter with port forwarding technique. Thus, the virtual machines and the host machine have unique IP addresses. Using these IP addresses, all message transaction is performed with socket communication in TCP and UDP protocols.

4.2.4 Ground Station Model

The ground station model used in the SIL System Version II has three main sub-modules. These sub-modules are exactly the same as the experimental test software in order to make the SIL simulations compatible with hybrid flight tests. The first sub-module is the Message Proxy Software written in Python and uses the UDP communication. Its main task is the reorganization of the received message packets from the UAVs and it conveys these reorganized messages to the related sub-module. Thus, it is planned to reduce network traffic by collecting and organizing in one main

unit instead of listening to data coming from the UAVs in sub-modules separately. However, some critical commands such as the waypoint commands of the UAVs generated by Mission Planning Software is sent directly to the UAVs without using an intermediary software.

The other sub-module of the ground station model is the Graphical User Interface for monitoring the status of the UAVs and controlling mission process and it is shown in the Figure 4.7. The GUI is designed in MATLAB and it has 6 main parts such as:

1. Interface control tab: Interface start/stop and tracking the connection status with the UAVs.
2. UAV guidance tab: Setting a click-and-go mission or fully autonomous search and rescue mission for a selected UAV or for all UAVs.
3. Video streaming tab: Start/stop the video stream for the selected UAV (This tab is active only the real flight tests since the SIL system doesn't include any video streaming simulation).
4. RF measurement control tab: Monitoring the RF measurement modes of the UAVs, the frequency detection results and instantaneous signal strength measurements.
5. Map screen: Visualize the locations of the UAVs, the estimated location of the target on the map.
6. Interface termination and date information tab.

The last but not least part of the ground station is the Mission Planning Software sub-module which is the MATLAB implementation of the Four Stage Searching and Localization Algorithm given in the Section 3.3. This sub-module includes whole autonomous mission management during the elapsed time between take-off and landing of the UAVs. Within that period, the Mission Planning Software is responsible to manage the UAVs to accomplish all stages of the searching and localization algorithm including the searching of the area and the position estimation of the RF source.

