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DESIGN AND CONSTRUCTION OF A GPS BASED UNMANNED GROUND VEHICLE (UGV)

M. Sc. THESIS

IN

MECHANICAL ENGINEERING

BY

HALİT HÜLAKO

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Design and Construction of a GPS Based Unmanned Ground Vehicle (UGV)

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in

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Supervisor

Prof. Dr. Sadettin KAPUCU

By

Halit HÜLAKO

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Halit HÜLAKO

ABSTRACT

DESIGN AND CONSTRUCTION OF A UNMANNED GROUND VEHICLE (UGV)

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In recent years, unmanned vehicles have been quite popular for the researchers and that vehicles are still being developed by the researchers and engineers. Unmanned vehicle has to do all operations without operator and has all capabilities as the operator controlled. In this study, tracking of waypoint by autonomous unmanned ground vehicle (UGV) have been studied. For this purpose, designed and constructed unmanned ground vehicle location is obtained by using GPS and compass and the microcontroller is utilized as a control / decision makers. The working principle of unmanned ground vehicle is as follows: At the beginning, waypoints or earth coordinates are loaded to PIC microcontroller, GPS module calculates the new position for every 200 ms to find current angle between North and line between the current position and destination\waypoint. Compass module also calculates the current heading value that shows the angle between north and course. According to this data microprocessor compares the results and chooses the correct angle of servo that controls the direction of UGV. Besides, Kalman filter algorithm and a guidance system was applied to UGV. The tests and results are given at the end of study. This platform will be used as a test vehicle to improve capability of tracking waypoints and path following.

Key words: Waypoint, UGV, GPS, Navigation

ÖZET

GPS TABANLI BİR İNSANSIZ KARA ARACININ TASARIMI VE YAPILMASI

HÜLAKO, Halit
Yüksek Lisans Tezi, Makine Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Sadettin KAPUCU
Eylül 2014, 50 sayfa

Son yıllarda, inansız araçlar araştırmacılar için oldukça popüler hale gelmiştir ve hala bu araçlar araştırmacılar ve mühendisler tarafından geliştirilmektedir. İnsansız araçlar bütün kabiliyetlere sahip olmalı ve yardım almadan bütün işlemleri gerçekleştirmelidir. Bu çalışmada bir insansız kara aracının (İKA) belirli bir konumdan belirtilen varış noktasına otonom gitmesi üzerine çalışılmıştır. Bu amaç için tasarlanan ve geliştirilen insansız kara aracında GPS ve pusula kullanılarak konumu belirlenmiş ve denetim/karar verici olarak da mikrodenetleyiciden faydalanılmıştır. İnsansız kara aracının çalışma çalışma prensibi aşağıdaki gibidir. Başlangıçta varış noktaları (way-points) ve/veya coğrafi koordinatlar mikrodenetleyicinin belleğine yüklenmektedir. GPS modül ile kuzey çizgisi ve anlık konum-varış noktası arasında oluşan açı her 200 ms'de bir hesaplanmaktadır. Böylece İKA'nın konumunu belirlenmektedir. Pusula sensoru de aracın kuzey ile yaptığı açıyı hesaplanmaktadır. Bu bilgilere göre mikrodenetleyici sonuçları karşılaştırıp İKA'nın yönlendirilmesini sağlayan servo motorunun yapacağı doğru açıyı komut olarak göndermektedir. Ayrıca, İKA'ya Kalman filtresi ve bir güdümleme algoritması uygulanmıştır. Çalışmanın sonunda, yapılan deneyler ve sonuçları sunulmuştur. Geliştirilen bu düzenek ile güzergah yolu veya yörüngesi izleme yeteneklerinin geliştirilmesi için test düzeneği olarak kullanılacaktır.

Anahtar Kelimeler: Varış noktası, İKA, GPS, Navigasyon

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LIST OF SYMBOLS/ABBREVIATIONS

lat_n	Latitude value
lon_n	Longitude value
Ψ_{Los}	LOS angle
P_k	Current way-point
P_{Los}	LOS position
P	Current position
θ	Angle of inclination
β	Heading
δ	Steering angle
$\hat{x}_k$	Posteriori state estimate
Z_k	Measured value
K_k	Kalman gain
u_k	Control input
v_k	Measurement noise
w_k	Process noise
$\hat{x}_k^-$	Priori state estimate
Q	Process noise covariance
A	Transition matrix
B	Control matrix
H	Observation matrix
P_k^-	Priori estimate error covariance

P_k	Posteriori estimate error covariance
UART	Universal Asynchronous Receiver/Transmitter
NMEA	National Marine Electronics Association
SBAS	Satellite-Based Augmentation Systems
GPS	Global Positioning System
DGPS	Differential Global Positioning System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
PIC	Peripheral Interface Controller
PWM	Pulse-Width Modulation
MCU	Micro Controller Unit
I2C	Inter-Integrated Circuit
INS	Inertial Navigation Systems
IMU	Inertial Measurement Unit
ADC	Analog-To-Digital Converter
GNC	Guidance Navigation Control
IR	Infrared
EGNOS	European Geostationary Navigation Overlay Service
ESC	Electronic Speed Control
LOS	Line of Sight
SLAM	Simultaneous Localization And Mapping
WAAS	Wide Area Augmentation System
MAV	Mini Aerial Vehicle

CHAPTER 1

INTRODUCTION

After increasing demands for the last several wars, autonomous unmanned vehicles (UVs) have been seen in modern warfare. Undoubtedly, thanks to defense technology, currently UVs have been used by civilians. UVs have used for search and rescue, agriculture, commercial applications and entertainment. An unmanned vehicle has to accomplish all missions successfully. When doing these operations, an unmanned vehicle can be autonomous, semi autonomous or completely human controlled remotely. An autonomous UV has to do all required processes without aid during mission as well. However, semi autonomous UVs need to be controlled by an operator [1].

Figure 1.1. An application on agriculture, unmanned tractor is being driven on a predefined path (left image). An UGV in traffic surveillance (right image) [3, 2]

With the interesting topics, UVs are very popular for researchers, however there are large amount of article about the UVs. Depending on growing interest, in our country, the articles about UVs are increasing rapidly. UVs can be called according to environment of mission or its type.

The list of UVs is as follows [1]:

- Unmanned aerial vehicle (UAV)
- Unmanned ground vehicle (UGV)
- Unmanned underwater vehicle (UUV)
- Unmanned surface vehicle (USV)
- Micro aerial vehicle (MAV)

Objective of this study is to construct an autonomous ground vehicle (UGV) and navigate with low cost sensors like GPS and Compass including giving information about techniques in all steps. This study is considered as an initial step to build a base for an autonomous mobile robot that is managed and controlled in unknown environment.

1.1. Guidance Navigation and Control system (GNC)

Guidance, navigation and control system is a system that manages and controls vehicle in order to send it to a desired destination point. When doing that operation, guidance, navigation and control system uses sensors actuators and a computer. Currently, the system has been used in aircrafts, ships, submarines, missiles etc. [4]. Guidance, navigation and control system consist of three subsystems as shown in Figure 1.2. and outputs of the subsystems enters the related system as input data [5]. The details of the GNC system are in subsequent sections.

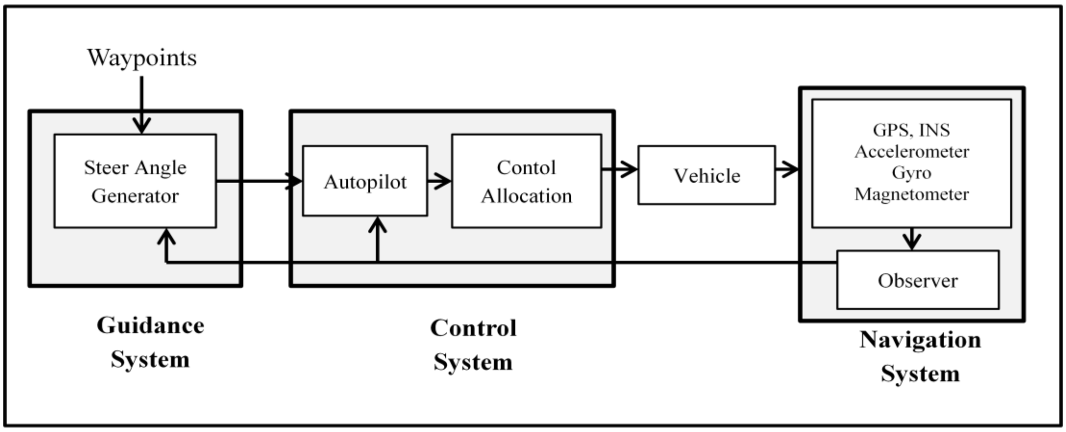

Figure 1.2. GNC system [5]

1.1.1. Guidance

Duty of guidance part is computing required steer angle in order to vehicle turn to desired destination point. When doing this operation a computer reads outputs of navigation part and way-points in order to find steer angle value [1]. According to systems, position, acceleration and velocity may need to be calculated in this part including generation of a path or trajectory [5]. Currently, there are many type of guidance algorithm are applied.

In this project, a microcontroller as a computer was used to calculate steer angle. In addition to this line-of-sight (LOS) guidance algorithm was used to find steer angle. Details of the microcontroller and algorithm are explained in Chapter 3 and Chapter 4 respectively.

1.1.2 Navigation

This section can be seen as measuring and learning current position velocity and acceleration data in order to enter control and guidance part. Generally, GPS, inertial navigation system (INS), inertial measurement unit (IMU), altitude sensor, encoders and vision cameras are used in navigation section.

An IMU are used in UVs, spacecrafts and missiles in order to learn vehicle attitude and maintain orientation with respect to a reference frame [6, 7]. The IMU sensors shown in Figure 1.3. are being used in inertial navigation system (INS) as well. INS computes and gives distance travelled with respect to a reference initial point. For this reason, INS is the most utilized system for indoor application, that is GPS where does not work, for instance for submarines.

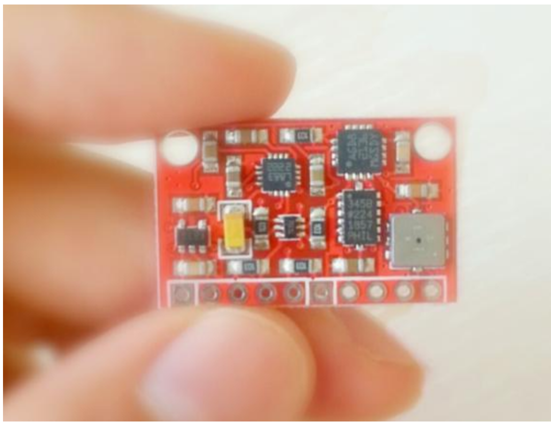

Figure 1.3. 9 DOF IMU (Gyroscope, Accelerometer, Magnetometer) including atmospheric pressure sensor

Generally, in order to obtain velocity and learn distance traveled, an encoder is used for UGVs. Recently, in order to learn its position in an unknown place, simultaneous localization and mapping (SLAM) technique creates map of its surroundings with the help of 3 dimensional Laser range finders and vision cameras for every required situation the map of environment is updated [7]. In this project, GPS and a compass sensor have been used in navigation section.

1.1.3. Control

The control system deals with finding required actions in order to keep vehicle at desired situation like path following and trajectory tracking. These actions are forces and moments which controls the vehicle. Outputs of the guidance and navigation system enter the control system. Guidance system computes desired situation so control system applies actions with respect to difference between guidance and navigation system [5]. To apply these actions, some control structures are used in order to obtain the best result.

Some of these control structures are listed as follows:

- Fuzzy Logic control
- Proportional-integral-derivative (PID) control
- Neural Network

In Fuzzy logic control system, the designer should evaluate all possible condition and project it to IF-THEN statements programmatically [8]. PID is the most widely used close-loop feedback controller for time based system. Control system based on reducing the difference between current and desired situations. So the system tries to minimize or finish this difference, which is error, in a smallest time value without happening an overshoot or oscillation [6]. Neural network is a mathematical imitation of human brain. Neural Network control structure does not require a mathematical model of the system as the conventional control methods. It built a mathematical relationship between inputs and outputs using artificial neurons.

1.2. Thesis Outline

The summarized chapter objects are given below:

Chapter 1 gives an introduction and summarizes guidance, navigation and the control system.

Chapter 2 gives and discusses the related studies and articles about UVs.

Chapter 3 explains chases of UGV and gives its properties. Besides, GPS, compass and microcontroller hardware and program structure were explained briefly.

Chapter 4 summarizes used guidance algorithm and presents graphics including program codes.

Chapter 5 explains Kalman filter briefly and gives its mathematical equations. Effect of Kalman filter on steer angle was graphically demonstrated.

Chapter 6 explains obstacle avoidance tools which are used for detection of objects and summarizes the applied technique.

Chapter 7 demonstrates graphical test result.

Chapter 8 gives conclusion and future plans related with the future works.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction

Nowadays, there are huge amount of articles about autonomous vehicles, navigation, guidance and control topics. Because of small amount of directly related articles, indirect related articles are presented in literature as well. Some of these articles according to their related importance to this study will be discussed.

2.2. Similar studies about navigation UGVs

Justin [9] has tried to do an autopilot algorithm in a single PIC chip. As similar to this study, in order to work with both 5 Hz GPS interrupt and PWM signals, a novel approach was processed in only single PIC microcontroller. In order to accomplish this, author has given a very useful way to solve problem and also clearly presented a program algorithm. To control a servo motor, PIC MCU should send position signal in 20 ms sequence. That signal has 0.5 to 2.5 ms high time value (high time value is changing according to position) i.e. 0.5 ms high time is for the 0 degree and 2.5 ms is for the 180 degree of rotation. When PWM signal is processed, this may cause an interrupt, microcontroller should not miss the NMEA data that coming from GPS via RS232. To catch NMEA data, PIC microcontroller should read USART buffer in 2.08 ms. Otherwise, microcontroller will fail the NMEA data line. That is known as a triggering process for the taking complete NMEA data line. Creating an ordinary program algorithm for the servo motor will cover large part of the microcontroller processing time. According to this data, the author produced a servo program structure. Interrupt of program has three steps. Firstly, 0.5 ms high time is constant for the all 20 ms signal. Secondly, according to servo motor position, a changing high time was chosen. The last part of program is for low time value to complement

20 ms PWM servo motor signal. For the first step (that is first 0.5 ms high time) a timer was set with a required value to overflow timer interrupt at 0.5 ms In second situation, same timer was set to a required value to overflow at 20 μs to complete 2000 μs. Microcontroller program should generate 100 times timer overflow interrupt. This means that, servo motor can control 1.8º position accuracy. The last part, for the complement of 20 ms, same timer was set to a required value. With this way, PIC microcontroller has a huge time interval to read GPS NMEA data, sensors and to do mathematical calculations. With this pulse train, the best program technique for the autopilot algorithm in a single chip.

