**DOKUZ EYLÜL UNIVERSITY**
**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

# INDOOR NAVIGATION CONTROL OF A MOBILE AUTONOMOUS VEHICLE

**by**
**Lütfi MUTLU**

**January, 2011**
**İZMİR**

# INDOOR NAVIGATION CONTROL OF A MOBILE AUTONOMOUS VEHICLE

**A Thesis Submitted to the**
**Graduate School of Natural and Applied Science of Dokuz Eylul University**
**In partial Fulfillment of the Requirements for the Degree of Master of Science**
**in Mechatronics Engineering, Mechatronics Engineering Program**

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**Lütfi MUTLU**

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## M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **“INDOOR NAVIGATION CONTROL OF A MOBILE AUTONOMOUS VEHICLE”** completed by **LÜTFİ MUTLU** under supervision of **PROF. DR. EROL UYAR** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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## INDOOR NAVIGATION CONTROL OF A MOBILE AUTONOMOUS VEHICLE


### ABSTRACT

In this thesis, a novel approach for navigation and guidance of a duo cycle autonomous robot vehicle control by using wireless control with ZigBee Modules is presented. For navigation the angular position and location of the vehicle is measured intermittent by means of an electronic compass sensor and a linear position encoder. Both measured values are then compared with microcontroller and PC with the reference points of a certain trajectory, so that a given path can be followed by the vehicle autonomously. In order to control and simulate the vehicle movements a computer program has been developed in Visual Basic programming language. Besides navigation a self developed algorithm is integrated to the system control for possible obstacle avoidance and optimal path finding. The results of experimental testing showed the effectiveness of the proposed approach.



**Keywords**: Zigbee, electronic compass, encoder, control, simulation, robot, optimal path finding.

**OTONOM GEZER BİR ARACIN**
**İÇ MEKAN YÖNLENDİRME KONTROLÜ**

# ÖZ

Bu tezde çiftteker tahrikli otonom bir robot aracın ZigBee kablosuz haberleşme protokolü kullanılarak kontrolü ve yönlendirilmesi için yeni bir yöntem sunulmuştur. Aracın açısal pozisyonu ile konumu elektronik bir pusula ve lineer pozisyon enkoderi ile aralıklarla ölçülerek yönlendirmesi gerçekleştirilmiştir. Ölçülen her iki değer bir bilgisayara aktarılarak belli bir yörüngenin referans koordinatları ile karşılaştırılıp, aracın bu yörüngeyi otonom olarak takip etmesi sağlanmıştır. Aracın kontrolü, simülasyonu ve hedef noktaların uzaktan gönderimi için Visual Basic programlama dilinde simülasyon programı geliştirilmiştir. Yönlendirme ile birlikte sisteme özel geliştirilmiş bir yazılım algoritması entegre edilerek muhtemel engel geçme ve en kısa yol bulma kabiliyetleri eklenmiştir. Sistemin etkinliği ve uygulanabilirliği deneysel test sonuçları ile gösterilmiştir.

**Anahtar Kelimeler:** Zigbee, elektronik pusula, enkoder, kontrol, simülasyon, robot, en kısa yol bulma.

**CONTENTS**

**Page**

# CHAPTER ONE

# INTRODUCTION

## 1.1 Overview

Autonomous robotic vehicle navigation relies on the vehicle being able to know where it is to an adequate degree of accuracy, and also to be able to sense the environment around it as required.

The guidance and the navigation of unmanned vehicles are important issues for making autonomous robots. If a robot is going to make a decision about performing a task which is expected from it, first of all it has to know its whereabouts and state in the working environment (Roumeliotis and Bekey, 2000). For example, people use their eyes and brain for feedback from their surroundings to decide what to do next, depending on the task they will perform. Nerves that are responsible of seeing create the image on the retina part of the eye and then send the information to the brain for processing. Then, the brain makes a judgment about how to act in this situation, and send the commands via nerves to the necessary parts of the body.

Likewise, if a robot, whether mobile or not, is required to achieve a mission, it has to get feedback from its environment. That being so, the robot uses some sensing devices to be aware of its current situation; which may include force, radiation, temperature, direction, inclination, acceleration, velocity or position. If the system in question is assumed to carry out navigational demands, these feedback data should include the vehicle's position, velocity and acceleration. In order for a robot to determine its present position accurately, first it has to take measurements from the real world and then post-process these data to eliminate the uncertainties that are always inherent in the measurement information. Afterwards, the robot can be said to have a reliable estimate of its current position which may be used for navigation purposes (Negenborn, 2003).

Because of the inconvenient use of GPS based systems in indoor applications a novel system is developed as introduced in this work.

## 1.2 The Global Positioning System (GPS)

The Global Positioning System (GPS) is a satellite-based navigation system that was developed by the U.S. Department of Defense (DoD) in the early 1970s. Initially, GPS was developed as a military system to fulfill U.S. military needs. However, it was later made available to civilians, and is now a dual-use system that can be accessed by both military and civilian users (FRP, 1999).

GPS provides continuous positioning and timing information, anywhere in the world under any weather conditions. Because it serves an unlimited number of users as well as being used for security reasons, GPS is a one-way-ranging (passive) system (Langley R. B., 1990). That is, users can only receive the satellite signals. This chapter introduces the GPS system, its components, and its basic idea.

### *1.2.1 Overview of GPS*

GPS consists, nominally, of a constellation of 24 operational satellites. This constellation, known as the initial operational capability (IOC), was completed in July 1993. The official IOC announcement, however, was made on December 8, 1993(Hoffmann-Wellenhof, B., H. Lichtenegger, and J. Collins,1994),. To ensure continuous worldwide coverage, GPS satellites are arranged so that four satellites are placed in each of six orbital planes (Figure 1.1). With this constellation geometry, four to ten GPS satellites will be visible anywhere in the world, if an elevation angle of 10° is considered. As discussed later, only four satellites are needed to provide the positioning, or location, information.

GPS satellite orbits are nearly circular (an elliptical shape with a maximum eccentricity is about 0.01), with an inclination of about 55° to the equator. The semimajor axis of a GPS orbit is about 26,560 km (i.e., the satellite altitude of about 20,200 km above the Earth's surface) (Langley, R. B., 1991). The corresponding GPS orbital period is about 12 sidereal hours (~11 hours, 58 minutes). The GPS system was officially declared to have achieved full operational capability (FOC) on July 17, 1995, ensuring the availability of at least 24 operational, nonexperimental, GPS satellites. In fact, as shown in Section 1.4, since GPS achieved its FOC, the number of satellites in the GPS constellation has always been more than 24 operational satellites.

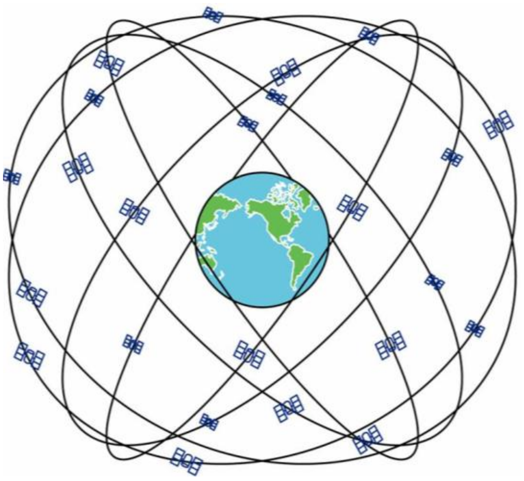

Figure 1.1 GPS constellation

### *1.2.2 GPS segments*

GPS consists of three segments: the space segment, the control segment, and the user segment (Figure 1.2) (Wells, D. E., 1987). The space segment consists of the 24-satellite constellation introduced in the previous section. Each GPS satellite transmits a signal, which has a number of components: two sine waves (also known as carrier frequencies), two digital codes, and a navigation message. The codes and the navigation message are added to the carriers as binary biphase modulations (Wells, D. E., 1987). The carriers and the codes are used mainly to determine the distance from the user's receiver to the GPS satellites. The navigation message contains, along with other information, the coordinates (the location) of the satellites as a function of time. The transmitted signals are controlled by highly accurate atomic clocks onboard the satellites.

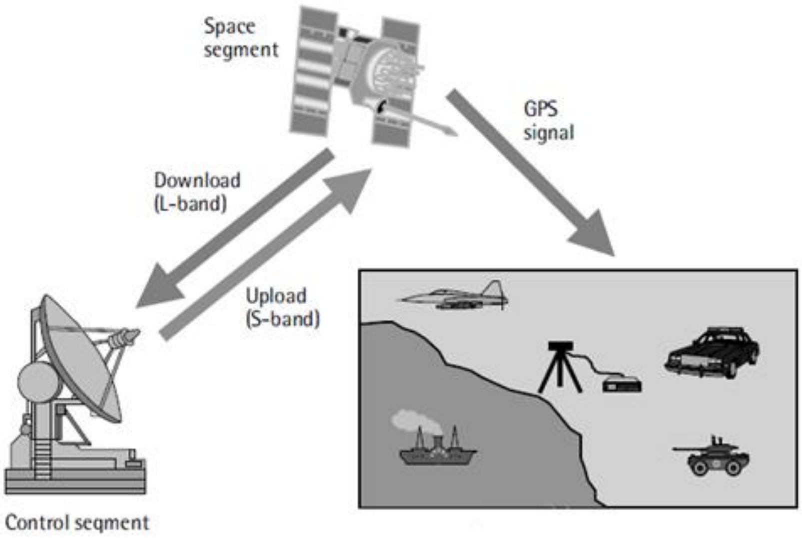


Figure 1.2 GPS segments

The control segment of the GPS system consists of a worldwide network of tracking stations, with a master control station (MCS) located in the United States at Colorado Springs, Colorado. The primary task of the operational control segment is tracking the GPS satellites in order to determine and predict satellite locations, system integrity, behavior of the satellite atomic clocks, atmospheric data, the satellite almanac, and other considerations. This information is then packed and uploaded into the GPS satellites through the S-band link. The user segment includes all military and civilian users. With a GPS receiver connected to a GPS antenna, a user can receive the GPS signals, which can be used to determine his or her position anywhere in the world. GPS is currently available to all users worldwide at no direct charge.