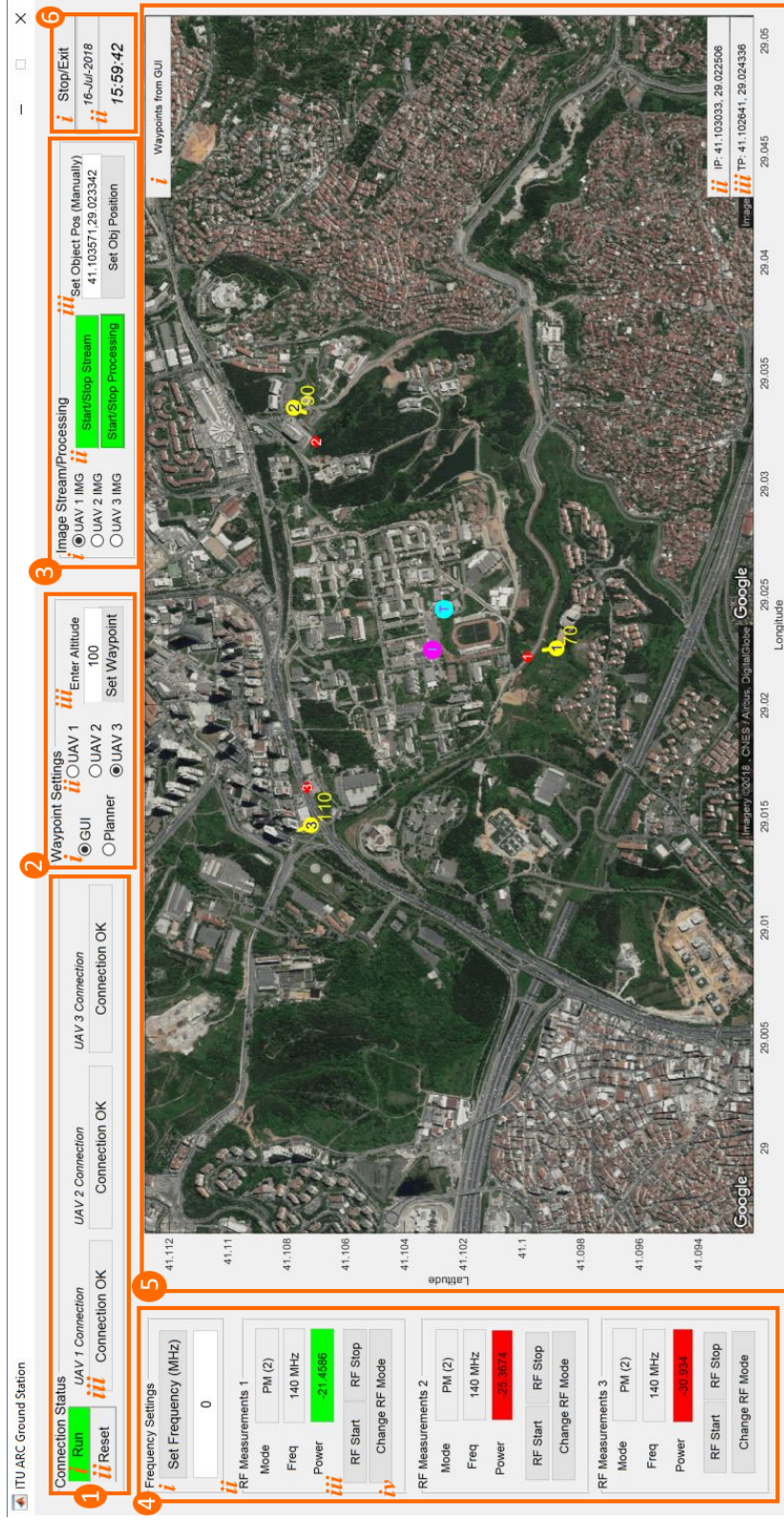


Figure 4.7 : Graphical User Interface.

5. COMPLETE SYSTEM ARCHITECTURE AND VERIFICATION OF THE ALGORITHM ON THE SIL TESTS

The methodology of the proposed solution is explained in previous sections from RF signal analysis to the theoretical explanation of the position estimation. In this chapter of the thesis, the implementation of the methodology is given in terms of both hardware and software. In order to verify the proposed searching and localization algorithm, the hardware details such as UAV platform, avionics architecture and the software implementation with full software architecture is given in this chapter. Since this thesis includes only the background of the previous work [1], the flight tests are not a part of this thesis. However, some of the RF measurements tests and its results are proposed to support the RF signal measurement approach which is given in Chapter 2.

5.1 UAV Platform and Hardware Architecture

The selection/design of the UAV platform is one of the most critical parts of the searching and localization applications as the utilization of the UAV directly affects the flight time. It is very important that the UAVs can fly as for as long as possible due to the uncertainty of the searching time to find the target. Therefore, a gasoline-powered UAV platform is preferred to carry proper payload over long flight time under the unfavorable weather conditions. Three Aeroworks 20cc-30cc Trainer GT ARF-QB UAV platforms were used in the experimental tests [47]. Figure 5.1 depicts an image of the UAV platform and Table 5.1 indicates its specifications.

Table 5.1 : Specifications of the Aeroworks Trainer GT UAV platform.

Wingspan	223 cm
Wing area	$0.85 m^2$
Fuse length	187 cm
Take-off Weight	5.4 kg
Engine	22 cc
Elevator movement up/down	± 10 mm
Ailerons movement up/down	± 6 mm
Rudder movement right/left	± 15 mm



Figure 5.1 : The gasoline-engine UAV platform used in the tests.

Considering the maximum weight of the UAV for take-off and the requirements of the search and localization algorithm, an avionics architecture is developed which consists of mostly COTS devices and it is given in the Figure 5.2. The architecture simply has three main parts. The power avionics consisting of batteries and regulators is the first main part. The second part is the flight avionics which includes the required components for a healthy and stable flight. As mentioned in the previous sections, the Pixhawk with ArduPlane autopilot was used to perform autonomous flights and the low rate telemetry connection between the ground station and the autopilot is provided by the RFD900x radios. The power and flight avionics are basic proportion of the architecture since they are essential for normal flight. The last but not the least part is the mission avionics consisting of the RF measurement sensor, the mission computer and wireless radio for high-speed communication. As it is given in the Section 2.1, the RTL-SDR V3 was used to measure the RF signal. In the designed architecture, it is connected to the mission computer which is a Raspberry Pi 3 B+ single board computer and Linux based Raspbian Stretch operating system runs on the mission computer. In addition to the RTL-SDR V3, the mission computer is also connected to a Raspberry

Pi Camera Module V2 to stream live video to the ground station. A Bullet M5 Wi-Fi modem is utilized to provide high rate communication between the mission computer and the ground station.