Michael and Gilbreath [10] have designed a way-point navigation system with low cost sensors and microprocessor for an unmanned ground vehicle (UGV). In this study, authors has used Kalman filter and some technique to reduce the errors caused from GPS and sensors. To eliminate noise and deficiency, differential global positioning system (DGPS) an approach has been developed. The noise of GPS on position has been eliminated with Kalman filter technique. Fortunately, MTK GPS receiver has a similar function known as satellite based augmented system (SBAS). With the help of this function position accuracy increase up to 2.5 m. So with the activating satellite based augmented system (SBAS) function, a huge part of the workload of program was reduced.

Bok-Joong Yoon and others [11] have proposed a navigation algorithm method with the GPS and compass tools. A control system was designed for the 250 kg vehicle and system images of vehicle were shown in this study. At the end of the article test result was presented and discussed. Similarly, Bok-Joong Yoon and other authors [12] proposed a navigation method with Multi-GPS, IMU and compass module. In order to reduce position errors, Multi-GPS, IMU and compass module sensor was combined. Multi-GPS system consists of 3 GPS receiver. Thus, Multi-GPS can reduce the errors and increase position accuracy according to single GPS receiver. In order to calculate linear acceleration of axis and rotation rates of three axes, IMU sensors was used. With the sensors, the graphs clearly show that more accurate results were obtained by the authors.

2.3. Autonomous UVs and Navigation

Differently, T. Puls et al. [13] have proposed to navigate between way-points for a four rotors Vertical Take Off and Landing (VTOL) helicopter. Control of the system and way-point navigation and zero cross-track angle algorithms are studied in the article. In a similar study, guidance, navigation and control was developed for VTOL helicopter [14] and VTOL helicopter navigation was carried out in [15].

Recently, S. Selvi and others [16] have proposed to navigate an UGV with the lowest number of sensor. For that reason, only GPS sensor was used and compass and gyroscope eliminated. In order to accomplish this, a geometrical approach was applied. For finding steering direction and steering angle of vehicle, co-ordinate of three different positions was used. Process logic of algorithm is as follows. At the beginning UGV moves arbitrarily up to determine heading angle. After that, algorithm finds steering angle in order to orient UGV to way-point.

Recently, Shweta Gupte et al. [7] have carried out a research about UAVs. This article is presents the knowledge about sensors, control structures, vision systems, navigation types and related articles. The article can be pathfinder for who are new in UVs field to learn tools and techniques.

A micro air vehicle (MAV) was navigated with vision-based horizon tracking technique in [17]. Young-Eun Song and Kwang-Joon Yoon [18] was designed an autopilot system for such a system.

Designing a low cost autopilot for an unmanned aerial vehicle (UAV) has been briefly explained in [8] and algorithm development of a low cost way-point navigation system is studied in [6]. An autopilot integration and its tests were studied in [19] for an UAV.

An autonomous UGV for the urban driving and also for DARPA Urban Challenge competition was presented in [20]. In this study, a minivan is equipped with 3 laser scanner and 2 vision cameras. In navigation part Multi GPS, DGPS and a compass was used, details of the systems have been introduced in the article.

2.4. Kalman Filter

Greg Welch and Gary Bishop [21] were intended to explain Kalman filter based on R.E. Kalman (1960) original papers. İbrahim Çayiroglu [30, 22] was tried to explain Kalman filter as simple as possible at the end of the study, an example has been explained by author step by step. This study is very important for one who is the new in Kalman filter.

CHAPTER 3

SOFTWARE AND HARDWARE DESCRIPTIONS

Unmanned Ground Vehicles (UGVs), in most cases, are small car designed to perform specific tasks. They carry a wide variety of sensors and electronic devices required to perform their missions. With the rapid growth of the microprocessors, and miniaturization of electronic components, UGVs can be constructed at very low cost to perform their missions in proper manner as manned ground vehicles. Goal of this thesis is to accomplish sending a robot selected earth coordinate, that is, tracking way-points via GPS receiver. A guidance program in microcontroller will guide the vehicle up to destination point. This section introduces components/systems which were used in the construction of UGV and C programming details to achieve the goal.

3.1. Earth Co-ordinate System

In order to identify and determine accurate position of a location, imaginary lines were derivate for earth. These imaginary lines cover the entire earth sphere according to their angles presented in Figure 3.1. Latitude lines start with Ecuador and increase towards to North and South poles. First longitude starts with Greenwich and increase up to 180 ^{o} for both East and West direction. Northern-East section was used as reference for the system.

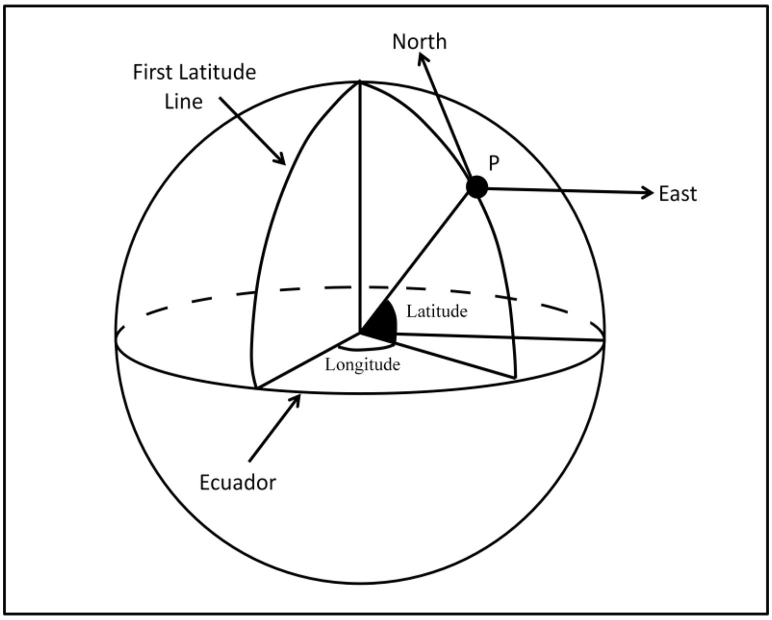

Figure 3.1. Representation of the Latitude and Longitude

3.2. Global positioning system (GPS)

Global positioning system (GPS) is fundamental part of the navigation system and a GPS works with the help of satellites. After initial use of GPS in 1960s, right now, being used by the user many areas. But unfortunately, there are some effects that reduce the quality of GPS signal. Ionosphere, troposphere and reflections of signals from building add errors to the GPS signal. In order to get 2D results, GPS should connect at least three satellites, similarly, in order to get 3D results, that is altitude, GPS should connect at least four satellites. Additionally, there are some techniques in order to improve accuracy. Differential Global Position System (DGPS) reference known exact point so, reduce errors in the GPS signal. Another way, in order to reduce error signal is correction. After GPS receiver connects the correction satellites, position accuracy can be increased up to 2.5 m. These systems are known as WAAS for US and EGNOS for Europe. There are similar systems for the other countries [23]. Fortunately, GPS receiver that is used in this Project (MTK3329 shown in Figure 3.2.) have (satellite based augmented system SBAS) correction property. In order to activate that properties user should send simple code lines serially to GPS receiver. After this process, GPS receiver will give position data more accurately.

Figure 3.2. MediaTek MTK3329 GPS Receiver [34]

In addition to the position data, global positioning system (GPS) can give the time, heading, and velocity. GPS receiver takes that data as National Marine Electronics Association (NMEA) message sentences. There are many types of NMEA message sentences. Some of NMEA message sentences are shown in Figure 3.5. Each type of sentences can consist different data but all of them start with ASCII character “$” and end with the <CR><LF> [23]. In this project RMC type of National Marine Electronics Association (NMEA) message sentence was used. The data of the RMC sentence separate from each other via commas and all data are in the ASCII text format [23]. An example of RMC sentence is presented in Figure 3.3.

$GPRMC,064951.000,A,2307.1256,N,12016.4438,E,0.03,165.48,260406, 3.05,W,A*55

RMC Data Format			
Name	**Example**	**Units**	**Description**
Message ID	$GPRMC		RMC protocol header
UTC Time	064951.000		hhmmss.sss
Status	A		A=data valid or V=data not valid
Latitude	2307.1256		ddmm.mmmm
N/S Indicator	N		N=north or S=south
Longitude	12016.4438		dddmm.mmmm
E/W Indicator	E		E=east or W=west
Speed over Ground	0.03	knots	
Course over Ground	165.48	degrees	True
Date	260406		ddmmyy
Magnetic Variation	3.05,W	degrees	E=east or W=west
Mode	A		A= Autonomous mode D= Differential mode E= Estimated mode
Checksum	*55		
<CR> <LF>			End of message termination

Figure 3.3. RMC sentence data format

Representation of Latitude and Longitude values are in degree, minute and second like 37 º 52' 27". When the Latitude and Longitude values are going to used in PIC microcontroller for the calculations, values are converted to the float point numbers as shown in Figure 3.4.

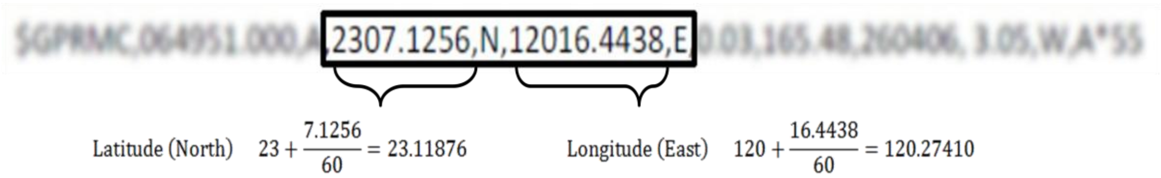

Figure 3.4. Converting Latitude and Longitude to floating point number

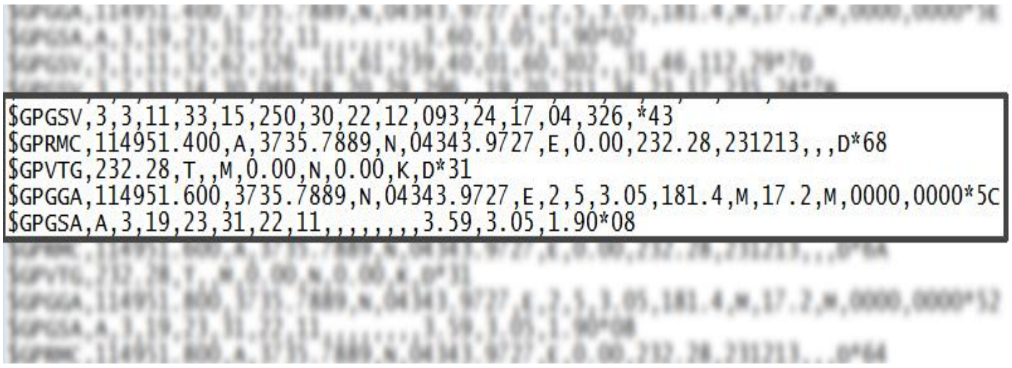

Figure 3.5. Some of NMEA sentences

The PIC microcontroller communicate with GPS receiver with the following parameters: 9600 baud, 8 data bits, no parity bit and 1 stop bit [23]. GPS receiver has high update rate value up to 10 Hz. According to velocity of UGV, 5 Hz update rate has been selected for the project. Higher value of NMEA sentence types, some of them are shown as highlighted in Figure 3.5, requires higher baud rate value. For that reason in our project, only RMC sentence with 5 Hz at 9600 baud has been used and this value enough in order to run communication properly between PIC and GPS receiver. In order to change the options and command the GPS receiver like NMEA output frequency, choosing NMEA sentence types, connecting SBAS satellites and changing baud rate, there are commands to program GPS receiver via serial communication. However, MiniGPS program, shown in Figure 3.6., has been used to command GPS receiver.

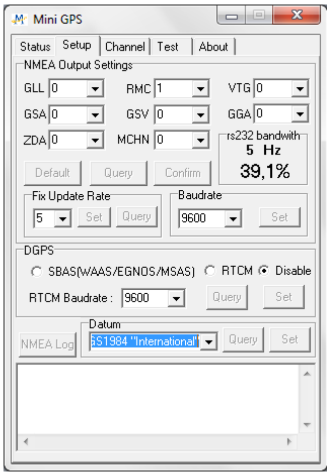

Figure 3.6. Mini GPS programmer software

3.3. Vehicle Chase and Motors

In this project, HSP crawler type vehicle chase and motors was chosen. Structure of vehicle is resistant to hard fields. Image of vehicle on test field is shown in Figure 3.7. It has 2 degree of freedom (DOF), one for rotation about the vertical axis, the other translation about the moving axis. Vehicle was designed properly to carry extra weight and a computer. Because advance control and navigation algorithms will-be implemented to the computer for future works. In order to control steer angle a servo motor and for thrusting two DC motors are used. Chase is made from aluminum and screws and nuts are chosen as aluminum so magnetic compass will not effect from magnetic materials. Some properties of vehicle are given in Table 3.1.