### *1.2.3 GPS: The basic idea*

The idea behind GPS is rather simple. If the distances from a point on the Earth (a GPS receiver) to three GPS satellites are known along with the satellite locations, then the location of the point (or receiver) can be determined by simply applying the well-known concept of resection (Langley, R. B., 1991). But how can we get the distances to the satellites as well as the satellite locations?

Each GPS satellite continuously transmits a microwave radio signal composed of two carriers, two codes, and a navigation message. When a GPS receiver is switched on, it will pick up the GPS signal through the receiver antenna. Once the receiver acquires the GPS signal, it will process it using its built-in software. The partial outcome of the signal processing consists of the distances to the GPS satellites through the digital codes (known as the pseudoranges) and the satellite coordinates through the navigation message.

Theoretically, only three distances to three simultaneously tracked satellites are needed. In this case, the receiver would be located at the intersection of three spheres; each has a radius of one receiver-satellite distance and is centered on that particular satellite (Figure 1.3).

From the practical point of view, however, a fourth satellite is needed to account for the receiver clock offset (Kaplan, E., 1990). The accuracy obtained with the method described earlier was until recently limited to 100m for the horizontal component, 156m for the vertical component, and 340 ns for the time component, all at the 95% probability level. This low accuracy level was due to the effect of the so-called selective availability, a technique used to intentionally degrade the autonomous real-time positioning accuracy to unauthorized users (Hoffmann-Wellenhof, B., H. Lichtenegger, and J. Collins, 1994).

With the recent presidential decision of terminating the selective availability, the obtained horizontal accuracy is expected to improve to about 22m (95% probability level) (Shaw, M., K. Sandhoo, and D. Turner, 2000), (Conley, R., 2000). To further improve the GPS positioning accuracy, the so-called differential method, which employs two receivers simultaneously tracking the same GPS satellites, is used. In this case, positioning accuracy level of the order of a subcentimeter to a few meters can be obtained.

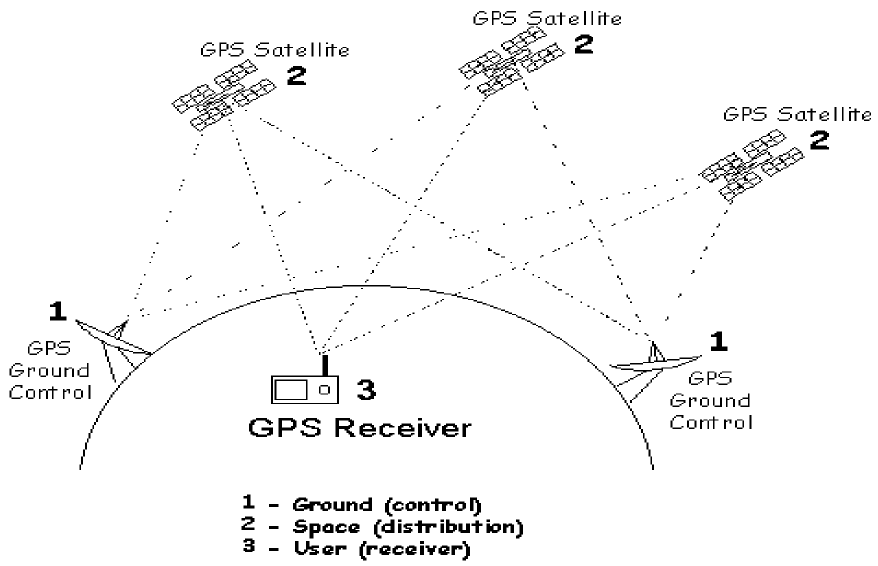


Figure 1.3 GPS communication scheme

Other uses of GPS include the determination of the user's velocity, which could be determined by several methods. The most widely used method is based on estimating the Doppler frequency of the received GPS signal Kaplan, E., 1990). It is known that the Doppler shift occurs as a result of the relative satellite-receiver motion. GPS may also be used in determining the attitude of a rigid body, such as an aircraft or a marine vessel. The word "attitude" means the orientation, or the direction, of the rigid body, which can be described by the three rotation angles of the three axes of the rigid body with respect to a reference system. Attitude is determined by equipping the body with a minimum of three GPS receivers (or one special receiver) connected to three antennas, which are arranged in a non-straight line (Kleusberg, A., 1995). Data collected at the receivers are then processed to obtain the attitude of the rigid body.

### *1.2.4 GPS positioning service*

As stated earlier, GPS was originally developed as a military system, but was later made available to civilians as well. However, to keep the military advantage, the U.S. DoD provides two levels of GPS positioning and timing services: the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS)

PPS is the most precise autonomous positioning and timing service. It uses one of the transmitted GPS codes, known as P(Y)-code, which is accessible by authorized users only. These users include U.S. military forces. The expected positioning accuracy provided by the PPS is 16m for the horizontal component and 23m for the vertical component (95% probability level).

SPS, however, is less precise than PPS. It uses the second transmitted GPS code, known as the C/A-code, which is available free of charge to all users worldwide, authorized and unauthorized. Originally, SPS provided positioning accuracy of the order of 100m for the horizontal component and 156m for the vertical component (95% probability level). This was achieved under the effect of selective availability. With the recent presidential decision of discontinuing the SA, the SPS autonomous positioning accuracy is presently at a comparable level to that of the PPS.

### *1.2.5 Why use GPS?*

GPS has revolutionized the surveying and navigation fields since its early stages of development. Although GPS was originally designed as a military system, its civil applications have grown much faster. As for the future, it is said that the number of GPS applications will be limited only to one's imagination.

On the surveying side, GPS has replaced the conventional methods in many applications. GPS positioning has been found to be a cost-effective process, in which at least 50% cost reduction can be obtained whenever it is possible to use the so-called real-time kinematic (RTK) GPS, as compared with conventional techniques (Berg, R. E., 1996). In terms of productivity and time saving, GPS could provide more than 75% timesaving whenever it is possible to use the RTK GPS method.

The fact that GPS does not require intervisibility between stations has also made it more attractive to surveyors over the conventional methods. For those situations in which the GPS signal is obstructed, such as in urban canyons, GPS has been successfully integrated with other conventional equipment. GPS has numerous applications in land, marine, and air navigation. Vehicle tracking and navigation are rapidly growing applications. It is expected that the majority of GPS users will be in vehicle navigation.

Future uses of GPS will include automatic machine guidance and control, where hazardous areas can be mapped efficiently and safely using remotely controlled vehicles. The recent U.S. decision to modernize GPS and to terminate the selective availability will undoubtedly open the door for a number of other applications yet to be developed. (Introduction to GPS, Ahmed El-Rabbany)

### 1.3 The Earth's Magnetic Field

Electronic compasses rely on the earth's magnetic field (Figure 1.4) for their operation, so it is important to assess the suitability of both the electronic compass and the earth's magnetic field in relation to the application of mobile robot guidance and navigation.

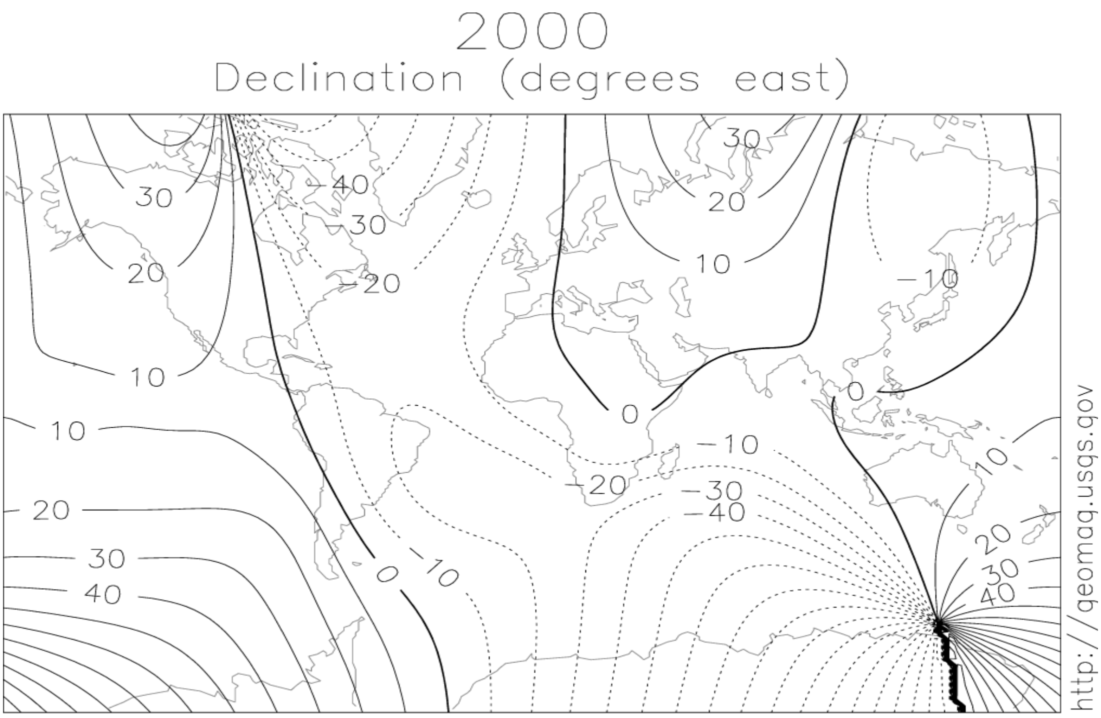


Figure 1.4 International Geomagnetic Reference Field (IGRF) in 2000

The earth's magnetic field has been a navigation tool since the 13th century when the 'Mariner's Compass' was used at times when the North Star was obscured. Early users of compasses were untrusting of them, as there was always an error between true and magnetic north (Figure 1.5). As time passed, this attribute of the earth's magnetic field was studied, compass corrections were documented and then the perception of the compass changed to that of an important navigation tool (The History of Navigation 2000)

Studies have shown that the earth's magnetic field has weakened by 10 percent since magnetic field strength records first begun in 1845. Modern studies of the earth's magnetic field also show that it is a dynamic system, known as Earth's 'geodynamo'. The slowly and constantly changing convection currents in the earth's liquid core are thought to create the earth's magnetic field. (Airs, L., 2005)