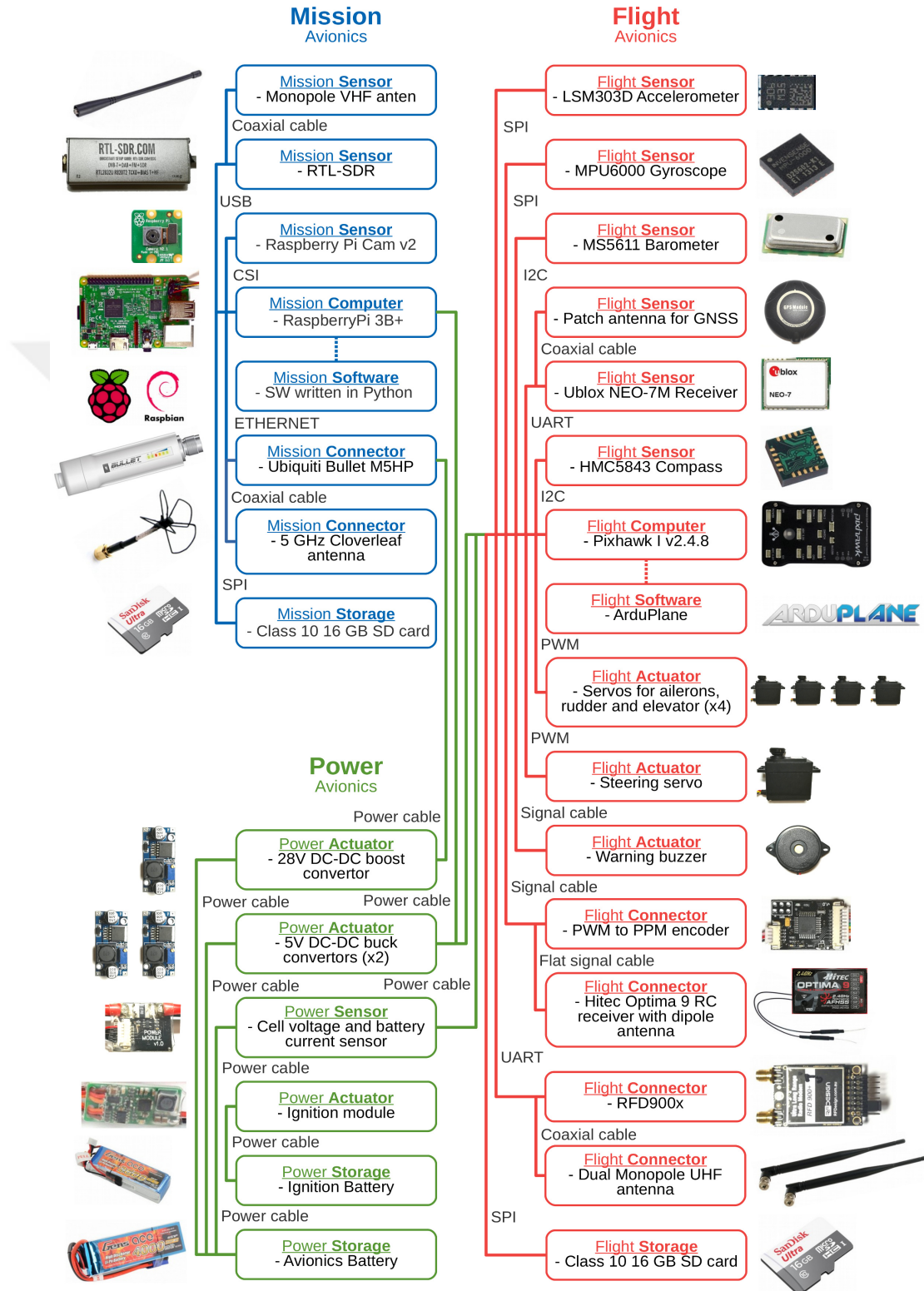


Figure 5.2 : Avionics architecture of the UAVs.