Figure 3.8. UGV top view

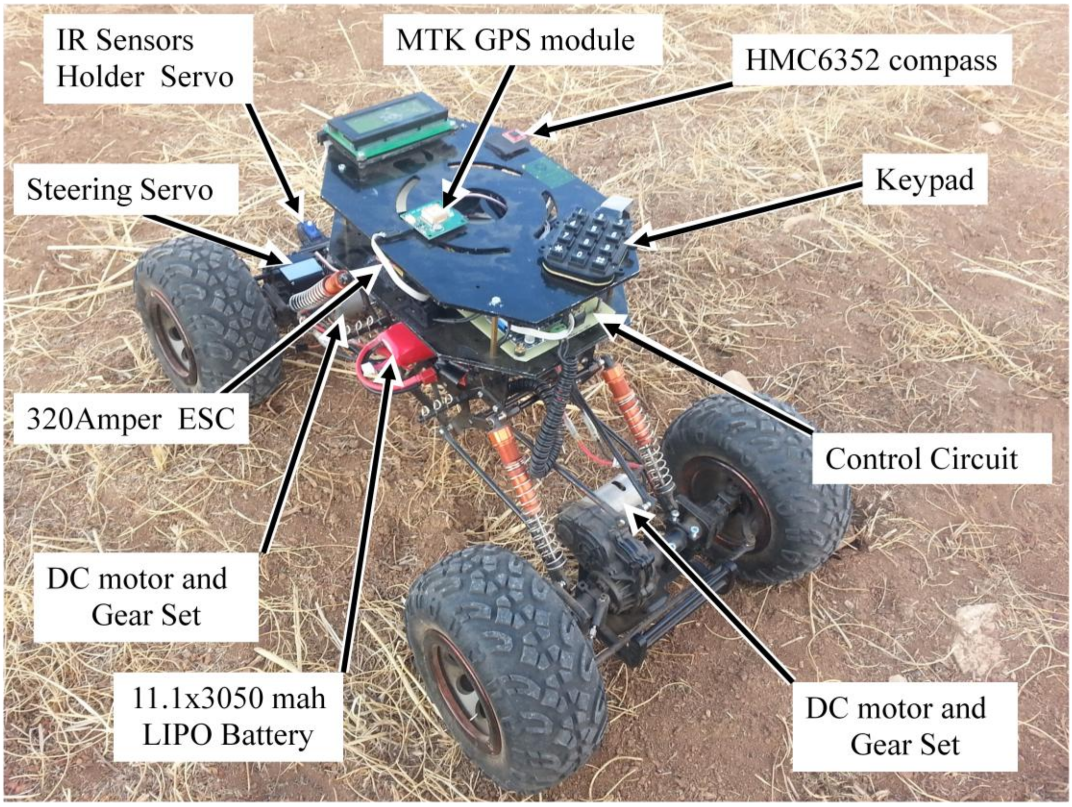

Figure 3.7. UGV system

Table 3.1. Some of properties of the chase

Motor	2XRS540
Weight	5300 g
Steering Motor	Sp9001
Battery	LIPO 11.1V - 3050mah
Lenght	645 mm
Height	225 mm
Gear Rate	1:48.15
width	375 mm

3.4. Honeywell Hmc6352 Compass Module

In order to find heading (that is deviation between direction of movement of the vehicle and North line according to CW presented in Figure 3.9) HMC6352 compass module sensor presented in Figure 3.8. was used. Sensor has 0.5 degree heading resolution. Ferrous metals and magnetic fields highly effect the compass sensor. For that reason, compass module sensor was put away from DC motors and ferrous based screws. And chase of the vehicle was chosen as aluminum material for this reason. Communication protocol between PIC microcontroller and compass sensor is Inter-Integrated Circuit (I2C). Address values of HMC6352 for the reading and writing is 43 and 42 in hexadecimal respectively. In order to take the heading value from sensor, ASCII character “A” (hex 41) should be written to the sensor after this step, 6000 us delay must be given in the program codes. Then, 2 bytes heading value is read from sensor by a microcontroller. This program codes were written in a function and whenever vehicle needed a new heading value program goes to this function. According to velocity and sudden maneuvers, proper refresh rate must be selected. Otherwise, lower refresh rate will reduce sensitivity of the position. In this study, 5 Hz refresh rate was found adequate.

Figure 3.9. Honeywell HMC6352 compass module sensor

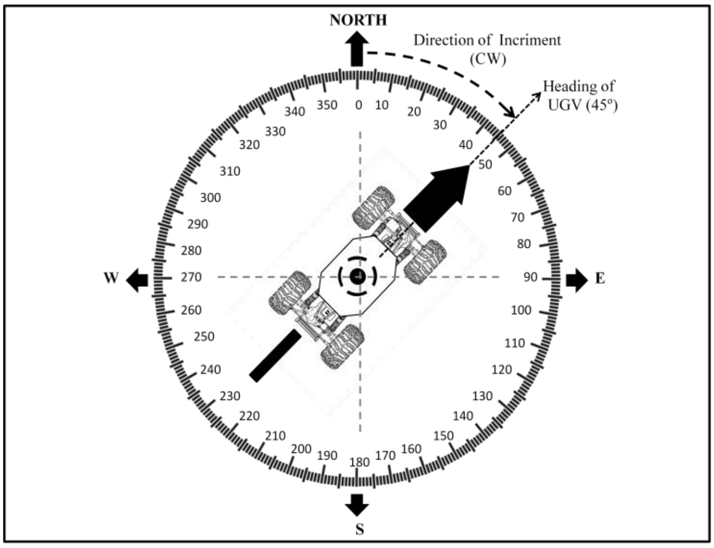

Figure 3.10. Representation of UGV Heading

3.5. PIC Microcontroller and CCS compiler

In this study, PIC microcontroller and as compiler CCS C was used. In order to read and control system, 18F452 8-bit PIC microcontroller was used. PIC18F4F52 has 32KB FLASH program memory and 256 bytes EEPROM memory. Some of features of the PIC18F452 presented in Table 3.2.

Table 3.2. Properties of the PIC18F452

Flash Program Memory	32K
CPU Speed (MIPS)	10
RAM	1,536 Bytes
Data EEPROM	256 Bytes
Digital Communication Peripherals	1-UART, 1-A/E/USART, 1-SPI, 1-I2C1-MSSP(SPI/I2C)
Capture/Compare/PWM Peripherals	2 CCP
Timers	1 x 8-bit, 3 x 16-bit
ADC	8 ch, 10-bit
Pin Count	40 pins

C based CCS compiler has many useful aspects for user. It has also easy way in order to control communication peripherals, timers, ADC and etc. without going into details. CCS allows carrying out 32 bit floating point math calculations [24]. Because of mainly used of floating point math in navigation system, this section will be very critical.

Figure 3.11. MICROCHIP PIC18F452 microcontroller

3.6. Program Details

In order to capture NMEA serial data from GPS with the help of RS232 serial interrupt (**INT_RDA**), Universal Asynchronous Receiver Transmitter (UART) module, that is hardware pins, was used. Similarly, hardware Inter-Integrated Circuit (I2C) was used to talk with an external EEPROM device and compass module. In order to save and store the latitude, longitude, headings, way-point headings, steer angles and filtered steer angles values of UGV that have been traced, ATMEL AT24C256 EEPROM was used. It has got an adequate memory up to 256K (32,768x8 bits) in order to store the test results. ADC ports were used to read IR sensors, and the timer was used to generate PWM signal and ESC. The related schema is shown in Figure 3.12.

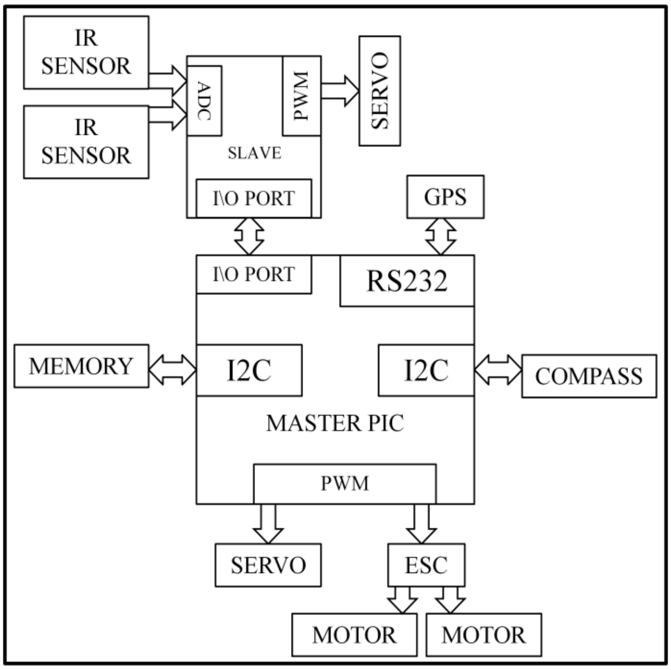

Figure 3.12. Scheme of embedded system

As a different study, in our project, a single PIC microcontroller is used for sensor reading and creating PWM pulse in order to control servos. Used technique in [9] was applied to the system for the constructed UGV. Details of the algorithm has been explained in [9] but here, we will try to explain our system as well. The summary of the technique is as follows. GPS sends data to the PIC microcontroller chip at 5 Hz and 9600 bits\s baud rate when PIC run timer in order to generate PWM signal for servo and ESC. 16 bit timer1 was constructed to do for PWM signal with 20 MHz crystal and p.s. value of 4. Interrupt of direction control signal consist of three section. Signal structure is depicted in Figure 3.13. The first one is for setting 20 ms low time value. Indeed servos generally are being controlled at 50 Hz. Second section is for performing constant high value up to -45º. 0º degree was taken as center value so servo angle will be +90º and -90º. And the last section is for adjusting and construction of servo direction control signal. In this section PIC microcontroller endeavor to generate many pulses at this interval and it eats up all process time with overflowing timer1. As well as it can produce high resolution of position because PIC microcontroller only deals with generation this special signal. Except the third section, in order to catch GPS message, sensor readings and carry out the calculation of guidance-navigation-control (GNC) system, it requires process time. With the help of this technique one can easily construct a GNC system on a single PIC chip. The block diagram of complete used algorithm is shown in Figure 3.14.

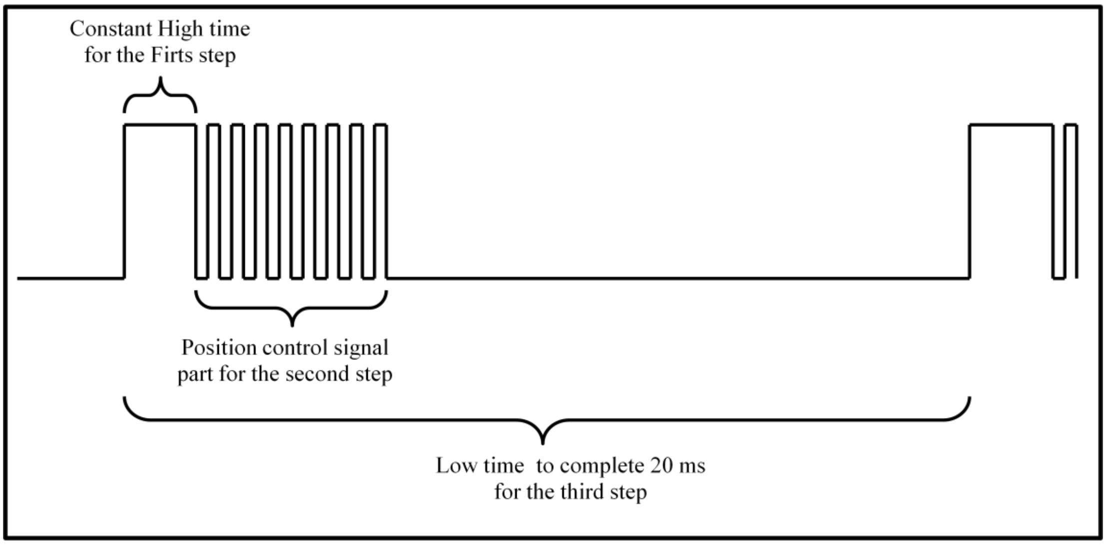

Figure 3.13. Servo control signal structure

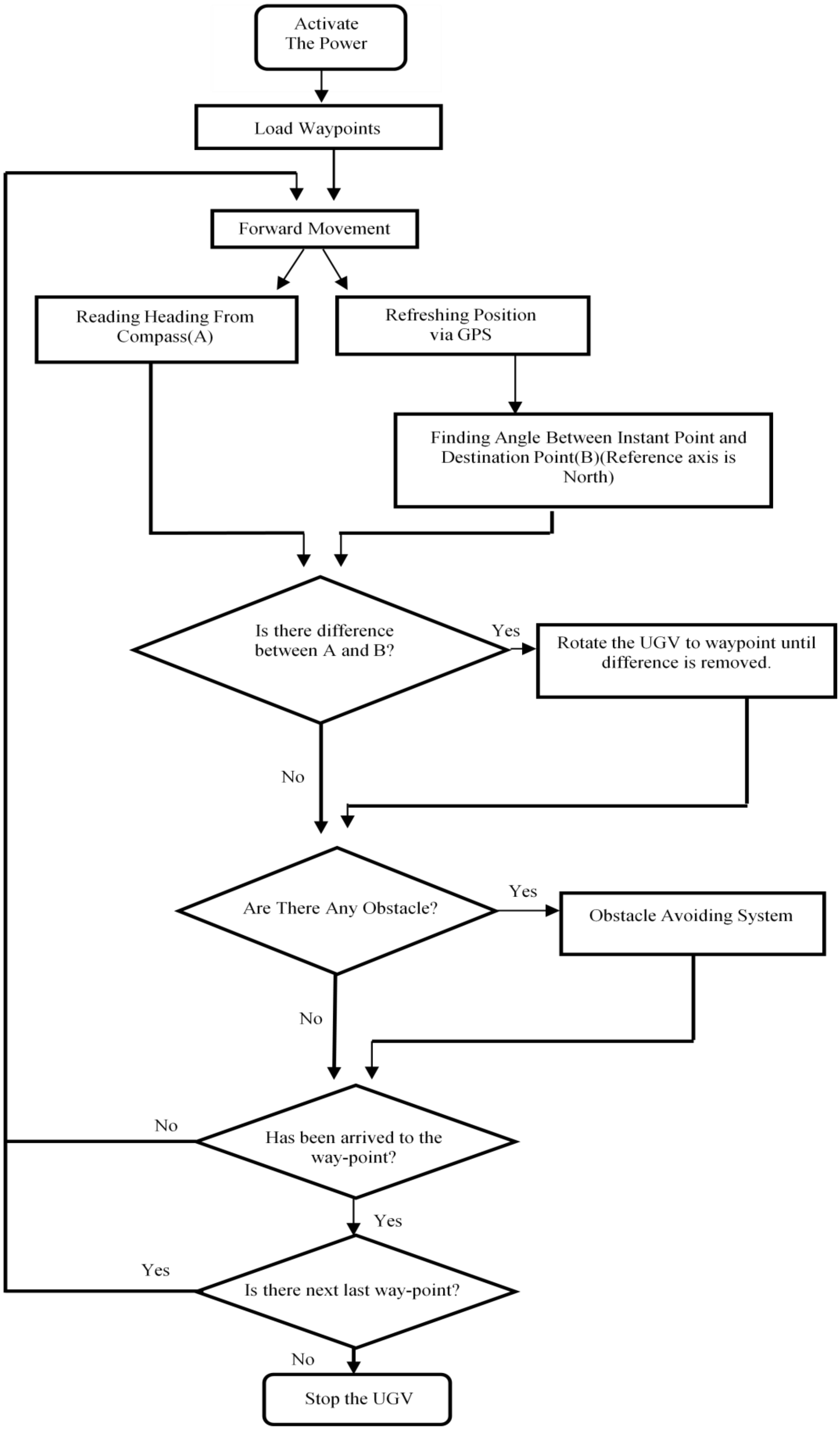

Figure 3.14. Block diagram of unmanned ground vehicle algorithm

CHAPTER 4

GUIDANCE SYSTEM

In general, the guidance system of a vehicle refers to a device or a group of devices used to navigation of it. It should be noted that navigation system is required to calculate instant position, but the guidance system refers to the calculation of the vector toward the desired position. This section introduces guidance system that was used in constructed UGV.