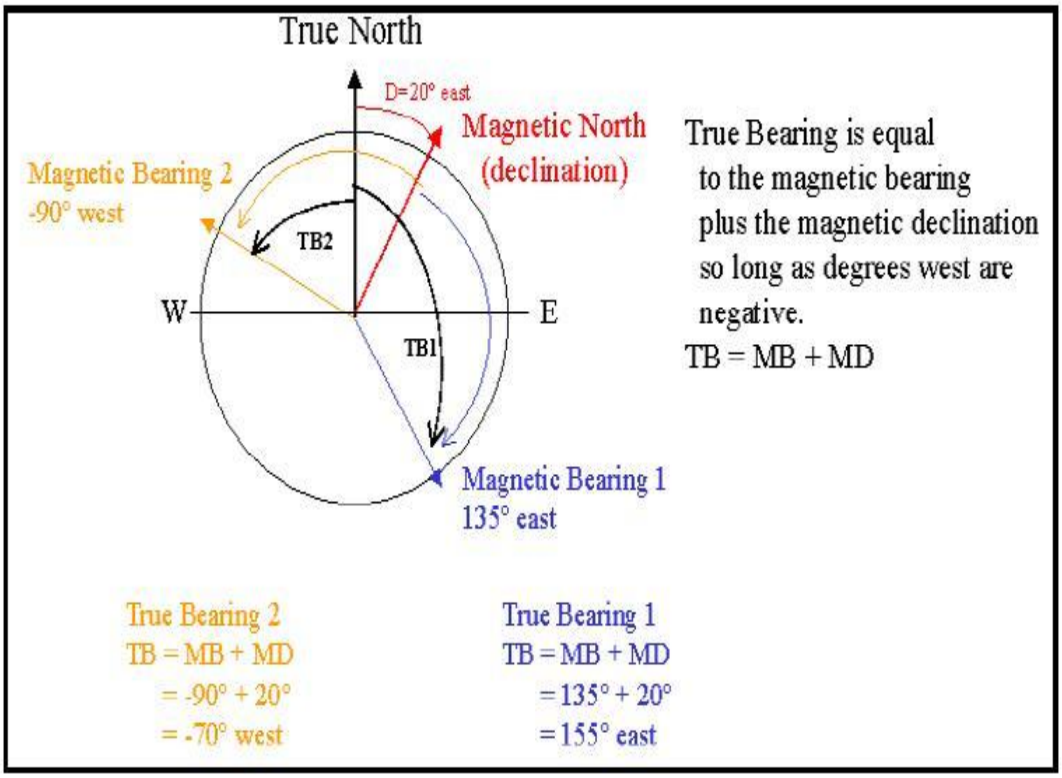


Figure 1.5 Differences of True North and Magnetic North.

# CHAPTER TWO

# COMMUNICATION TECHNOLOGIES

## 2.1 Protocols

A protocol is a set of rules that defines how the computers will manage their communications. The protocol may specify how data is formatted for transmitting and when and how each node may transmit.

PCs and many microcontrollers have built-in components (UARTs) that handle many of the details automatically, or with limited program assistance. When there are just two devices, the rules need to specify whether both ends can transmit at once, or whether they need to take turns. With three or more devices, things become more complicated. Because all nodes usually share the same path, each device has to know when it may transmit, as well as whether a received communication is meant for itself or another node.

Besides the data path, a link may use additional lines to indicate when a transmitter has data to send, when a receiver is able to accept new data, or other control or status information. The process of exchanging status information about a transmission is called handshaking. The control and status signals are handshaking signals. Hardware handshaking uses dedicated lines for the signals. Some links use software handshaking, which accomplishes the same thing by sending special codes in the data path.

### *2.1.1 Message Format*

A message is a block of data intended for one or more receivers. The message format defines what type of data the message contains and how the data is arranged within the message. All nodes have to agree on a format.

When there is more than one receiver, the receivers need a way to detect which node is the intended receiver. For this reason, network messages usually include the receiver's address. In a very simple network, a message may consist of just two bytes: one to identify the receiver and another containing data.

Messages may include other information as well. To enable receiving nodes to detect the start and end of a message, the message may include codes to indicate these, or bytes specifying the length of the message. A message may also include one or more bytes that the receiving node uses in error-checking.

### *2.1.2 The Link*

The physical link between computers consists of the wires or other medium that carries information from one computer to another and the interface that connects the medium to the computers.

The requirements of a link help to determine which interface to use and what medium to use to connect the nodes. In the types of systems the distance between computers may range from a few feet to a few thousand feet. The time between communications may be shorter than a second, or longer than a week. The number of nodes may range from two to over two hundred.

Most links use copper wire to connect computers, often inexpensive twisted-pair cable. The path may be a single data wire and a ground return, or a pair of wires that carry differential signals. Other options include fiber-optic cable, which encodes data as the presence or absence of light, and wireless links, which send data as electromagnetic (radio) or infrared signals in the air.

An interface may use existing ports on the computers, or it may require added ports or adapters. Table 2.1 compares popular interfaces that a monitoring or control system might use.

The IrDA (Infrared Data Association) interface can use the same UARTs and data formats as RS-232 (with added encoding), but the data transmits as infrared energy over a wireless link. IrDA is useful for short, line-of-sight links between two devices where cabling is inconvenient. MIDI (Musical Instrument Digital Interface) is used for transferring signals used by musical instruments, theatrical control equipment, and other machine controllers.

It uses an optically isolated 5-milliampere current loop at 31.5 kbps. Microwire, SPI, and I2C are synchronous serial interfaces that are useful for short links. Many microcontrollers have one or more of these interfaces built-in.

Table 2.1 Comparison of popular computer interfaces.

| Interface | Format | Number of Devices (maximum) | Length (maximum, feet) | Speed (maximum, bits/sec.) |
|---|---|---|---|---|
| RS-232 (EIA/TIA-232) | asynchronous serial | 2 | 50-100 | 20k (115k with some drivers) |
| RS-485 (TIA/EIA-485) | asynchronous serial | 32 unit loads | 4000 | 10M |
| IrDA | asynchronous serial infrared | 2 | 6 | 115k |
| Microwire | synchronous serial | 8 | 10 | 2M |
| SPI | synchronous serial | 8 | 10 | 2.1M |
| $I^2C$ | synchronous serial | 40 | 18 | 400k |
| USB | asynchronous serial | 127 | 16 | 12M |
| Firewire | serial | 64 | 15 | 400M |
| IEEE-488 (GPIB) | parallel | 15 | 60 | 1M |
| Ethernet | serial | 1024 | 1600 | 10M |
| MIDI | serial current loop | 2 | 15 | 31.5k |
| Parallel Printer Port | parallel | 2, or 8 with daisy-chain support | 10-30 | 1M |

USB (Universal Serial Bus) and Firewire (IEEE-1384) are new, high-speed, intelligent interfaces for connecting PCs and other computers to various peripherals. USB is intended to replace the standard RS-232 and Centronics printer ports as the interface of choice for modems and other standard peripherals. Firewire is faster and designed for quick transferring of video, audio, and other large blocks of data.

Ethernet is the familiar network interface used in many PC networks. It's fast and capable, but the hardware and software required are complex and expensive compared to other interfaces. The alternative to serial interfaces is parallel interfaces, which have multiple data lines. Because parallel interfaces transfer multiple bits at once, they can be fast.

Usually there is just one set of data lines, so data travels in one direction at a time. Over long distances or with more than two computers in a link, the cabling for parallel interfaces becomes too expensive to be practical. The Centronics parallel printer interface predates the PC and just about every PC has included a Centronics-compatible interface. The IEEE-1284 standard defines new connectors, cables, and high-speed protocols for the port's 17 lines. Because the interface has been standard on all PCs, it's been pressed into service as an interface for scanners, external disk drives, data-acquisition devices, and many other special-purpose peripherals. IEEE-488, which began life as Hewlett-Packard's GPIB (General-purpose Interface Bus) is another parallel interface popular in instrumentation and control applications. (Axelson, J., 1998)

## 2.2 Serial Communication

Serial communication is a popular means of transmitting data between a computer and a peripheral device such as a programmable instrument or even another computer. Serial communication uses a transmitter to send data, one bit at a time, over a single communication line to a receiver. You can use this method when data transfer rates are low or you must transfer data over long distances. Serial communication is popular because most computers have one or more serial ports, so no extra hardware is needed other than a cable to connect the instrument to the computer or two computers together.

Serial Communication occurs when data is transmitted bitwise and in a sequential manner over a single wire. RS232 is a physical interface standard for the interconnection of devices, carrying signals between ±5v and ±12v. A UART or a

Universal Asynchronous Receiver/Transmitter is the IC component which manages the transmission and reception of serial data. It converts the serial data to parallel data which can be used by the CPU.

RS232 uses

- +3 to +12 volts to indicate an ON (SPACE) state
- -3 to -12 volts to indicate an OFF (MARK) state

The "dead area" between -3v and +3v is to prevent noise from affecting communications. Microprocessor systems which operate on 3 or 5 volts don't need to provide an extra power source to power the -12 and +12v RS232 circuitry. RS232 chips generate these voltages using a single 3 or 5 volt power source.

Each transmitted character is packaged in a character frame that consists of a single start bit followed by the data bits, the optional parity bit, and the stop bit or bits. Figure 2.1 shows a typical character frame encoding the letter m.

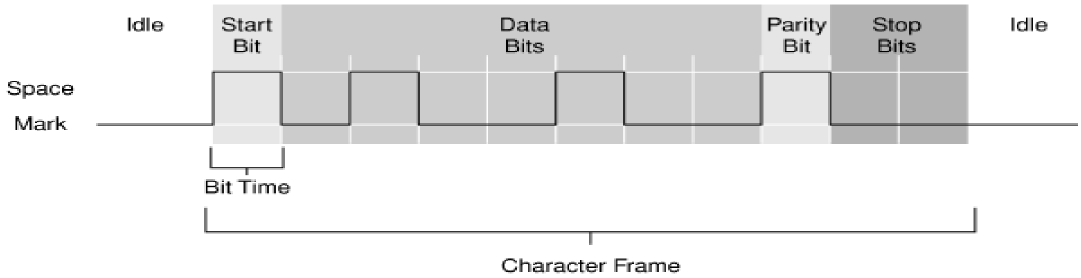


Figure 2.1 Typical character frame encoding.