5.2 Software Architecture

The software architecture of the proposed solution is presented in Figure 5.3 and it can be summarized under two groups: the UAV software and the ground station software

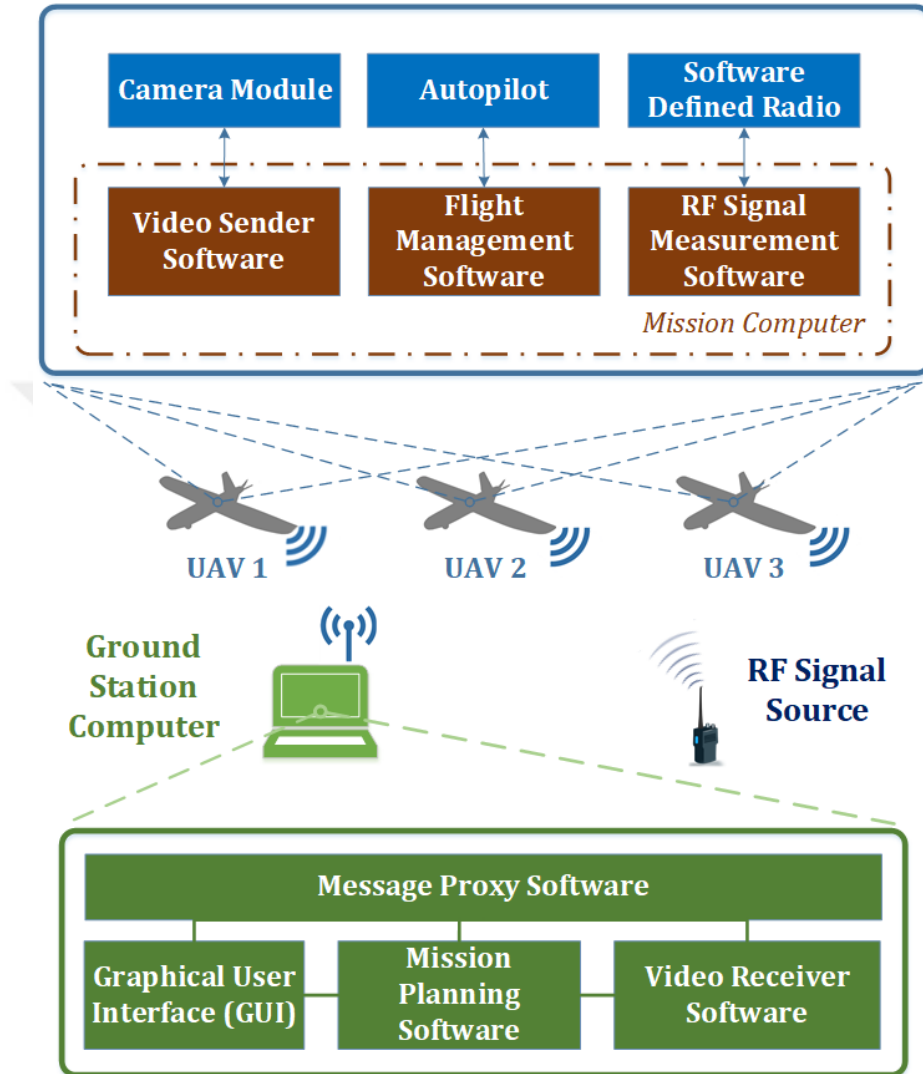


Figure 5.3 : Software architecture of proposed solution.