4.1. Introduction

Indeed, a guidance system can be done in many ways, in order to reach and orient the UGV to predetermined position point, the guidance algorithm should produce optimum results with the considering generally weather, road condition, obstacle and collision avoidance. However, there are many types of well known guidance algorithm like Pure Pursuit and Line-of-sight (LOS) guidance algorithm [1, 5]. Interested readers may find much more detail about line-of-sight (LOS) guidance algorithm in [25].

In order to get position data global positioning system (GPS) was used. UGV compares latitude-longitude of current position and desired point. The desired point is called as way-point. When an UGV reaches the way-point then the guidance switches to next way-point. R_k indicates the way-point circle radius. When UGV enters the borders of the this way-point, that is way-point circle, the UGV will turn to the next way-point. A predefined circular area for each way-points perceives whether UGV reaches the way-point or not [5, 25]. This can be defined as a distance value or just an amount of constant floating point number value. According to complexity of the system, a way-point can consist such values of time, altitude for UAVs. In our system, way-points have taken as two dimensional values presented in equation 4.1. [5].

$$wp = \{(lat_0, lon_0), (lat_1, lon_1), .. (lat_n, lon_n)\} \quad (4.1.)$$

The path of UGV should trace just a list of way-points. According to designed system, UGV can track a segment line between two way-points or multiple numbers of adjacent way-points on a straight line. The latter technique is being refined in order to generate smoother path. As shown Figure 4.1, in single way-point method when UGV reaches the corner, it will turn sharply to next way-point (left image). Adjacent way-points near with each other is just a several meters so it is created smoother path for UGV (right image of the Figure 4.1) [26].

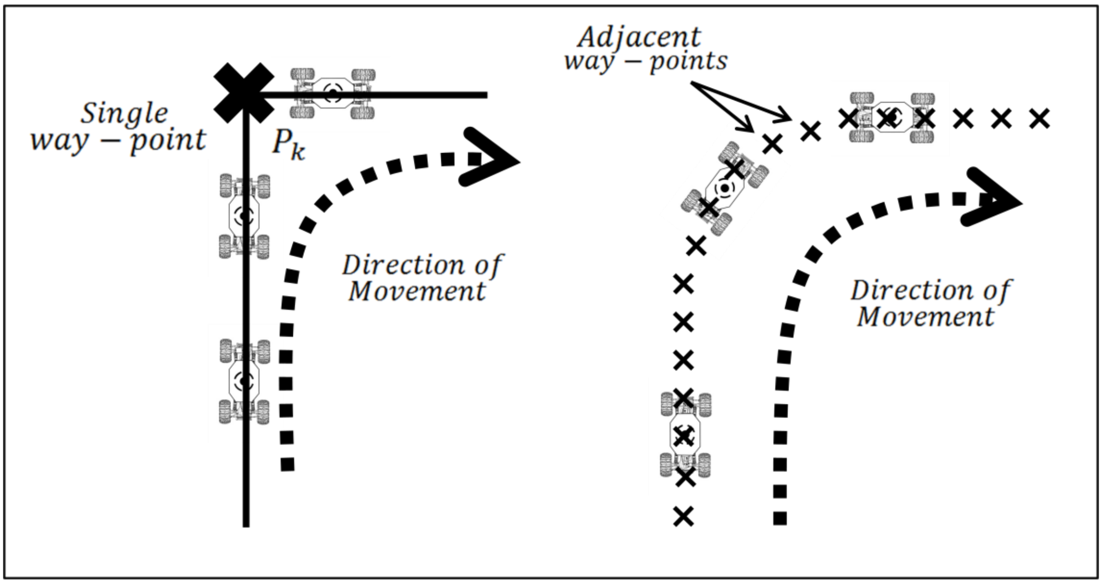

Figure 4.1. Single way-point method (left image) and adjacent way-points methods (right image).

4.2. Line-of-Sight (LOS) guidance algorithm

In this section the guidance algorithm will be briefly discussed and shortly mention about line-of-sight (LOS) guidance algorithm. Much more detail about Line-of-sight (LOS) guidance algorithm can be found in [25]. The goal of line-of sight (LOS) guidance algorithm is to reduce the difference between current position and LOS position, so guidance will carry vehicle to desired destination point. Here, the LOS position is different from way-point. The LOS position is a point on a segment line between two way-points in order to approach the line and exactly track it. In other words, the LOS guidance reduces cross-track distance error. The cross-track distance error is a difference between current vehicle position and path, trajectory or simple line between 2 way-points [25]. This situation is depicted in Figure 4.2.

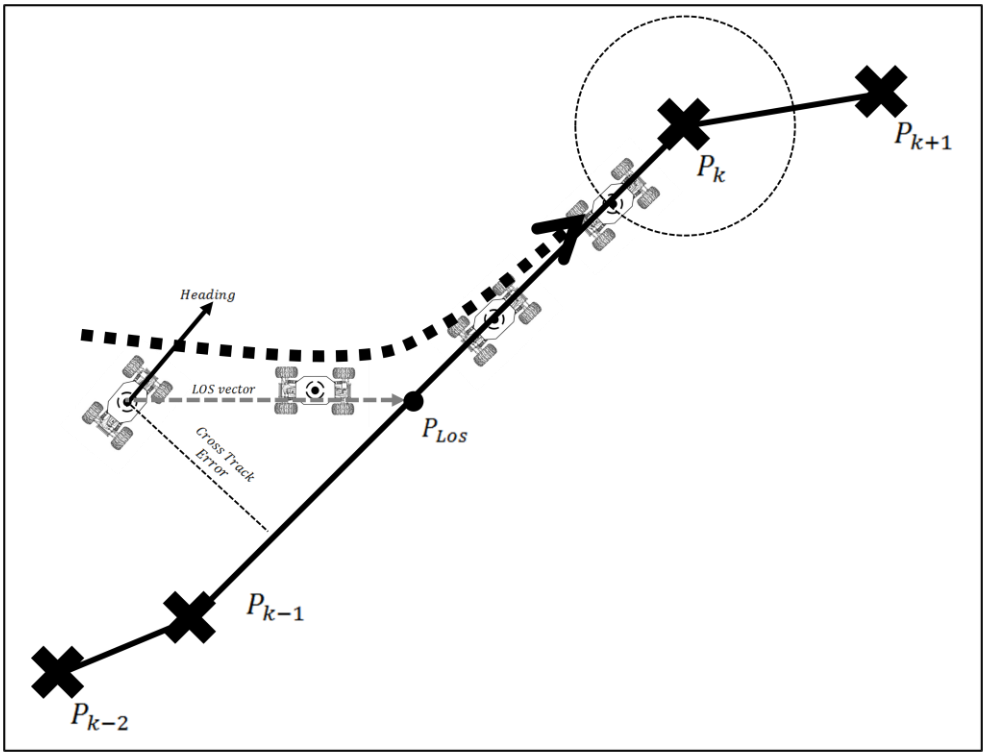

Figure 4.2. Schematic representation of the LOS guidance to reduce cross-track distance error in order to approach the path and the way-point.

In this study, early stage of line-of-sight (LOS) guidance algorithm was implemented. In our guidance system, Ψ_{Los}, P_k are heading or LOS angle and current way-point respectively. P_{Los} , P are LOS position and current position as well. P_{Los} is the current way-point P_k, this means that, the vehicle will lock the current way-point at all conditions without regard line or path between P_k and P_{k-1}. North axis is taken as reference axis in the co-ordinate system, so comparing LOS angle was compared and the heading was done with respect to the north axis [25]. LOS angle is calculated by equation:

$$\Psi_{LOS} = \tan^{-1}\left(\frac{P_k lat - Plat}{P_k lon - Plon}\right) \tag{4.2.}$$

In order to get a continuous map the calculation of LOS angle is shown in Figure 4.3-7 the technique is explained in detail in [25]. Graphical representation and used technique for four quadrants in the co-ordinate system are given including program codes. The schematic representations presented in Figure 4.3-7 are taken from [25] and [27].

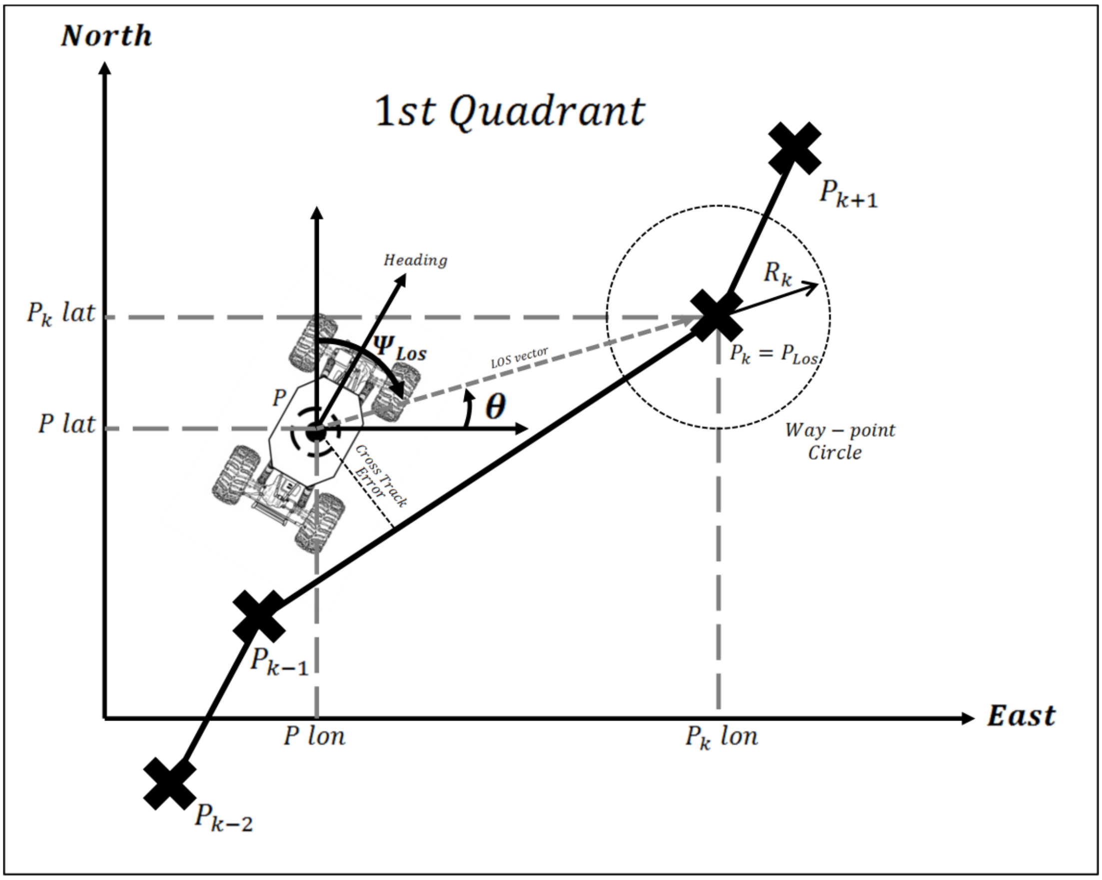

Figure 4.3. Schematic presentation of the LOS angle on first quadrant

The program code for the first quadrant:

```
If (Pklon>Plon) {
If (Pklat>Plat) {
Theta=atan((float)( Pklat-Plat)/(float)( Pklon-Plon));
Theta = Theta *180/3.14;
LOS_angle=90- Theta;
//1. Quadrant
}
}
```

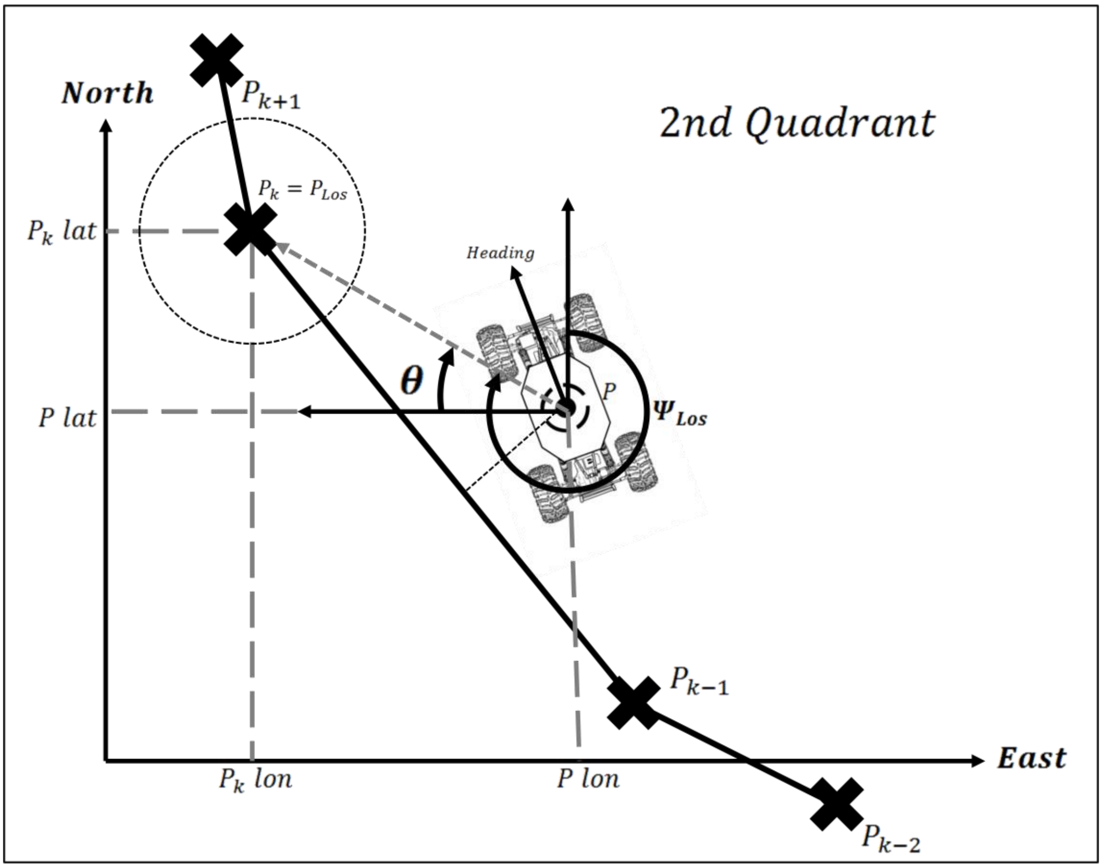

Figure 4.4. Schematic presentation of the LOS angle on second quadrant

```
The program code for the second quadrant:
If (Pklon<Plon){
If (Pklat>Plat){
Theta =atan((float)( Pklat-Plat)/(float)(Plon-Pklon));
Theta = Theta *180/3.14;
LOS_angle=270+ Theta;
//2. quadrant
}
}
```