Knowing the structure of a character frame and the meaning of baud rate as it apply to serial communication, we can calculate the maximum transmission rate, in characters per second, for a given communication setting. This rate is just the baud rate divided by the bits per frame. If the transmission rate is set at 9,600 baud, we get 9600/11=872 characters per second. Notice that this is the maximum character transmission rate. The hardware on one end or the other of the serial link might not be able to reach these rates, for various reasons.

## 2.3 I2C Protocol

The I2C bus was designed by Philips in the early '80s to allow easy communication between components which reside on the same circuit board. Philips Semiconductors migrated to NXP in 2006. The name I2C translates into "Inter IC". Sometimes the bus is called IIC or I²C bus.

The original communication speed was defined with a maximum of 100 kbit per second and many applications don't require faster transmissions. For those that do there is a 400 kbit fast mode and - since 1998 - a high speed 3.4 Mbit option available. Recently, fast mode plus a transfer rate between this has been specified.

I2C is not only used on single boards, but also to connect components which are linked via cable. Simplicity and flexibility are key characteristics that make this bus attractive to many applications.

Most significant features include:

•Only two bus lines are required

•No strict baud rate requirements like for instance with RS232, the master generates a bus clock

•Simple master/slave relationships exist between all components

Each device connected to the bus is software-addressable by a unique address

•I2C is a true multi-master bus providing arbitration and collision detection

Communication is established and 8-bit bytes are exchanged, each one being acknowledged using a 9th data bit generated by the receiving party, until the data transfer is complete. The bus is made free for use by other ICs when the ‘master’ releases the SDA line during a time when SCL is high. Apart from the two special exceptions of start and stop, no device is allowed to change the state of the SDA bus line unless the SCL line is low.

If two masters try to start a communication at the same time, arbitration is performed to determine a “winner” (the master that keeps control of the bus and continue the transmission) and a “loser” (the master that must abort its transmission). The two masters can even generate a few cycles of the clock and data that ‘match’, but eventually one will output a ‘low’ when the other tries for a ‘high’. The ‘low’ wins, so the ‘loser’ device withdraws and waits until the bus is freed again.

The HMC6352 communicates via a two-wire I2C bus system as a slave device. The HMC6352 uses a layered protocol with the interface protocol defined by the I2C bus specification, and the lower command protocol defined by Honeywell. The data rate is the standard-mode 100kbps rate. The bus bit format is an 8-bit Data/Address send and a 1-bit acknowledge bit. The format of the data bytes (payload) shall be case sensitive ASCII characters or binary data to the HMC6352 slave, and binary data returned. Negative binary values will be in two’s complement form. The default (factory) HMC6352 7-bit slave address is 42(hex) for write operations, or 43(hex) for read operations.

The following timing diagram (Figure 2.2) shows an example of a master commanding a HMC6352 (slave) into sleep mode by sending the “S” command. The bottom two traces show which device is pulling the SDA line low.

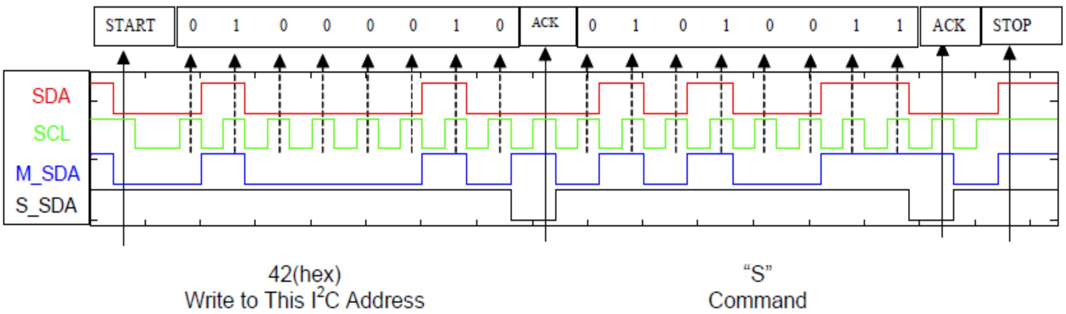


Figure 2.2 Timing diagram

I2C bus control can be implemented with either hardware logic or in software. Typical hardware designs will release the SDA and SCL lines as appropriate to allow the slave device to manipulate these lines. In a software implementation, care must be taken to perform these tasks in code.

## 2.4 Zigbee Module

ZigBee (Figure 2.3) is the set of specs built around the IEEE 802.15.4 wireless protocol. The IEEE is the Institute of Electrical and Electronics Engineers, a non-profit zrganization dedicated to furthering technology involving electronics and electronic devices. The 802 group is the section of the IEEE involved in network operations and technologies, including mid-sized networks and local networks. Group 15 deals specifically with wireless networking technologies, and includes the now ubiquitous 802.15.1 working group, which is also known as Bluetooth®. The standard itself is regulated by a group known as the ZigBee Alliance, with over 150 members worldwide.

While Bluetooth® focuses on connectivity between large packet user devices, such as laptops, phones, and major peripherals, ZigBee is designed to provide highly efficient connectivity between small packet devices. As a result of its simplified operations, which are one to two full orders of magnitude less complex than a comparable Bluetooth® device, pricing for ZigBee devices is extremely competitive, with full nodes available for a fraction of the cost of a Bluetooth® node. ZigBee devices are actively limited to a through-rate of 250 Kbps, compared to Bluetooth®'s much larger pipeline of 1Mbps, operating on the 2.4 GHz ISM band, which is available throughout most of the world.

ZigBee has been developed to meet the growing demand for capable wireless networking between numerous low-power devices. In industry ZigBee is being used for next generation automated manufacturing, with small transmitters in every device on the floor, allowing for communication between devices to a central computer. This new level of communication permits finely-tuned remote monitoring and manipulation. In the consumer market ZigBee is being explored for everything from linking low-power household devices such as smoke alarms to a central housing control unit, to centralized light controls.

The specified maximum range of operation for ZigBee devices is 300 feet (100m), substantially further than that used by Bluetooth® capable devices, although security concerns raised over "sniping" Bluetooth® devices remotely, may prove to hold true for ZigBee devices as well.

Due to its low power output, ZigBee devices can sustain themselves on a small battery for many months, or even years, making them ideal for install-and-forget purposes, such as most small household systems. Predictions of ZigBee installation for the future, most based on the explosive use of ZigBee in automated household tasks in China, look to a near future when upwards of 60 ZigBee devices may be found in an average American home, all communicating with one another freely and regulating common tasks seamlessly.

XBee 1mW Wire Antenna Features:

•3.3V @ 50mA

•250kbps Max data rate

•1mW output (+0dBm)

•300ft (100m) range

•Built-in antenna

•Fully FCC certified

•6 10-bit ADC input pins

•8 digital IO pins

•128-bit encryption

•Local or over-air configuration

•AT or API command set

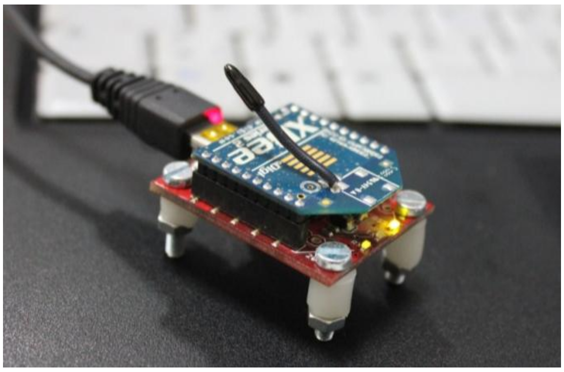

Figure 2.3 XBee 1mW Wire Antenna

# CHAPTER THREE

# INDOOR NAVIGATION SYSTEM AND THE VEHICLE

## 3.1 Robot Vehicle

A duo cycle robot vehicle in form of a tank is equipped with necessary electronic communication and control devices as seen in Figure 3.1.

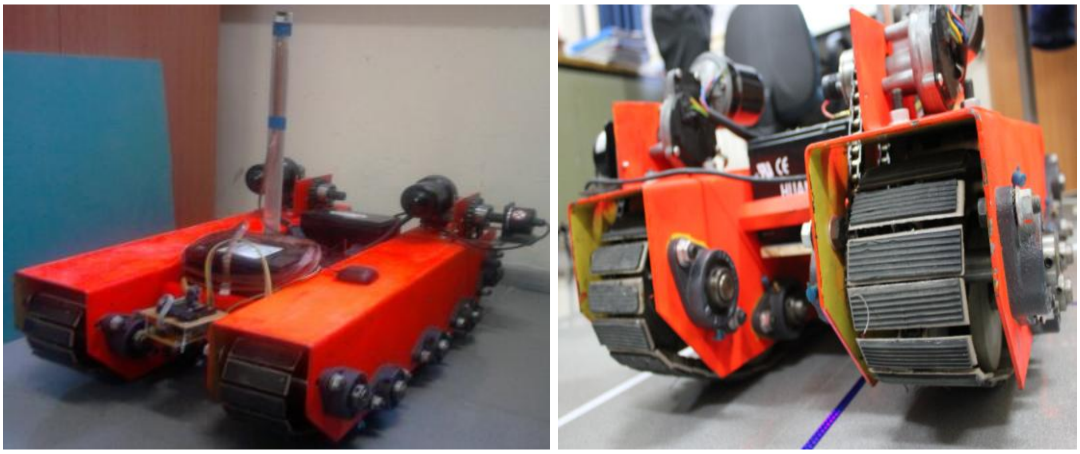

Figure 3.1 The Vehicle (Tank)

Also the time response of the vehicle to motion input changes are investigated, so that a consequent sampling time (here 0.5 second) can be chosen for an efficient control algorithm. Firstly the angular velocities of the rear wheels of the vehicle are exactly measured and in accordance the velocity of the midpoint C of the rear axis is investigated with the equations as given in chapter 4. The taken out way of C in a given time can so be calculated easily and with enough accuracy.