5.2.1 UAV Software

According to the proposed searching and localization solution, each UAV is responsible to perform three main tasks. The first of these tasks is to provide high rate communication between the Pixhawk autopilot and the ground station computer. This task is assigned to the flight management software in the mission computer. The flight management software is a script written in Python and it takes the current position and orientation information from the autopilot and sends this information to the GUI

using the USB connection between the mission computer and the autopilot. Since the Pixhawk autopilot uses the MAVLink message protocol, it is required the transform messages into proper message format. However, MAVLink message protocol has long and complicated message frame and this makes the development process a little bit harder especially during the implementation of different messages. To simplify this process, the Dronekit library was used to wrap MAVLink messages in Python as it is referred in the SIL system. Likewise, the received waypoint commands from the ground station are sent to the autopilot using this software. UDP socket communication is used to communicate the flight management software with the ground station.

Another task of the mission computer is frequency detection and signal strength measurement using the RTL-SDR V3. Given solutions for detection and measurement problem in Section 2.2 and 2.3 are implemented as RF signal measurement software in Python. Accessing to the RTL-SDR V3 is carried out using Pyrtlsdr Python wrapper over USB [48]. Similar to the flight management software, the RF signal measurement software is also communicates with the ground station via UDP.

The last task of the mission computer is live video stream to the ground station. As it is given in the previous Section 5.1, a Raspberry Pi Camera Module V2 is connected to the Raspberry Pi 3 B+ with CSI connection. To stream video, a video sender script is written in Python and in order to capture images from the camera module, Picamera Python library is used [49]. Using socket communication, captured images from the camera are streamed to the ground station in the MJPEG format.

5.2.2 Ground Station Software

Monitoring the UAVs is a very important task in the flight mission. In this point, the ground station design becomes very important. Therefore, modularity and robustness are taken as the main purpose in the design stage of the ground station software. Also, it is considered that the ground station design is independent from the UAVs to make hybrid flight test possible with virtual and real UAVs. For this reason, the ground station software is the same as the ground station in the SIL Version II given in the Section 4.2. The only exception is the ground station used in the real tests, has video receiver software to receive video streams from the selected UAV.

The ground station software includes four main software modules and the first module is the message proxy software which is written in Python and it is responsible to arrange message traffic between the UAVs and the ground station. The reason behind this structure, it is hard to control and monitor the divided message communication into different ports in socket communication. Therefore, a message proxy software is developed to receive periodic messages from UAVs and transfer them to related software modules. On the other hand, the waypoint commands is directly sent from the mission planning software to the UAVs in order to prevent delays on critical commands.

Status of the UAVs and the mission process is monitored in the Graphical User Interface which is designed in MATLAB and depicted in 4.7. The GUI used in the real tests, is exactly the same as the GUI in the SIL Version II. In addition to the SIL System, the video streaming control from the selected UAV is possible in the real flight tests. The GUI allows the waypoint commands sent from the mission planning software and it is possible to remove or addition selected UAV to the autonomous mission process from the GUI. The mission planning software is also written in the MATLAB and it is basically the implementation of the algorithm given in the Figure 3.3.

As it is mentioned above, the last part of the ground station software is the video receiver software which is the equivalent to the video sender software in the UAVs. Using this software, received MJPEG stream is parsed and shown in the ground station computer screen.

All software modules of the ground station are separated and communicates with each other with UDP protocol. In this way, the ground station has a modular structure and a problem on one of these softwares, does not block the whole ground station functioning. As a result, it is planned to design reliable and redundant ground station architecture and to perform the developed search and localization algorithm efficiently.

5.3 SIL Test Results of Four Stage Searching and Localization Algorithm

In the SIL tests of the Four Stage Searching and Localization Algorithm, the searching environment is selected as a $5 \times 5 \text{ km}^2$ area and the range of the RF measurement

equipment is limited as 1 km. In addition to that, it is assumed that the propagation frequency is already known since the SIL system doesn't include the frequency detection stage.



Figure 5.4 : Screens of the second and third virtual machines during the SIL test.