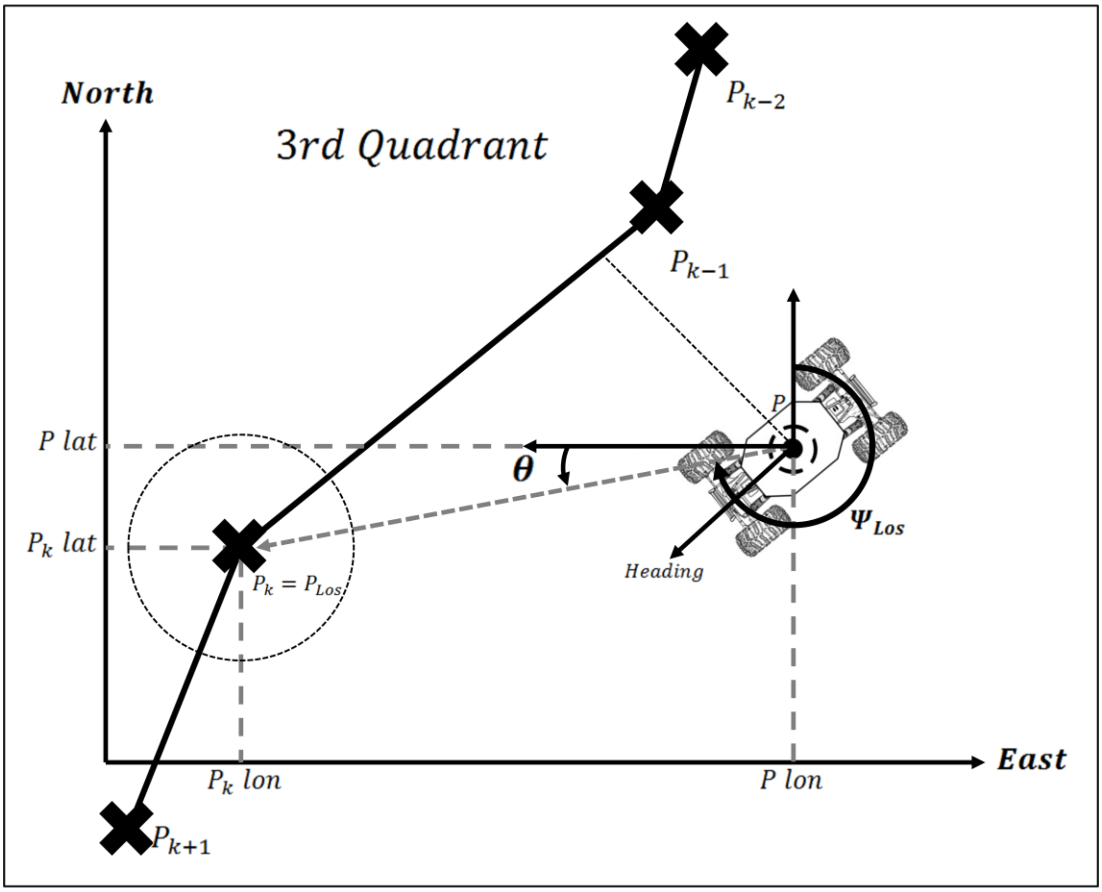

Figure 4.5. Schematic presentation of the LOS angle on third quadrant

The program code for the third quadrant:

```
If (Pklon<Plon){
If (Pklat<Plat){
Theta =atan((float)(Plat-Pklat)/(float)(Plon-Pklon));
Theta = Theta *180/3.14;
LOS_angle=270- Theta;
//3.quadrant
}
}
```

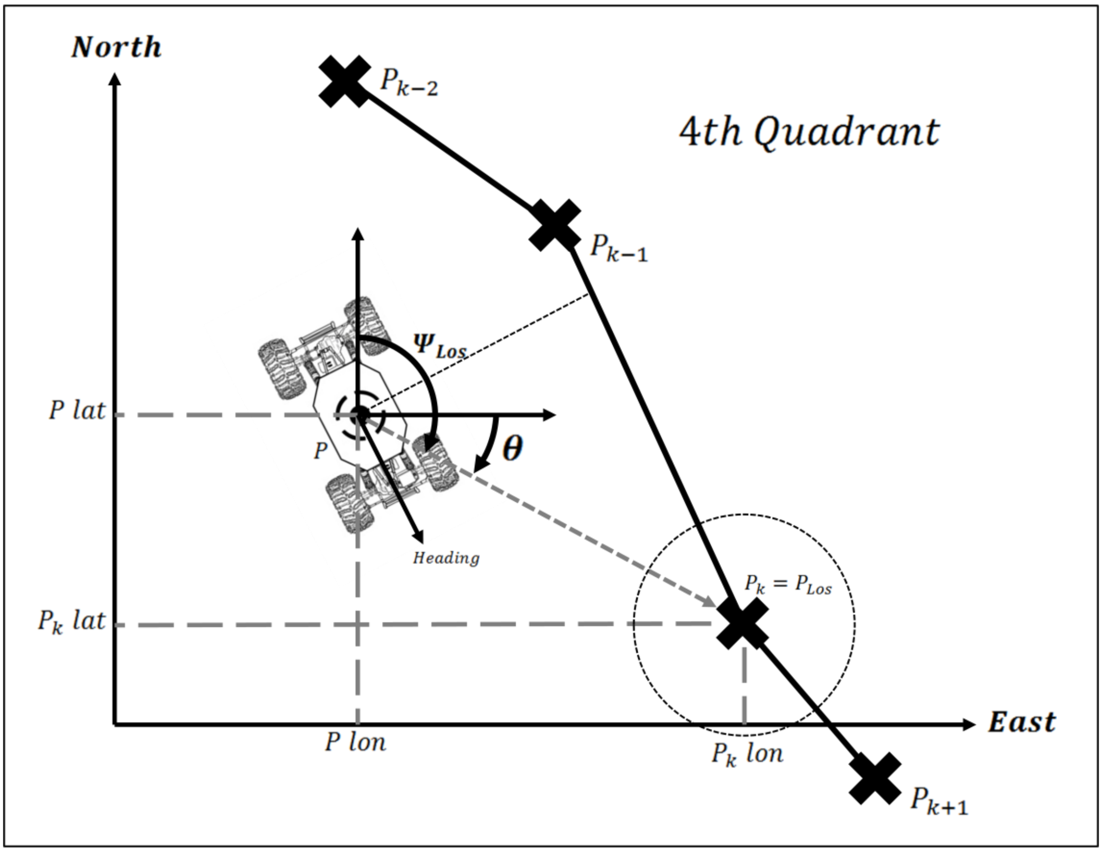

Figure 4.6. Schematic presentation of the LOS angle on fourth quadrant

```
The program code for the third quadrant:
if(Pklon>Plon){
if(Pklat<Plat){
Theta = atan((float)(Plat-Pklat)/(float)( Pklon-Plon));
Theta = Theta *180/3.14;
LOS_angle=90+ Theta;
//4.quadrant
}
}
```

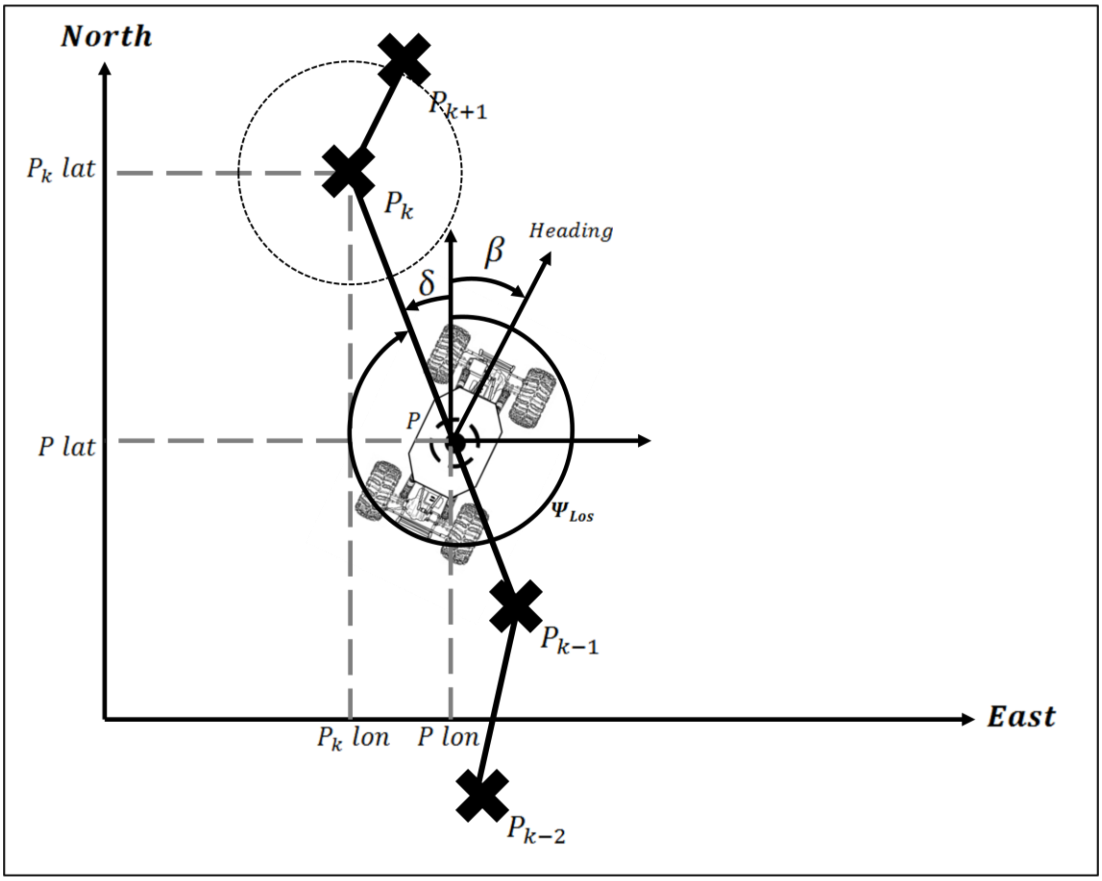

Figure 4.7. Schematic presentation of the steering angle on co-ordinate system

The program code for the third quadrant:

```
Steering_angle= LOS_angle –heading;
If (Steering_angle <-180){
Steering_angle =360+ Steering_angle;
}
If (Steering_angle >180){
Steering_angle = Steering_angle -360;
}
If ((Steering_angle >45)&&( Steering_angle <=180)){
Steering_angle =45;
}
If ((Steering_angle <-45)&&( Steering_angle >=-180)){
Steering_angle =-45;
}
```

```
if((Steering_angle >=-45)&&( Steering_angle <=45)){
Send Steering_Servo direction signal;
}
```

The steering angle is found with differentiating the LOS angle and the heading angle. The Kalman filter algorithm was applied to this value as well. And then, the steering value is used for preventing full rotation when orient the way-point. The steering angle was kept between -45 and +45 angle value, that is full turning of wheels will be kept between -45 and +45. According to the steering angle value, a proper servo position signal value will be sent to servo motor. Servo signal value is proportionel with this value as well. For instance, zero steering angle value will be the 1.5 ms but 1.5 ms value may deviate around it.

CHAPTER 5

KALMAN FILTER

5.1. Introduction

Kalman filter predicts the state of a dynamic system using input and output information of it with prior knowledge. From a theoretical point of view, the main assumption of the Kalman Filter is that the underlying system is a linear dynamic system and difference between model outputs and sensor measurements (errors) obeys the Gaussian distribution of errors. The method has been enriched and developed by embedding plug-ins and generalization. This section describes briefly the Kalman Filter and its applicability on steering angle of the UGV in order to keep it on the path.

5.2. Filtering Techniques

Errors and environmental effects like vibrations will affect heading of UGV at instant evaluations therefore UGV will change servo angle in each discrete time interval even if small changes can be temporary. As an advance study, in order to get smoother, cleaner or filtered data, a smoothing or filtering algorithm should be implemented for steering angle command. There are many different types of smoothing and filtering algorithms. Low Pass filter, Moving Average filter, Exponential smoothing and especially Kalman filter are used in scientific studies [28]. Undoubtedly, Kalman filter is the most powerful filtering algorithm in all filtering techniques because of its predictor-corrector type and commonly used method in navigation system as well [29].

5.3. Kalman Filter Details

Kalman filter was discovered by Rudolf Kalman. Kalman filter is commonly used in aerospace, navigation, robotic and statistic. The reason why it is widely used in the systems is that Kalman filter can estimate condition of the system. Therefore, this filtering algorithm gives better result with the prediction of past, present and future [21].

5.4. Formulation of Kalman Filter

Initially, for discrete-time interval, a model according to Kalman filter equations is to be formulated [21, 29]. List of first step equations is as follow;

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \tag{5.1}$$

$$z_k = Hx_k + v_k \tag{5.2}$$

Here x_k is the estimate state. Z_k is the directly measured value or raw sensor value and our goal is to filter it. In this study, Z_k is the difference between way-point heading and compass heading, that is heading of UGV. u_k, v_k, w_k variables indicates control input, measurement and process noise respectively. $k-1$ present previous condition and k is for current condition. $A,\ B,\ H$ matrixes can change in the process but in this study these values as constant during the process [21,29].

Then, for the second step, 2 groups of Kalman filter equation should be evaluated. First group, is time update also known as Predictor. $\hat{x}_k^-,\ Q$ and P_k^- values shows priori state estimate, process noise covariance and error covariance respectively [29]. Q was taken as a constant for this study arbitrarly. Equations of time update group are written below;

$$\hat{x}_k^- = A\hat{x}_{k-1}^- + Bu_{k-1} \tag{5.3}$$

$$P_k^- = AP_{k-1}^- A^T + Q \tag{5.4}$$

Second group equations of second step is measurement update equations also known as corrector. After all calculations an improved estimate state has been obtained.. List of equations of measurement update group are written below;

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{5.5}$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-) \tag{5.6}$$

$$P_k = (I - K_k H)P_k^- \tag{5.7}$$

Firstly, K_k Kalman gain (5.6) then the posteriori state estimate ($\hat{x}_k$) with the prior state estimate ($\hat{x}_k^-$) is calculated. Finally, posteriori error covariance (P_k) is to be found in order to feedback time update [29].