In this application a constant velocity of the point C is assumed, although a velocity control for an accurate path following is required. But using a very simple control algorithm with an intermittent correction by appropriate choice and investigation of sampling distances, a very good tracking accuracy within few centimetres is reached.

The position (location and orientation) of the vehicle is dedicated continuously with appropriate sampling measurements and are sent then via ZigBee Module to the main (stationary) PC, where after some calculations in accordance to the control algorithm first the orientation is corrected and then the vehicle is guided to the next destination point by the micro controller driven DC Motors. This process is then continuously repeated until the last destination point on the path is reached.

### 3.2 Mechanical Properties of the Vehicle

ZigBee integrated control card and driving card with relays placed back of the tank. The electronic compass sensor is in the middle and above 38 cm from the tank to avoid the magnetic field of motors and the tank.

The physical specifications of the system are,
Width x Length x Height = 50 x 72 x 20 cm
Width x Length x Height = 62 x 72 x 32 cm (With motors and encoder)
Length of limb for compass sensor is 38 cm

### 3.3 Motors

Each wheel is being rotated by two separate 24 VDC electric motors in order to able to get more accurate movement especially in narrow route through the obstacles. The technical specifications of the DC electric motor are shown in Table 4.1

Table 4.1 The specifications of the motor

| | | |
|---|---|---|
| Type | DC | |
| Voltage | 24 VDC | |
| Mode | I | II |
| Current | 2 A | 2.5 A |
| Power | 18 W | 20 W |
| Rotation | 27 rpm | 32 rpm |
| Torque | 6 Nm | |
| Breaking Torque | 30 Nm | |
| Direction | CW | |
| Class | S1 | |
| Weight | 2.720 kg | |

## 3.4 Encoder

By converting shaft rotation into electronic pulses, encoders are used to electronically monitor the position of a rotating shaft. The encoder's output pulses are counted and evaluated by a control unit to determine machine position and velocity, which provides exceptional accuracy and flexibility when controlling motion. The high mechanical and electronic operating speeds associated with optical encoders increase system speeds and accuracy, decrease cycle times, and boost overall productivity in the manufacturing environment. Autonics rotary encoders (Figure 3.2) of various sizes and types offer high-quality and precise measuring of the operating position and speed of the rotating shaft, etc. for more precise control of the objects.


Figure 3.2 50mm Incremental Rotary Encoder, Shaft Autonics E50S8 Series

## 3.5 Electronic Compass Sensor

The earth's magnetic field is about 0.6 gauss in an open-air environment, and has a direction from the magnetic south pole to the magnetic north pole. This pointing to the north pole is the basis for magnetic compassing. At the equator, the magnetic field direction is entirely a horizontal vector, but as you compass further into the northern or southern hemispheres the magnetic field will point partially downwards (northern hemisphere) or upwards (southern hemisphere). This angle down or up at the earth's surface is called the inclination (dip) angle.

Two-axis magnetic compasses measure the horizontal vector components of the earth's magnetic field using two sensor elements in the horizontal plane but orthogonal to each other. Called the X and Y-axis sensors, each sensor on an electronic compass assembly measures the magnetic field in its sensitive axis and the arc tangent Y/X provides the heading of the compass with respect to the X-axis. A two-axis compass can remain accurate as long as the sensors remain horizontal, or orthogonal to the gravitational (downward) vector. In moving platform applications, two axis compasses are mechanically "gimbaled" to remain flat and accurate.

Three-axis magnetic compasses contain magnetic sensors in all three orthogonal vectors of an electronic compass assembly to capture the horizontal and vertical components of the earth's magnetic field. To electronically gimbal the compass, the three magnetic sensors are complemented by a tilt-sensing element to measure the gravitational direction. The tilt sensor provides two-axis measurement of compass assembly tilt, known as pitch and roll axis. The five axes' of sensor inputs are combined to create a "tilt-compensated" version of the X and Y-axis magnetic vectors, and then computed into a tilt-compensated heading. In this project Sparkfun Compass Module - HMC6352 (Figure 3.3) is used.

Features of HMC6352 are:

- Simple I2C interface
- 2.7 to 5.2V supply range
- 1 to 20Hz selectable update rate
- True drop-in solution
- 0.5 degree heading resolution
- 1 degree repeatability
- Supply current: 1mA @ 3V

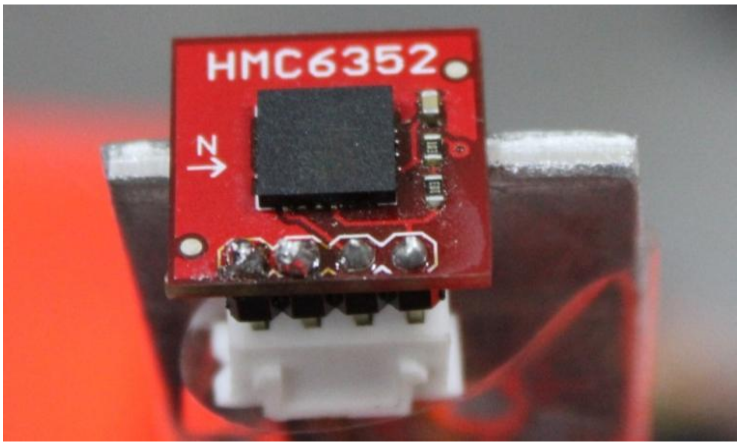


Figure 3.3 Compass Module - HMC6352

### 3.6 Control Unit and Drivers

Electronic part of the project consists of controller board and driver board (Figure 3.4). In control board, PIC 16F877 microcontroller is used. Microcontroller simultaneously sends and gets serial data from/to computer via ZigBee, counts the encoder data, gets angle values from electronic compass sensor with I2C Protocol. PIC program (Appendix A) written in C programming language.

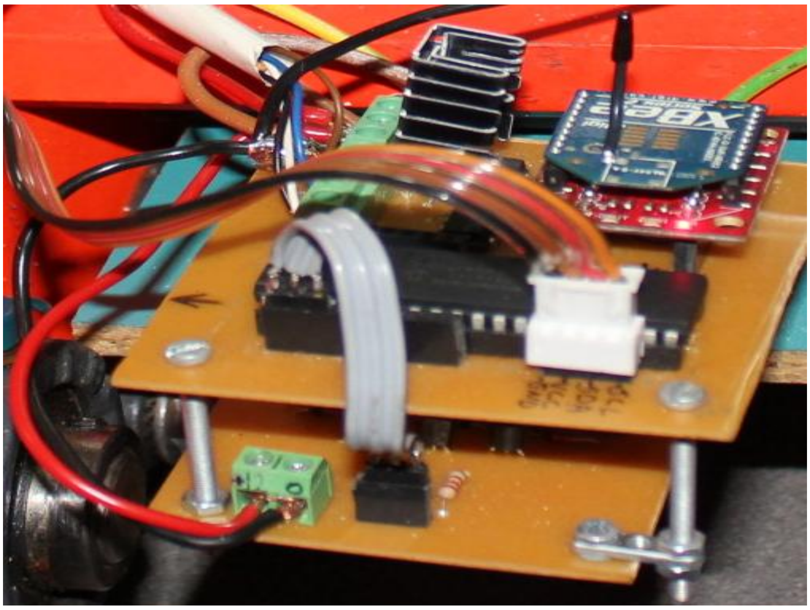

Figure 3.4 Controller board (up) and driver board (under the controller board)

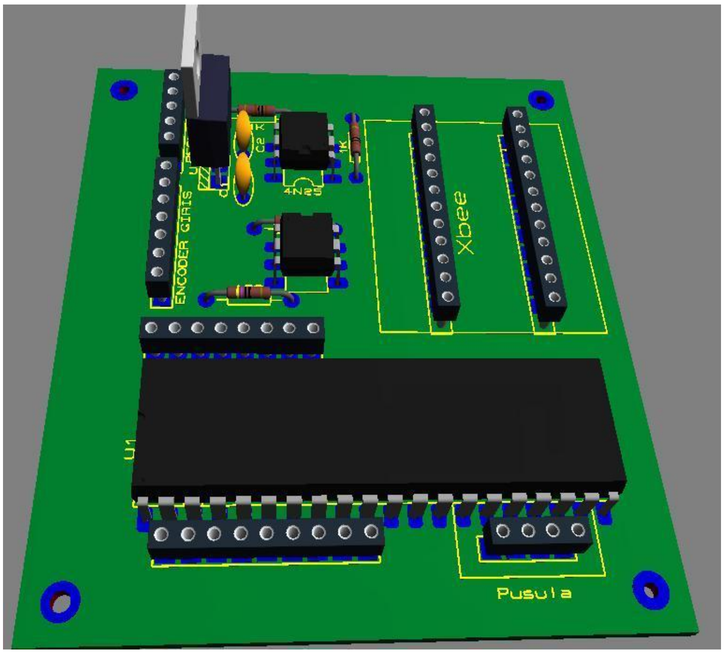


Figure 3.5 Controller board

Motor driver board (Figure 3.6) gets commands from microcontroller and drives the motors with relays.

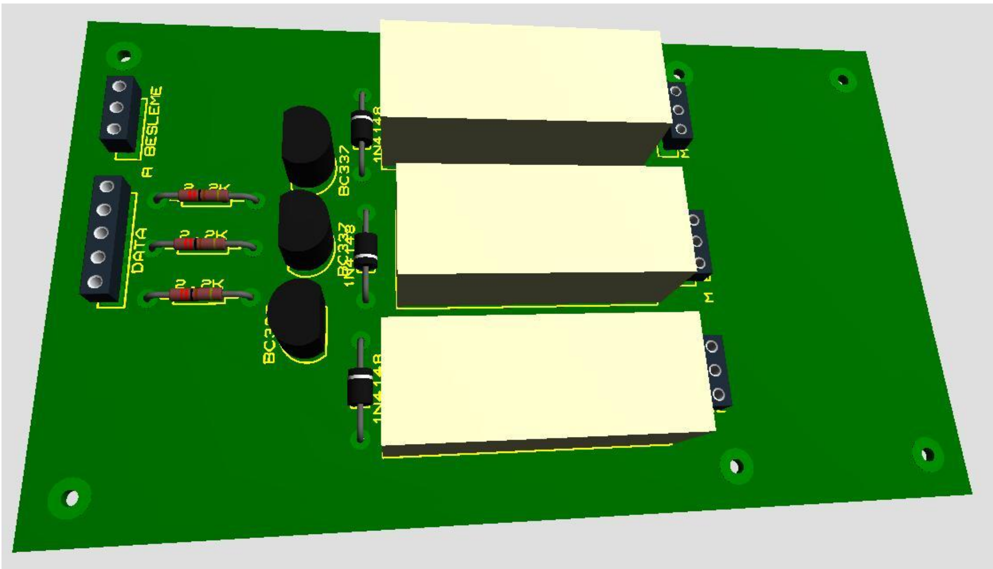


Figure 3.6 Motor driver board.