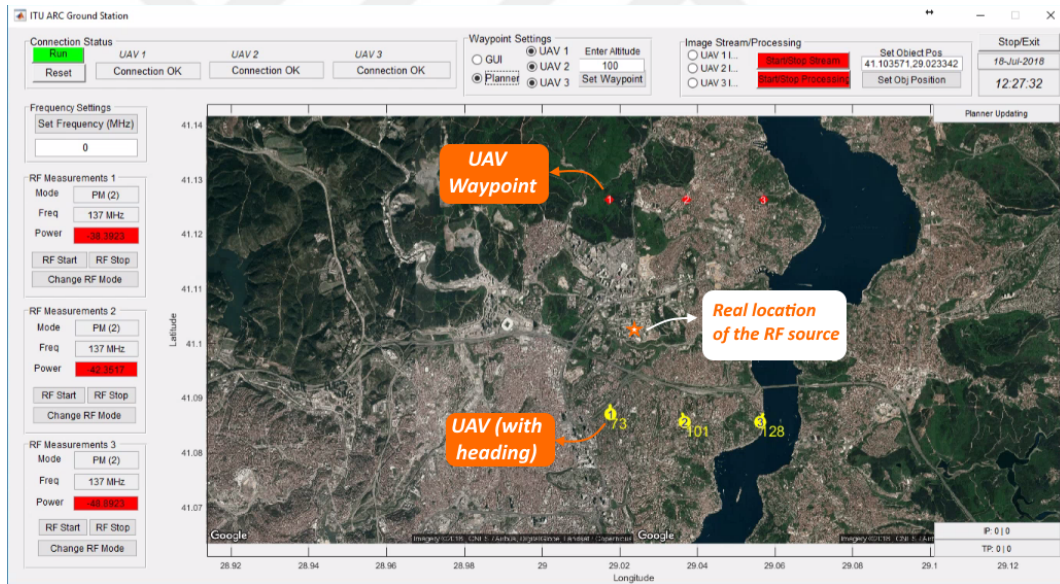


Figure 5.5 : An image of GUI screen in searching stage of the SIL testing.

The whole process of the developed algorithm is monitored using Mission Planner ground station and developed ground station algorithms. After virtual take-off of the UAVs, all UAVs start loitering around some arbitrary points. This pre-localization period is given in the Figure 5.4 which show the screens of the second and the third virtual machines.

After the initialization stage, the searching of the RF source is started by the Mission Planning Software. As it is given in the Section 3.3, the environment is divided into

sub-areas based on the number of the UAVs and each UAV tries to measure the first acceptable RF signal. This stage is shown in the Figure 5.5.



Figure 5.6 : An image of GUI screen when the first UAV measure the RF signal strength in the SIL testing.

When at least one UAV enters the RF signal range, the second stage of the developed algorithm begins. At this stage, the position estimation with PF is initialized. The GUI screen of the first measurement is shown in Figure 5.6.

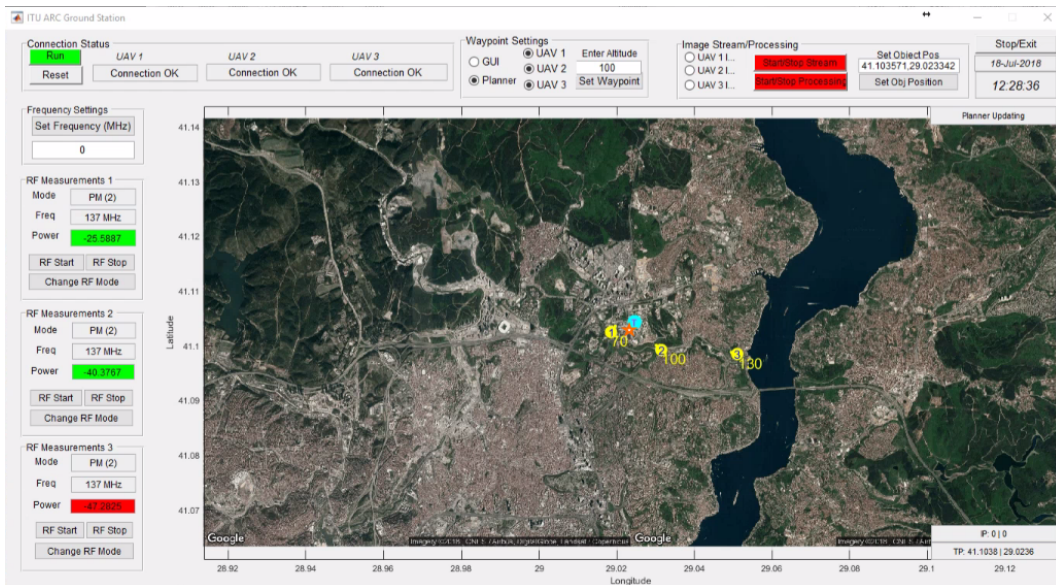


Figure 5.7 : An image of GUI screen when the PF based position estimation was being performed in the SIL testing.