The time update or predictor projects the system to the ahead. Measurement update gives feedback to the time update equations. This cycle occurs in each discrete time interval [29]. Schematic review of Kalman filter cycle is depicted in Figure 5.1. In order to start cycle, the first $\hat{x}_{k-1}^-$ and P_{k-1}^- must be done. Closer estimates for $\hat{x}_{k-1}^-$ will faster approach to actual value [30, 22].

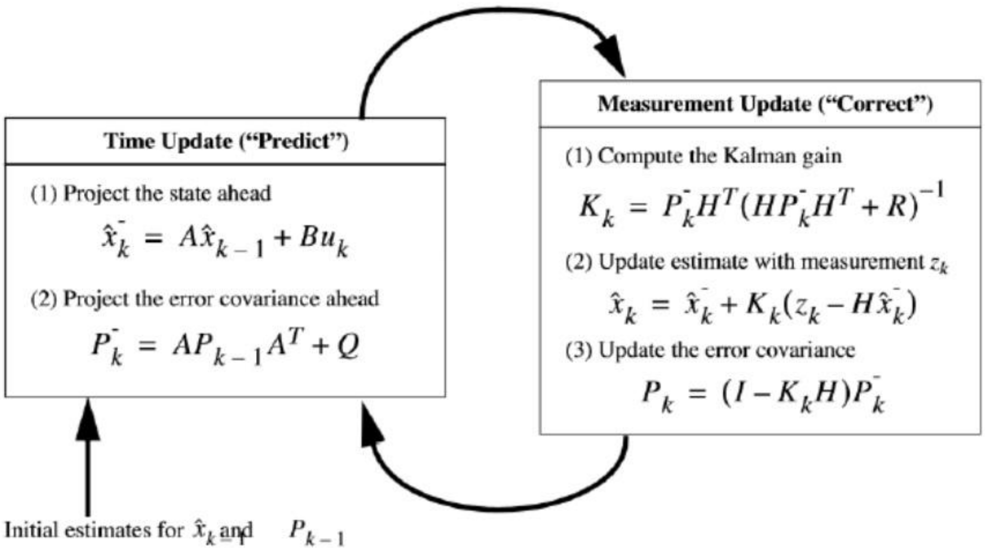

Figure 5.1. Schematic presentation of Kalman filter cycle

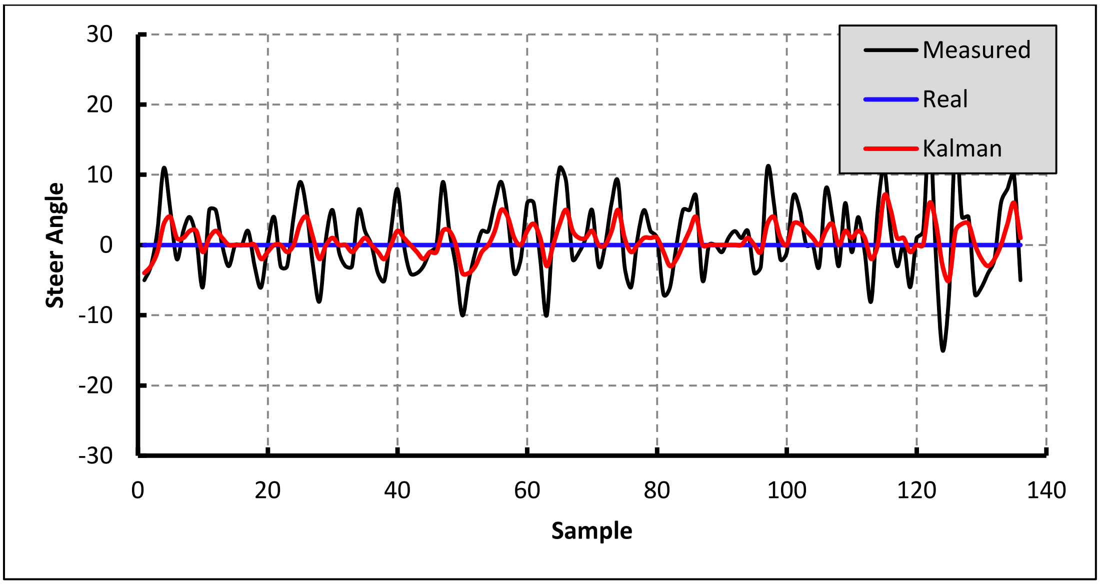

Figure 5.2. Filtered Steer angle during a test

With tuning R and Q values filter can obtain better performance [21]. Figure 5.3. shows slower changes according to direct measured values. The values were founded with estimation. After some iteration the best values can be found.

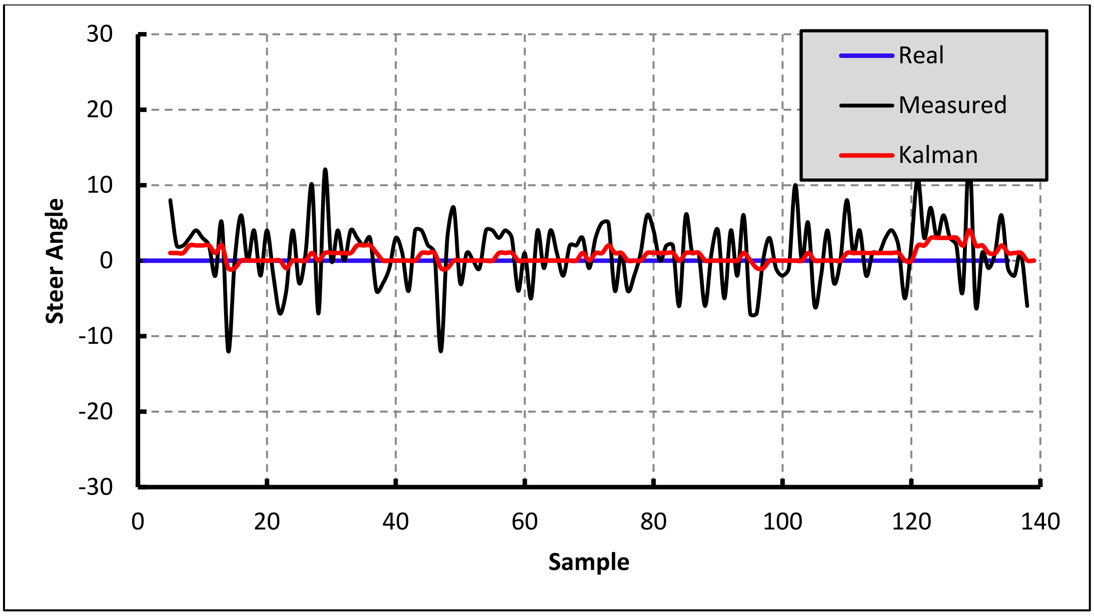

Figure 5.3. Effect of R and Q values on posteriori state estimate ($\hat{x}_k$)

With the slower change according to direct measured values, long time turning problem caused at this time. The effect can be seen in Figure 5.4. In order to avoid from taking a long time turning of UGV, an algorithm was implemented to UGV program. This situation causes problems for long discrete time intervals. That is, it will take a long time up to catch the actual value. The algorithm was tested with this actual value in simulation program and Figure 5.5. was then obtained.

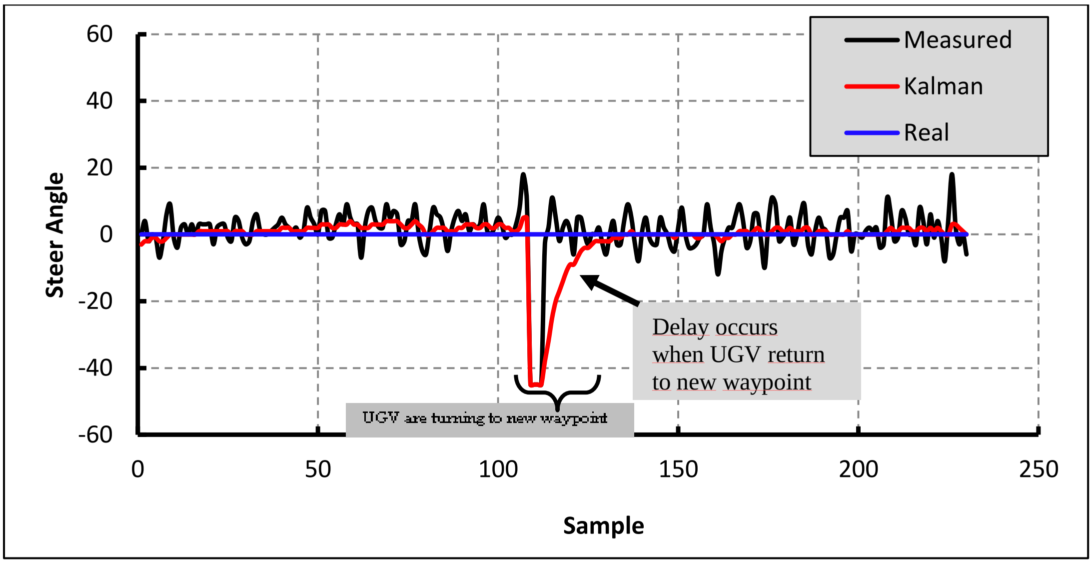

Figure 5.4. Problem of turning next way-point

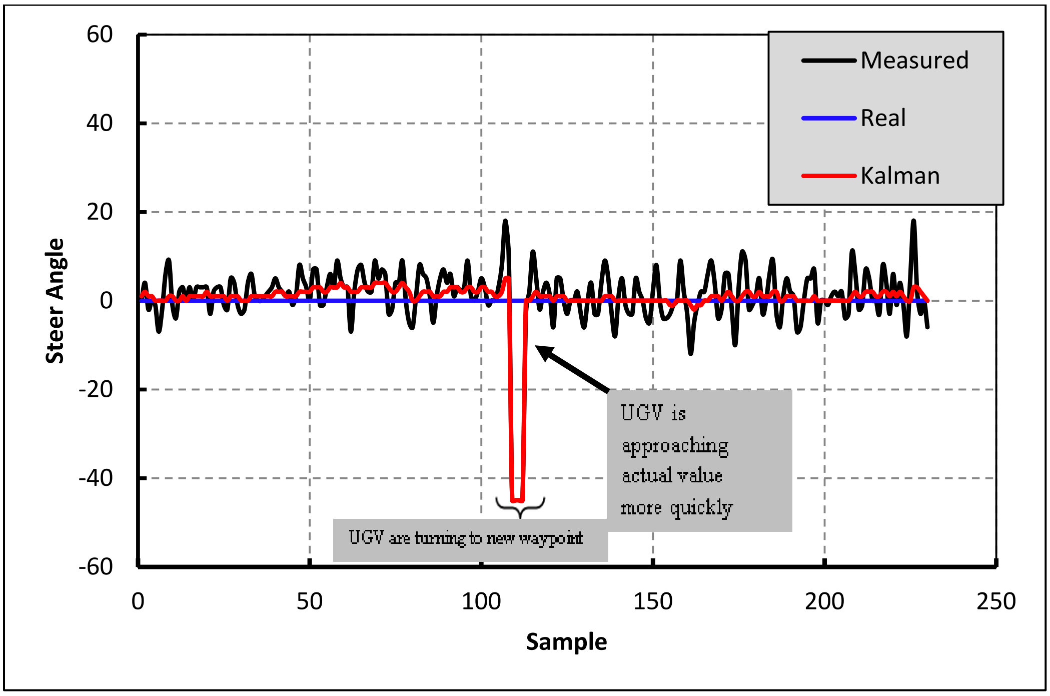

Figure 5.5. Reducing difference between posteriori state estimate ($\hat{x}_k$) and actual value during turning the next way-point

CHAPTER 6

OBSTACLE AVOIDANCE SYSTEM

6.1. Introduction

Obstacle avoidance issue is the one of most important object in autonomous unmanned vehicles [9]. A robust obstacle avoidance system requires sensors systems and robust avoidance algorithms. Therefore a robot can overcome obstacles without problem. To detect obstacles, there are some sensors mainly used in this field like laser range finders, LIDAR, RADAR, sonar and vision sensors. LIDAR is being used to measure distance from environment in three dimensions (Figure 6.1). A laser beam is used to measure distance from reflected surface. A rotating mirror reflects laser light in order to measure distance from other angels [31]. Even though LIDAR gives highly accurate results, high power consumption, high weight and volume and longtime values for the scanning can be seen as disadvantage for LIDAR [9, 10]. In the same principles, RADAR uses radio waves instead of laser light [31].

Figure 6.1. A Laser range finder [32]

For obstacle avoidance system, cameras are mainly used as obstacle detecting sensors. Vision sensors, that are cameras, can be onboard camera or two cameras in order to get more accurate result [7]. Such a commercial camera is depicted in Figure 6.2. Recently, stereo vision technique has been used to obtain three dimensional result and data about situation of obstacle, nevertheless the system needs a powerful computer to be able to obtain satisfactory results [9, 10].

Figure 6.2. Stereo vision camera [33]

Finally, ultrasonic, infrared and one line laser range finders are widely used sensors in robotic for detecting obstacle. Although these sensors can be purchased at lower prices, low accuracy and limited distances and capabilities can be seen as disadvantages [7].

6.2. The Details of used Technique in this study

In the concept of using low cost sensors, in this study two infrared (IR) sensors have been used to detect obstacles just at front side of UGV. These sensors have been mounted on a rotating plane that was installed on a servo motor. In order to scan environment, according to position of the obstacle, the UGV chooses right or left direction as (shown in Figure 6.3.) in order to avoid this obstacle.