## CHAPTER FOUR

## MOVEMENT AND NAVIGATION

### 4.1 Mobility and Autonomy

The mobility of the robots indicates how freely they move around by themselves in order to perform their tasks. If the mobile robot is completely driven by a remote human controller, it is said to be non-autonomous and only the interpretation of the commands that they receive from human controllers is expected from these types of robots. Semi-autonomy means that either the robot can navigate through its environment by itself or can be steered by a human controller. Depending on the danger and the urgency of the task, the robot can take the full command or leave it to human beings. In the case of fully-autonomy, no external guidance or human interaction is needed due to the abilities of the fully-autonomous mobile robots about recognizing their environment and their capability of intelligent motion and action. (Banta, A., 2000), (Cordesses L., Thuilot B., Martinet P., Cariou C., 2000)

### 4.2 System Implementation

The basic implementation of the wireless navigation system is given in Figure 4.1. A PC is used to simulate and execute high level control operations via ZigBee Modules receiving navigation data from the sensors (electronic compass and linear encoder) and sending to microcontroller through USB port as shown in Figure 4.2

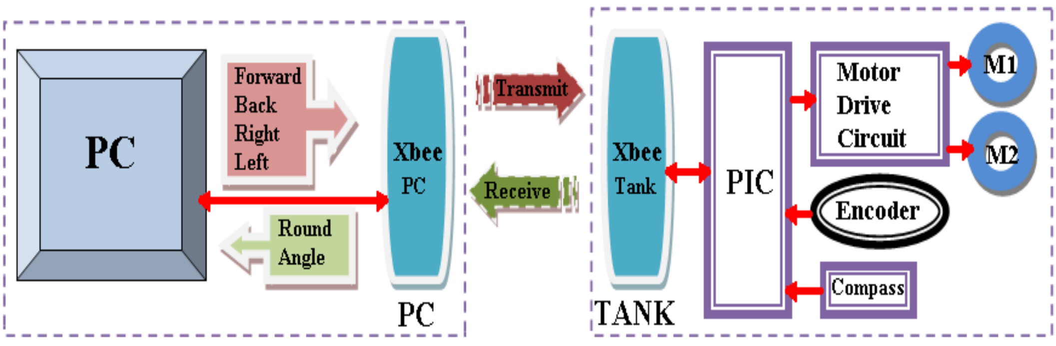


Figure 4.1 General Implementation of the system

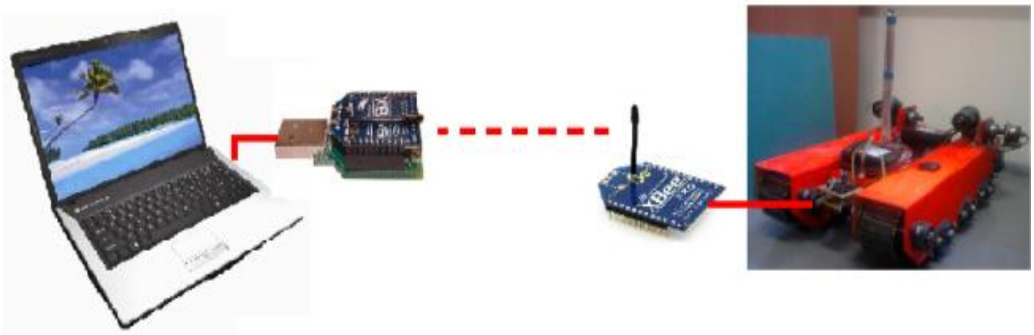


Figure 4.2 ZigBee communication scheme

Low level operations are then executed by a microcontroller (PIC 16F877) which drives the DC motors of the robot vehicle to navigate it. Through an original software program written in Visual Basic, the navigation control and optimal path finding algorithms with integrated obstacle avoidance will be executed. A simulation algorithm is also integrated to the program to investigate the orientation and location of the vehicle as mentioned in Chapter 5.

### 4.3 Kinematics of the Motion

Tracking of a given path (path following) with global coordinates, is the main aspect for the guidance of the vehicle. As first step, the vehicle as a holonomic model and its non-linear kinematics equations are given with following assumptions:

The vehicle is built up as a caterpillar track of length L, equipped with geared chain mechanisms, which are controlled from rare wheels (Figure 4.3). The center point of rear axle C and its linear velocity v is taken as the base aspects to the motion. The velocities ω of the both rear wheels are chosen as main control parameters. (Mutlu L. and Uyar E., 2010)

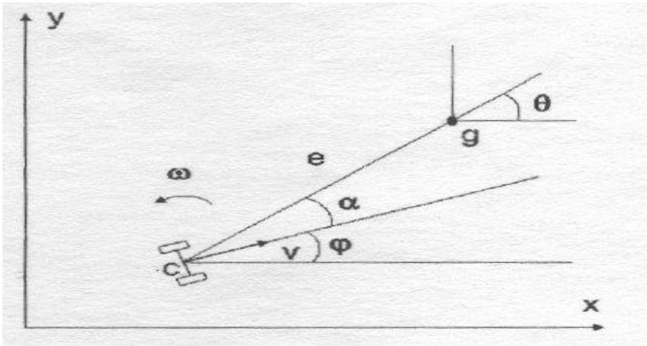


Figure 4.3 Kinematical model of the vehicle

The kinematical model of the vehicle as shown in Figure 4.3 and the kinematics equations that relate the linear and angular velocity of the robot with the angular velocity of each wheel can be expressed as:

$$\begin{bmatrix} v \\ w \end{bmatrix} = \begin{bmatrix} R/2 & R/2 \\ -R/D & R/D \end{bmatrix} * \begin{bmatrix} w_L \\ w_R \end{bmatrix} \tag{1}$$

$$\dot{x} = v.\cos\varphi$$
$$\dot{y} = v.\sin\varphi \tag{2}$$
$$\dot{\varphi} = w$$

Where $w_R$ and $w_L$ represent the right and left wheel angular velocities, v and w denote the linear and angular velocities of a coordinate frame attached at center point C. The parameter R stands for the wheel radius and the inter-wheel distance is 2D. Now, the vehicle can be considered as a point at C which has to follow given waypoints in an absolute coordinate system (x, y). If the coordinates of some successive points are given as $P_1(x_1,y_1)$, $P_2(x_2,y_2)$ and $P_3(x_3,y_3)$ then the vector equations between successive points can be written as;

R1 = (x1) i + (y1) j (3)

R2 = (x2-x1) i + (y2-y1)j (4)

R3 = (x3-x2) i + (y3-y2) j (5)

The distances and orientation angles between the waypoints can then be calculated from the coordinates instantaneously.

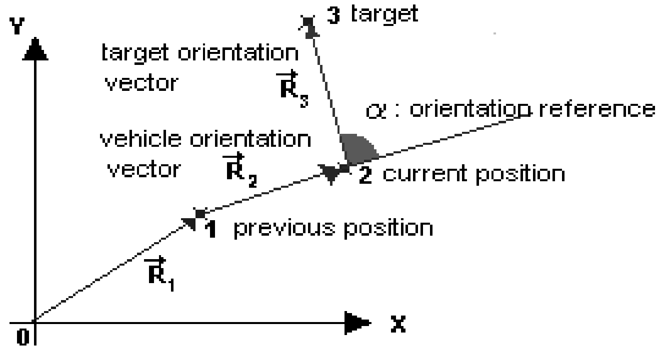


Figure 4.4 Position and orientation of the vehicle

### 4.4 Control of the System

We consider the dominant dynamics of the two independent DC motors, which drive the wheels of the vehicle. The dynamic relation between the input voltage u(t) and the angular velocity of the motor shaft w(t) is expressed by the following differential equation (8). To correct the orientation in sampling increments, the time for a turn angle of 180 degrees around midpoint C is dedicated. Also the way of the midpoint by the time is dedicated with some measurements. Assuming that both motors have the same dynamics, Equation (1) can be used to obtain a dynamic model relating the differential/common mode voltages applied to the motors and the vehicle's angular/linear velocities:

$$Tw_i'(t) + w_i(t) = Ku_i(t); \quad \mathrm{i} = 1{,}2 \tag{6}$$

$$v(t) + Tv'(t) = \frac{KR}{2} u_+(t) \tag{7}$$

$$w(t) + Tw'(t) = \frac{KR}{D} u_-(t) \tag{8}$$

For the guidance of vehicle, reference way points are given and with estimating an optimal sampling time in accordance to the given trajectory, the vehicle is guided by classical P algorithms with changing gain. By software written in Visual Basic programming language whole trajectory calculations and control actions are executed by the stationary computer. Assuming a motion in the plane, the plane coordinates are evaluated from both measured sensor values for orientation of the vehicle.

## CHAPTER FIVE

## COMPUTER PROGRAM AND OPTIMAL PATH FINDING

### 5.1 Computer Program

Computer program is written in Visual Basic Programming Language to simulate and control the vehicle. In the program target points are given and these points are stored in program memory and the vehicle follows these target points in order. Simulation program has some properties like Virtual Mode to simulate the vehicle behaviours offline, Manual Mode to control the vehicle manually and Car Mode to simulate a car type vehicle. In Car Mode also PID control can be used to control the vehicle more effective. Target angle, target distance and errors related to these targets are shown in program (Figure 5.1).