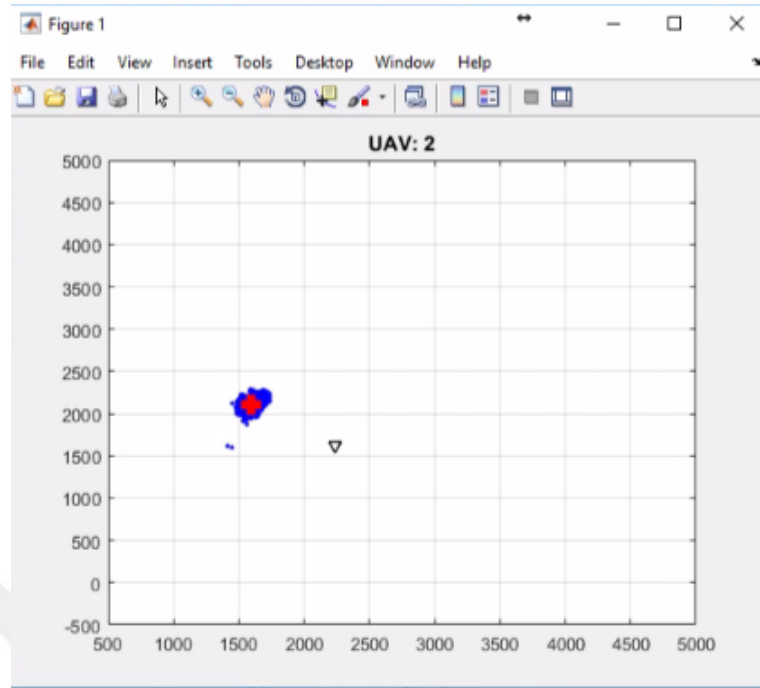


Figure 5.8 : Particles distribution in the PF based position estimation stage in the SIL testing.

The third stage of the developed localization algorithm is the PF based position estimation stage. At this stage, the position of the RF source is estimated with PF using the measurements from the UAVs.

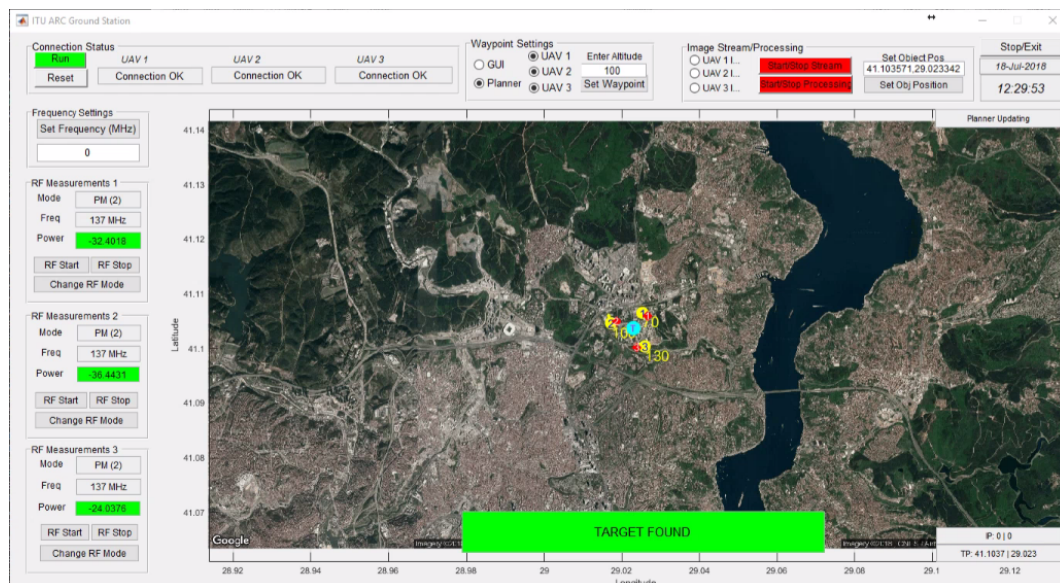


Figure 5.9 : An image of GUI screen when the EKF based position estimation was being performed in the SIL testing.