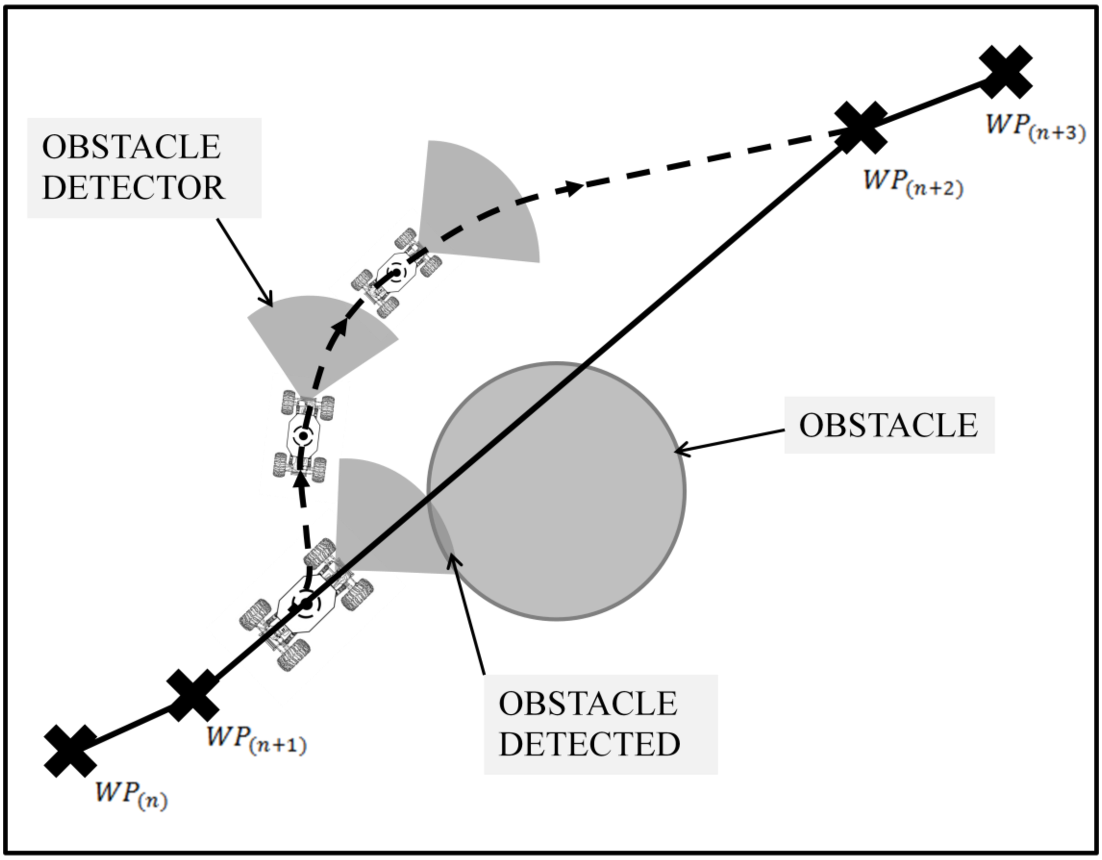

Figure 6.3. A Laser range finder

A 12F725 PIC microcontroller was used to read and convert analog to digital data and in order to drive system servo. Noisy sensor outputs were cleaned by a filter. When sensors detect an obstacle, UGV changes its direction up to avoid the obstacle with respect to right or left sensor. The sensor system which is installed on test bed UGV is shown in Figure 6.4 below. Sensors tracing the obstacle is shown in Figure 6.5.

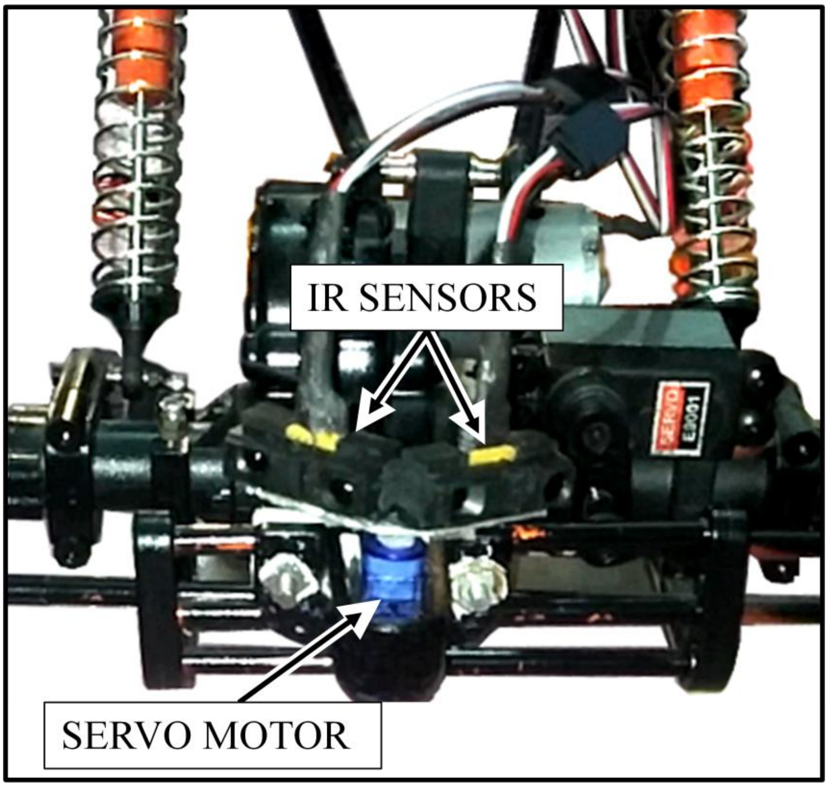

Figure 6.4. Obstacle avoidance system of UGV

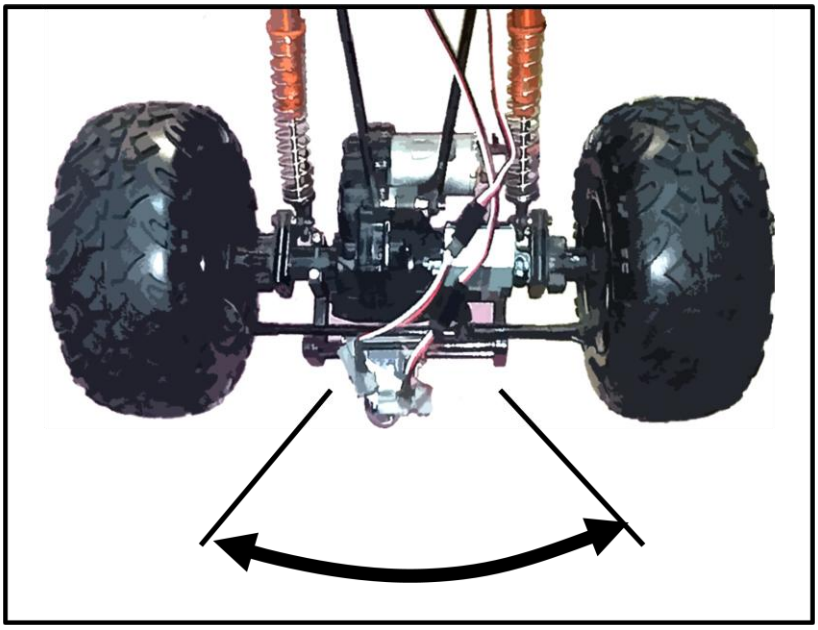

Figure 6.5. Sensors trace the obstacles for smaller time on the head of servo

CHAPTER 7

TEST AND RESULTS

This section shows the test results of constructed UGV and introduces GPS visualizer mapping program. Different tracking examples are given during 3 way-point tests

7.1. GPS visualizer

Fortunately, there is a program in order to represent traced path of UGV. GPS visualizer (www.gpsvisualizer.com) program are used to visualize navigation result.This is given as Figure 7.1. This mapping program is free and you can visualize your navigation results just with the several click after loading co-ordinates [23]. A displayed test result is shown in Figure 7.2.

Figure 7.1. GPS visualizer program

Figure 7.2. A visualized test result in GPS visualizer program

7.2. Graphical Results

During the UGV goes way-points, PIC microcontroller loads coordinates of instant point and steering angle to external EEPROM for every 200 ms. Test result consist of four different number. These are latitude, longitude, raw steering angle value and filtered steering angle value respectively. In order to write a floating point number 4 bytes are used, that is 10 bytes was used for 4 variables in every 200 ms interval in external EEPROM. At the beginning of UGV program, way-points are loaded, after this process is done a for-loop is processed for the way-points up to finish tracking. Way-points that should be tracked by UGV can be loaded via both keypad and a computer. After tests, the results are loaded to the computer serially via RS232. All results were transferred to a text file and then Excel file in order to see graphical results.

The tests were done at relatively hard field for the constructed UGV at Siirt-Kurtalan city nearby Konakpınar village in Turkey. Some images of test field are shown in Figure 7.3. Graphical results are as follows;

Figure 7.3. Some images at the test field.

Tracking result for 4 way-points:

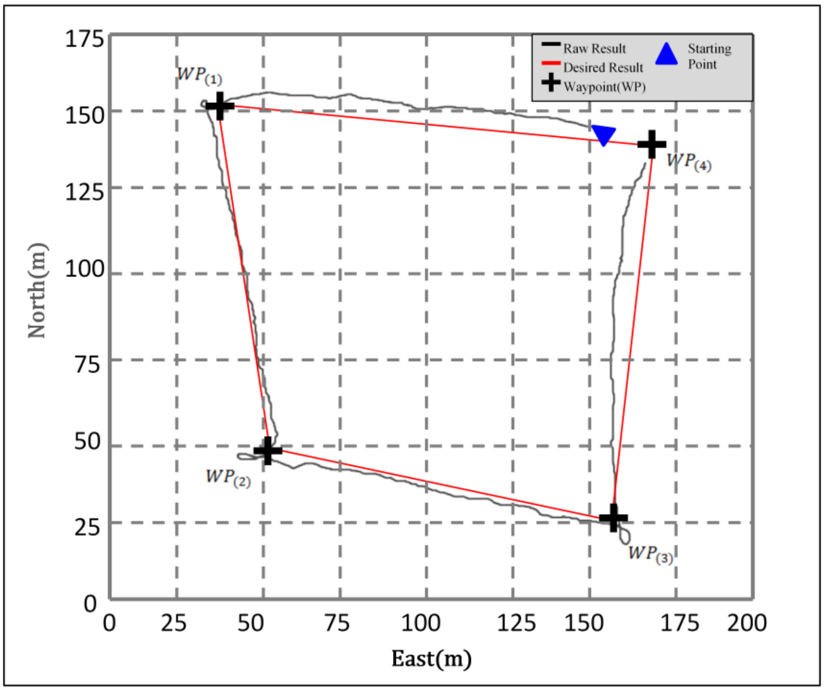

Figure 7.4. UGV tracking results for 4 way-points (with the raw results)

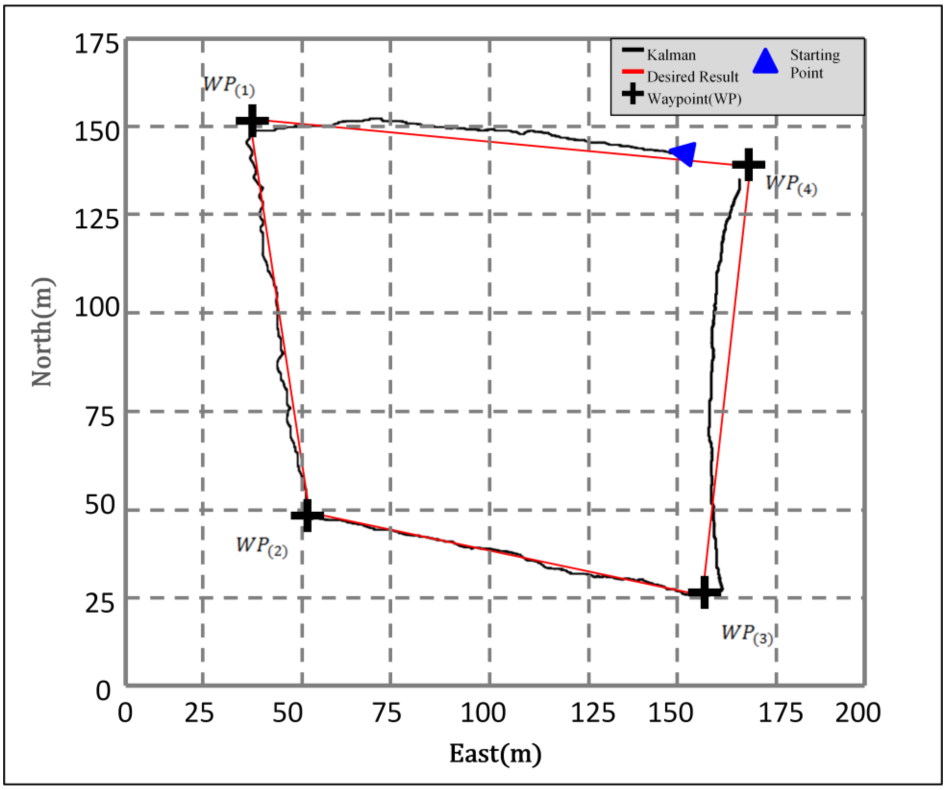

Figure 7.5. UGV tracking results for 4 way-points (filtered results)

Tracking result for 3 way-points test:

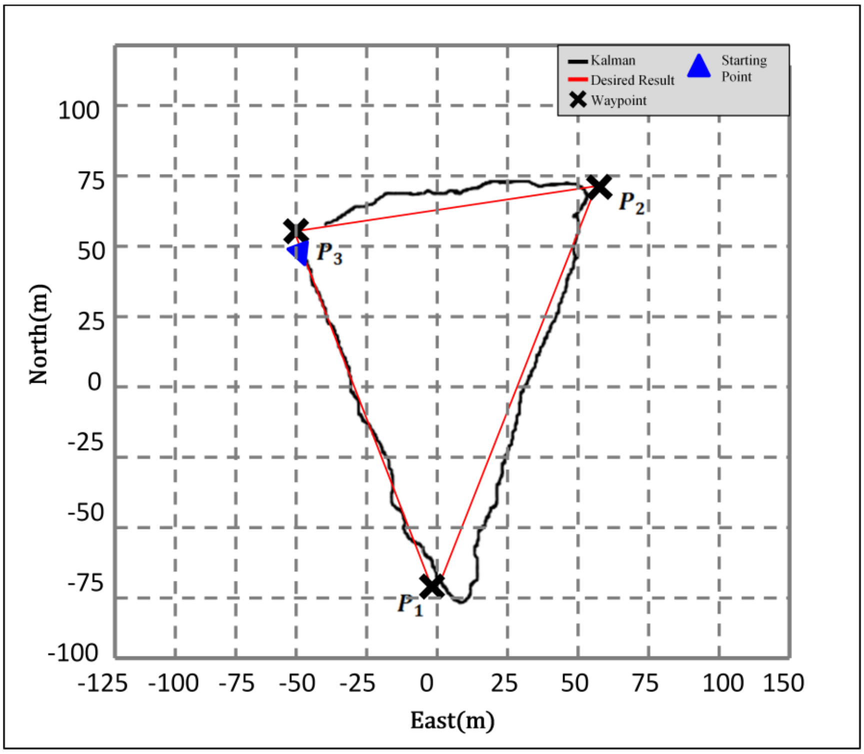

Figure 7.6. UGV tracking results for 3 way-points

Graphical results for 3 way-points test:

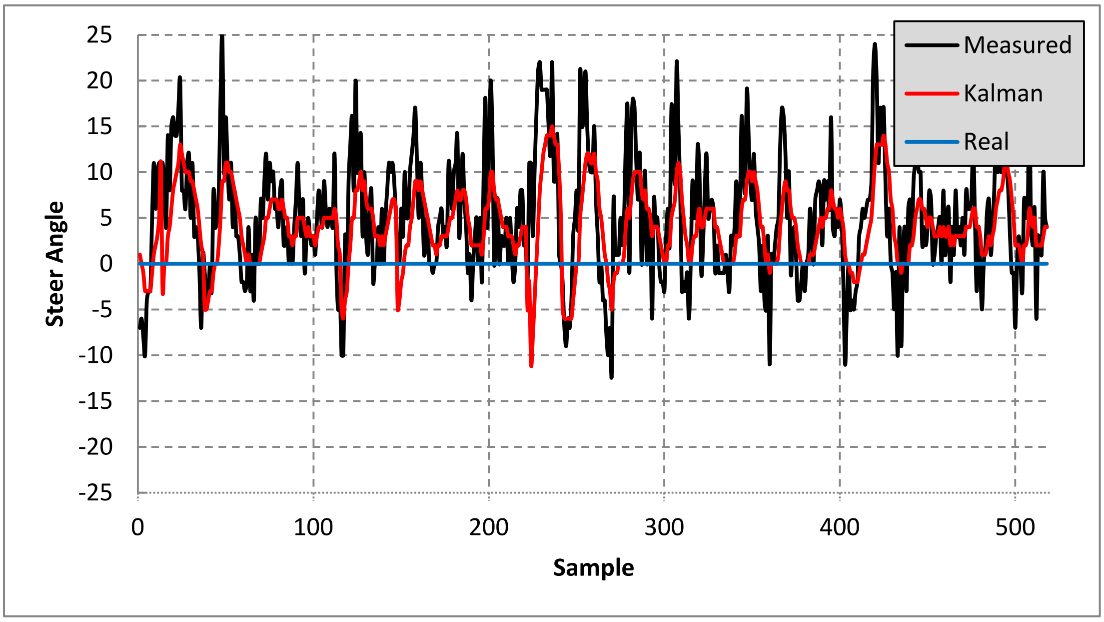

Figure 7.7. Steering values between starting point and first way-point during 3 way-points the test

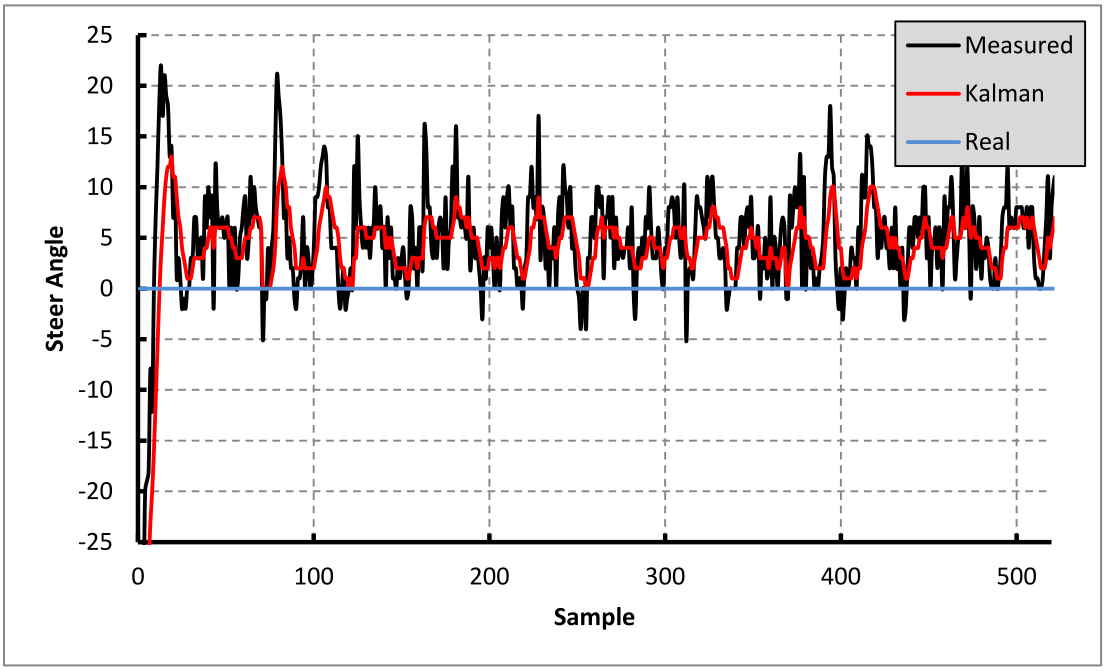

Figure 7.8. Steering values between first way-point and second way-point during 3 way-points the test

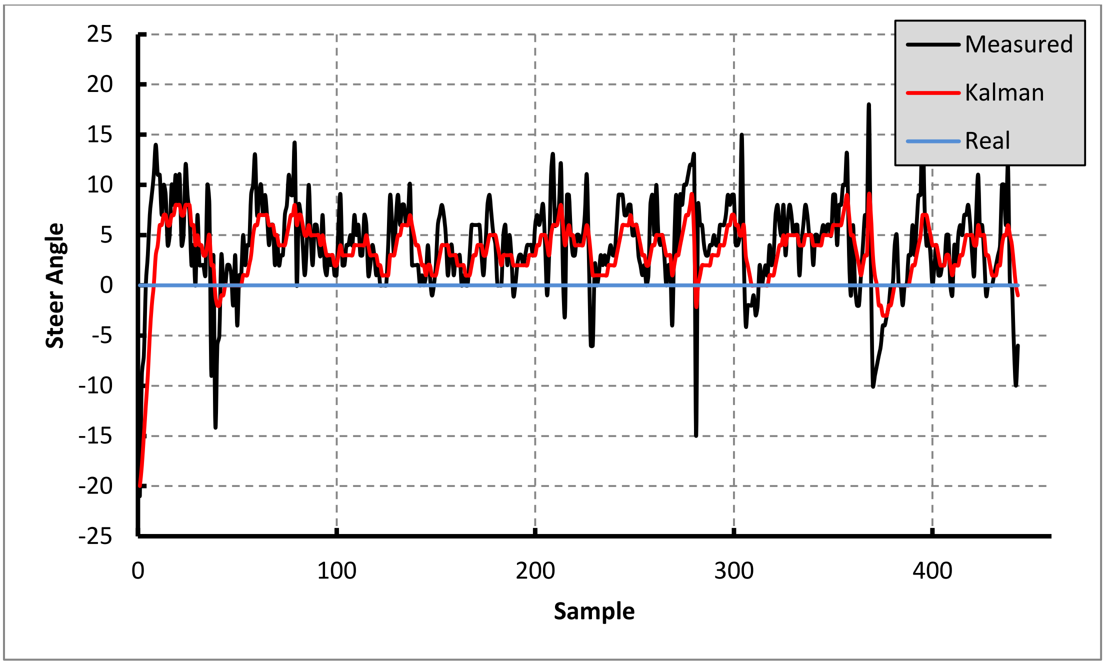

Figure 7.9. Steering values between second way-point and third way-point during 3 way-points the test

To demonstrate the ability of the UVG to track a path which is formed by multi way-points with small distances, an experiment is carried out. As it is seen in Figure 7.12. The representation of UGV track will change according to selected R_k value.

Tracking result for semi circular path:

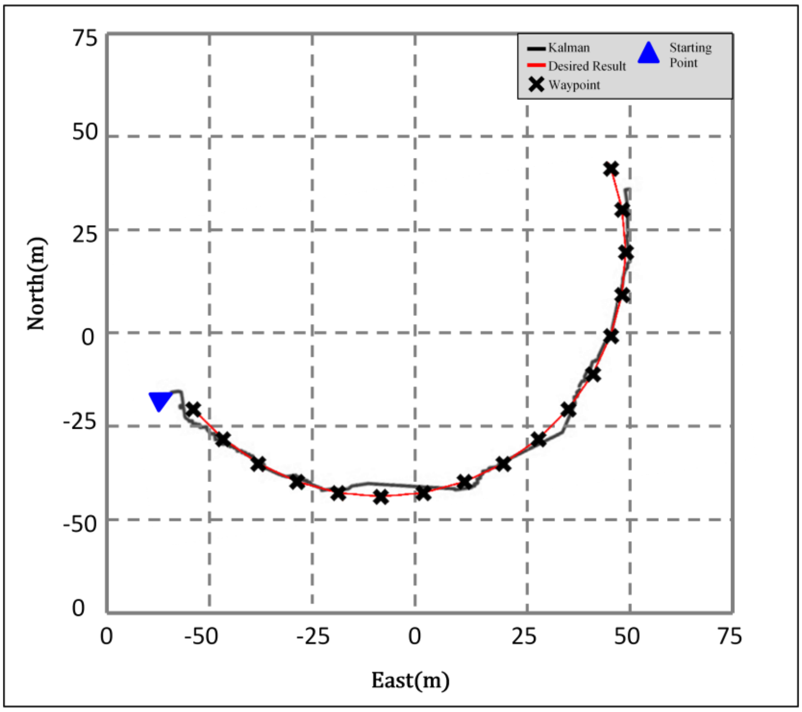

Figure 7.10. UGV tracking results for generated path

Graphical results for semicircular path:

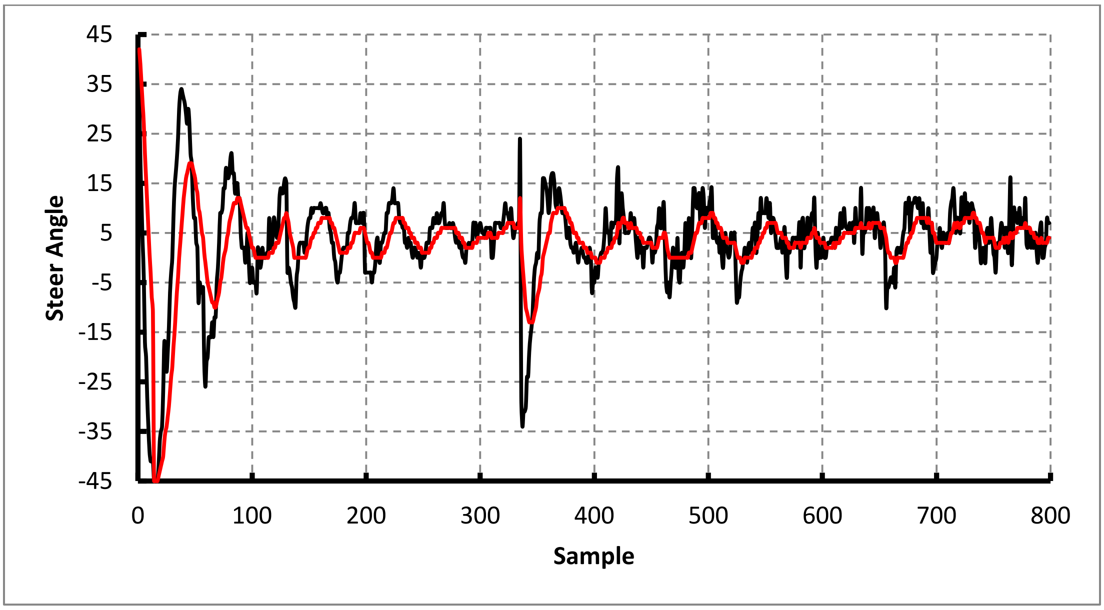

Figure 7.11. Steering results for the path

Main source of the errors on Figure 7.4, Figure 7.5, Figure 7.6 and Figure 7.6 are due to low accuracy of position data which is taken from GPS. Because GPS position signal have large error band, the details are presented in the Chapter 3. In addition to this, high way-point circle (R_k) values or passing over the way-point will cause the big cross track error values. Because of the guidance algorithm that was used in this study takes P_k and P_{Los} equality, UGV guidance will disregard the cross track error. Besides, low position accuracy or low resolution of steering servo causes problems on track of UGV. In order increase stability, reduce cross track between way-points and fluctuations around it, robust guidance algorithms, control structure like PID or advanced control techniques and filtering algorithm including orientation sensors IMU needed to be used.

CHAPTER 8

CONCLUSIONS

8.1 Discussion on the Present Study

In this project a GPS and compass based unmanned ground vehicle (UGV) was constructed and navigated and then the test results were presented at end of the thesis. Details of used techniques were explained. Discussions are combined on the autopilot system, noisy data filtering and obstacle avoiding system.

8.2. About Autopilot System

A complete autopilot system was implemented by using a single microcontroller chip. In order to accomplish that issue, a proper technique was needed to drive servo PWM form which controls the servo. So, microcontroller can able to detect GPS messages while driving a servo. Otherwise, multiple microcontrollers have to be used to do an autopilot unit. So, each PIC chip will be used to deal with different control unit.

8.3. About the Noisy Data Filtering

The raw outputs of the guidance system have a noisy shape because of vibration and environmental reasons. For that reasons, UGV has been performing fluctuation around of the LOS vector. In order to overcome this problem, Kalman filtering was used to eliminate noise which causes unwanted fluctuations when tracking way-points

8.4. About the Obstacle Avoidance System

Finally, in order to avoid obstacles, an obstacle avoidance system has been installed on the front side of the constructed UGV. Two IR range finder sensors were used and mounted on a servo to scan obstacles.

8.5. Recommendation for the Future Work

The design of constructed UGV was planned and constructed to do some research using it for future studies. Upper plate of designed UGV will carry a computer in order to implement and compute advance guidance algorithms. In addition to this, sensorial result will transfer to computer and the result will be processed.

The following studies can be carried out as future work:

- Firstly, Kalman data fusion can be applied to compass sensor output and GPS heading values, then, test can be performed in order to see effect of Kalman fusion.
- Encoders can be used to read wheel speed and so travelled distance can be calculated to obtain precise localization of the UGV.
- IMU sensors can be added to system. With IMU sensors, INS system can be done and then INS can be combined with the GPS. When the GPS signals are interrupted for a case of in tunnels or electronic interface, IMU can allow GPS receiver to be in function.
- A complete proportional-integral-derivative (PID) control can be applied to control motor motion direction.
- A two dimensional Laser range finder and stereo vision system can be used to avoid detected obstacles and holes and study on three dimensional profile of environment.
- Undoubtedly, the hardest parts of unmanned vehicles are ground vehicles because of complicated environment conditions, avoiding large number of unwanted situations and surveillance. For that reason, robust algorithm or solutions should be applied to UGVs. Therefore, for the long term purpose, novel obstacle avoiding techniques can be studied.

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