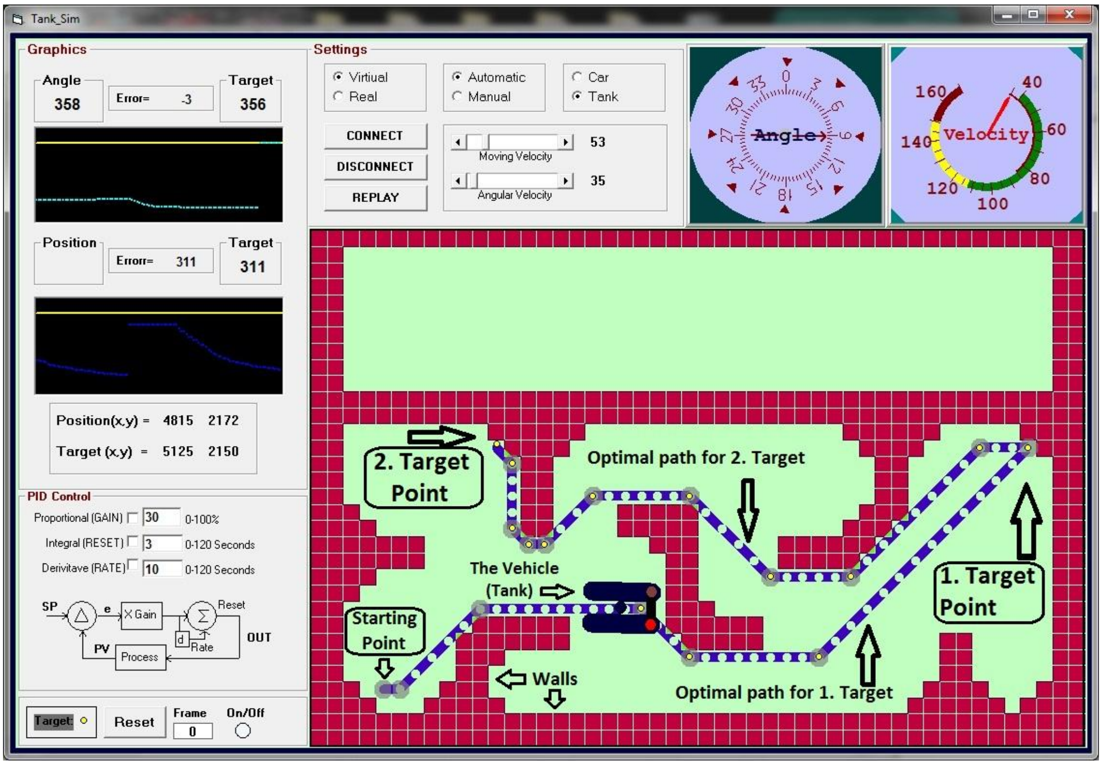


Figure 5.1 Computer program in Virtual-Tank Mode

## 5.2 Optimal Path Finding

For navigation tasks and trajectory planning an optimal path finding program is developed in Visual Basic programming language. In the program, map (movement space) is divided to points (pixels) as shown in Figure 5.2. Starting from the target point, all points are numbered in the following form;

Number ‘0’is given to the target point and number ‘1’ to neighbour points (except the walls) of number ‘0’. Number ‘2’ is given around the number ‘1’’s ... number ‘n’ is given around the number ‘n-1’’s. In the numbering, walls are not numbered. Number ‘n’ gives the farthest point distance to the target point in the map. Starting point number gives the distance to the target point.

For drawing the shortest way to the target; starting from the starting point number, first line is drawn to the lowest number around the starting point number. And then the next line is drawn to other lowest number around the last lowest number. This line drawing procedure continues till to the last lowest number equal to zero (the target point number).

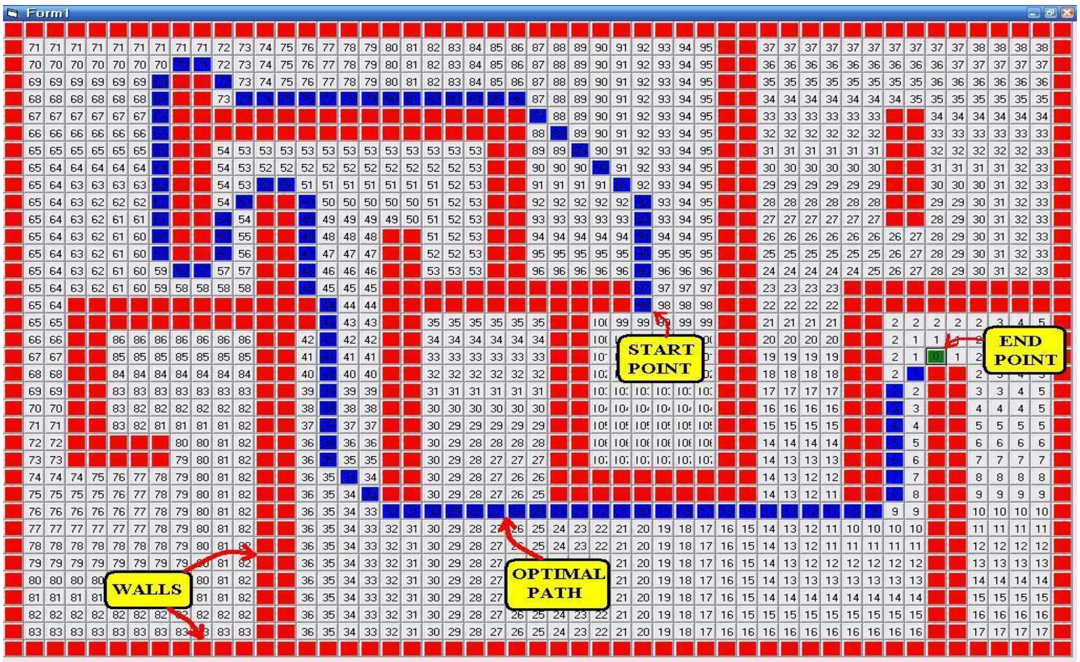


Figure 5.2 Optimal path finding program demo map which divided to points (pixels) and numbered.

For indoor navigation, optimal path finding has big importance to avoid the robot from dead ends and to find optimal path to the target. Optimal path finding program works very efficiently and finds the optimal path quickly even in a complicated labyrinth (Figure 5.3). This autonomous program is much more successful than manually controlled indoor navigation system for optimal path finding and navigating the vehicle. For example in Figure 5.3 when the target point is clicked, 102 sub-target points (yellow points) and optimal path (blue lines) is drawn in a second.

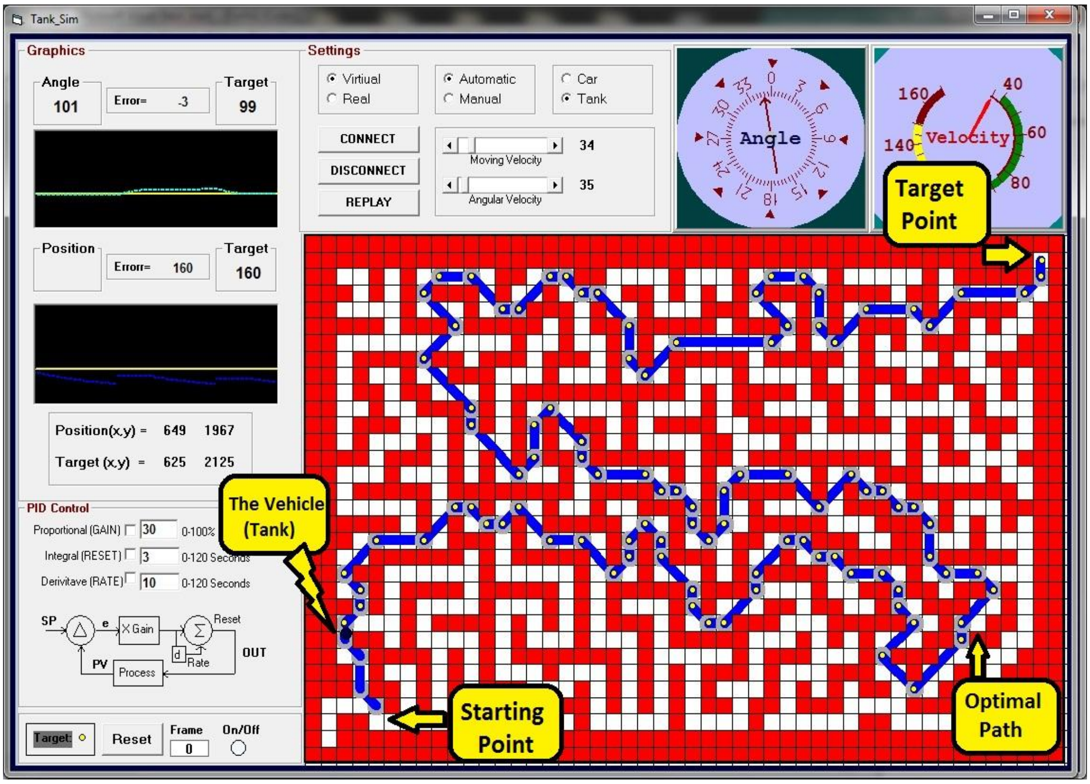


Figure 5.3 Labyrinth solving or optimal path finding program

## CHAPTER SIX

## EXPERIMENTS

Some experiments have been carried out to investigate the dynamic of the control system. First of all the response and data capture ability of the system are investigated so that, reasonable control parameters can be estimated. Microcontroller simultaneously sends data sets via ZigBee modules. Incoming data sets to the PC can be seen by HyperTerminal program or X-CTU program (Figure 6.1). These data sets is analyzed in Visual Basic and Compass Value (A) as angle, Encoder Value (K) as pulse (1 cm = 33 pulse) and Target Value (H) can be seen in program window.