An image of GUI screen when two UAVs measure the RF signal strength is shown in the Figure 5.7. The result of the PF position estimation is also shown in Figure 5.7 and the MATLAB figure of the distribution of the particles is depicted in Figure 5.8.

When all UAVs enter the RF signal range, the last stage of the localization begins. In this stage, all UAVs measure the RF signal strength, send these measurements to the ground station and EKF based position estimation is performed by the Mission Planning Software. Based on the estimated position, a circular path around this estimated location is calculated and corresponding waypoints is sent to the UAVs. An image of the GUI screen when this process was being performed is shown in the Figure 5.9.



6. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, an efficient and low-cost localization solution is proposed to solve the search and rescue problem based on the RF signal sources and the multi-UAV systems. Over the last twenty years, unmanned system technologies have shown significant improvements and the efficiency of the UAVs has increased in terms of both the cost and the flight time by these technology improvements. Considering the operational cost, the requirement of qualified human resource and risk factor of the current search and rescue operations, utilization of the UAVs can be convenient especially in the searching and localization part of these operations. For this reason, a fully autonomous architecture is developed to search and localize RF signal sources using multi-UAV systems.

At the beginning of the work, the RF signal measurement techniques are studied with the localization techniques. Based upon the RF signals emitted from a handheld radio carried by the searching target, each UAV is equipped with an SDR device. Since it is computationally efficient, lightweight and easy to use, RTL-SDR V3 is mounted on each UAV. Also, there are many open source software compatible with SDR devices and they are available on different programming languages. Utilization of these devices and single-board computers on the UAVs, the raw signal measurements are converted to the signal strength values using signal processing techniques such as FFT. In addition to that, a frequency detection algorithm is presented based on the frequency spectrum analysis. Using the developed measurement technique, RF signal measurement tests are performed and the modified signal propagation model is presented based on the free-space propagation.

In order to estimate the position of the RF source from signal strength measurements, the deterministic techniques are studied at first. However, these techniques such as trilateration do not perform good localization results due to the RF signal noise. For this reason, the position estimation problem is solved using recursive state estimation methods. Taking advantage of multiple measurements from the UAVs, an EKF based

position estimation technique is developed using three distance values obtained from the signal strengths and three reference position information from the UAVs. This solution can be applied after three UAVs enter the RF signal range which is determined in order to measure appropriate signal strengths based on the measurement tests. On the other hand, the elapsed time during the searching is very crucial in the search and rescue operations. Also, the flight time of the UAV is limited due to its size and payload. Considering these points, another position estimation method based on the PF using single UAV to accelerate the search and localization process. The main idea, when a UAV enters the signal range, it starts the localization with PF based position estimation, other UAVs are directed to that signal received area and the localization can be completed after all UAVs measurements. Using this idea, a searching and localization algorithm is presented in this thesis.

Before conduct the flight tests, two different SIL testing environments are developed in order to test the localization algorithm. Starting from a complex environment design with good visuality, a compact, fast but efficient solution is preferred in the SIL environment design process. Although the first version proposes good visual quality with X-Plane flight simulator, it is required at least three different computers with high hardware requirements. Also, the initialization process takes a long time. Hence, a second SIL environment is designed in order to make fast and efficient testing possible. The second SIL environment has more compact structure and it is easier to use. In addition to that, the second version can run a computer since it uses virtual machines to simulate UAVs.

In addition to the SIL environment, hardware and software architectures are proposed in order to substantiate these presented algorithms. The proposed architectures include the required hardware equipment, the avionics of the UAVs and the implementation of the developed algorithms. Using these implementations, the SIL tests are conducted as part of this thesis and the test results are presented.

For the future work, the proposed solution can be extended to more generalized search and localization problem such as mobile target with improvements. Since this thesis includes only the conceptual background of the previous work [1], the improvements can be tested with more experimental tests. In addition to that, the target localization technique can be supported with vision-based target detection. Since each UAV is

equipped with a camera, the localization of the target can be improved using computer vision techniques in the searching and rescue operations.





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