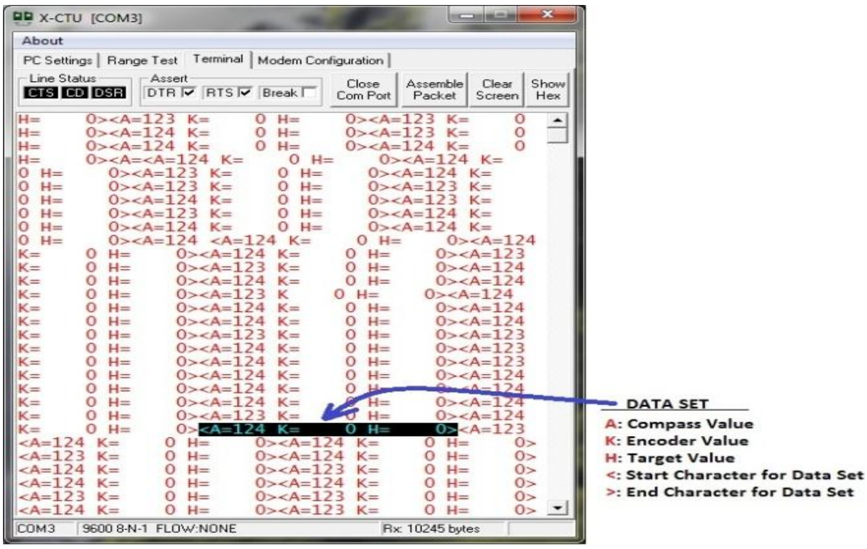


Figure 6.1 Data sets which microcontroller sends to PC via ZigBee modules.

The measured values are feedback to be compared with the given reference coordinate values, which are specified as next following point on the desired. According to the position error, the turning direction and linear velocities for the both wheels of the vehicle are controlled in accordance to chosen gain in Car Mode. In Tank Mode both motors has same constant speed and turning operation occurs before going forward. Firstly Tank turns to decrease the absolute error under 2 degrees, if the error between -2 and 2 degrees Tank starts to go forward until the distance error becomes 10 cm. An optimal path finding and obstacle avoidance algorithm is also integrated in the main control program. Various tests with different gain values are made to obtain available and optimal path following with changing curvatures. For experiments 2.6m x 4.5m area is used in Mechatronics Laboratory as can be seen in Figure 6.2 and computer program for simulation and control (Figure 6.3).

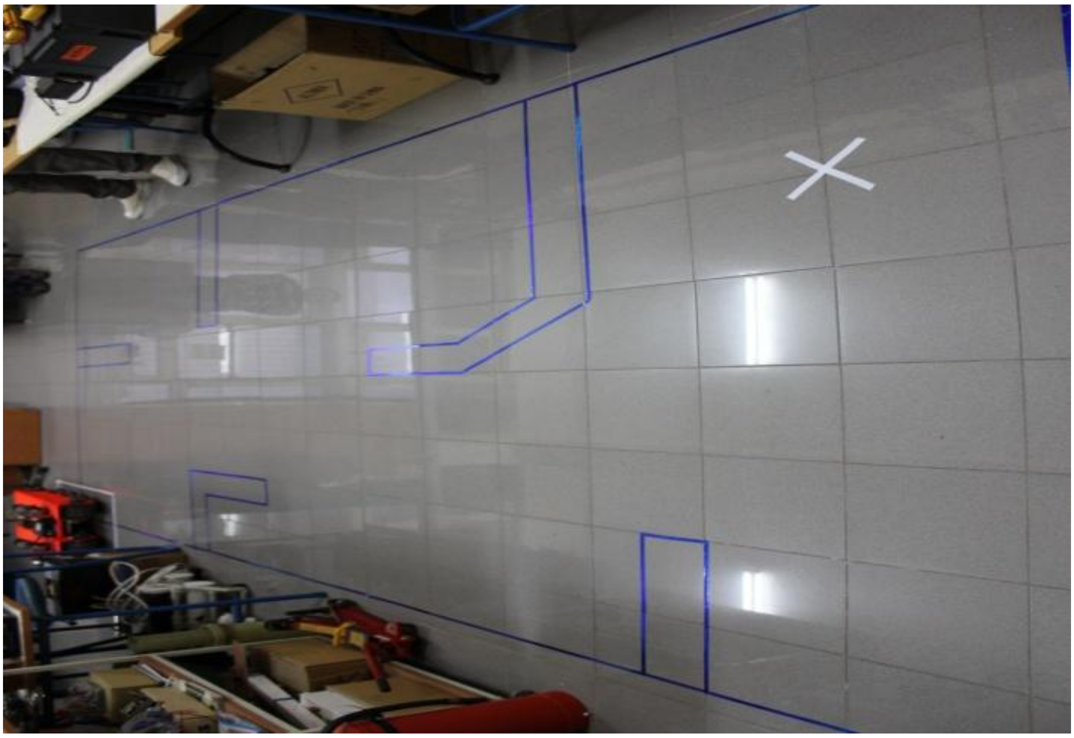

Figure 6.2 Experiment area with blue lines which imitate walls.

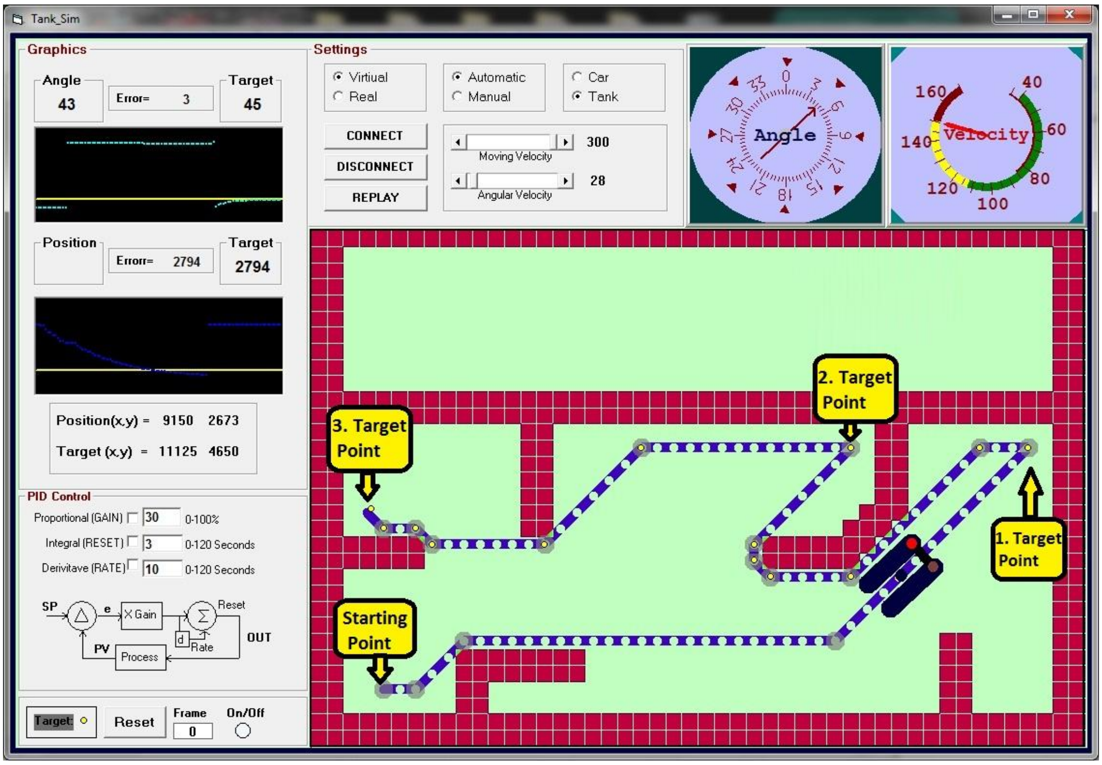


Figure 6.3 Simulation view of the experiment area

To investigate the effects of the output parameters on control ability, experiments are being made with various turn angles and velocities. The open and closed loop responses of the system are experimented separately using various test distances and paths; also to observe the tracking ability and accuracy of the system (Figure 6.4).

The closed loop response of the system is tested by giving some reference waypoints in land plane. The tracking ability of the vehicle in accordance some given way points are shown in Figure 6.4.

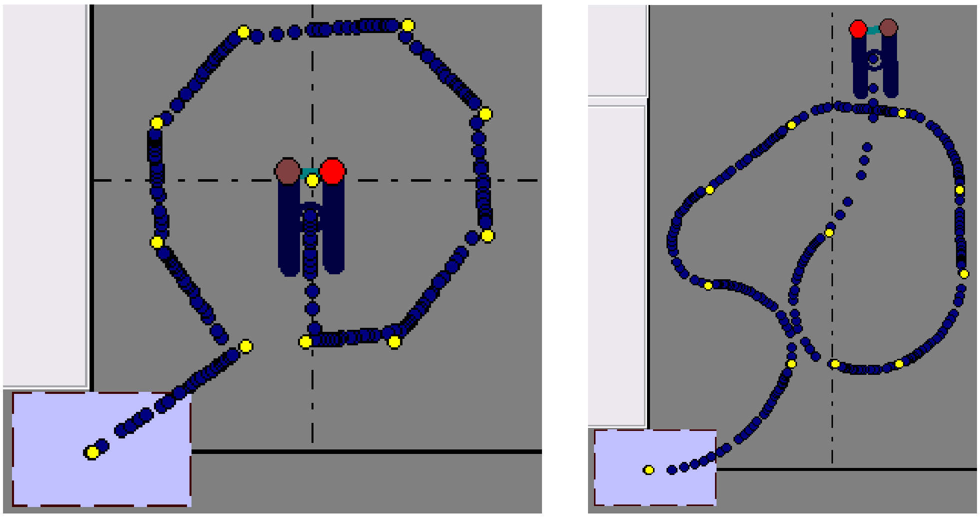

Figure 6.4 Closed loop control and trajectory following of the vehicle in Tank Mode (left) and Car Mode (right)

# CHAPTER SEVEN

# CONCLUSION

The trajectory following of a caterpillar duo cycle vehicle with chain drive is implemented and tested in this work. The non- linearity's of the system in an online application is overcome using special control algorithms. In a former work using camera (image effects) (Uyar E., Cetin L., Gören A., 2005), (Groavac S. A., 2002) in closed residences to estimate the distances, a nonlinear transformation table was used and the accurate measuring distances were limited till to 2 m because of the nonlinearities and sight area of the camera.

These are overcome here using an electronic compass and linear encoder system which has a great accuracy in indoor operations. So the dependence of the camera images to light conditions is also eliminated. On the other hand the direct detection and correction of the coordinates in every sampling instance made it possible to compensate the position (location) and orientation errors and so it provided to a great trajectory following accuracy in spite of an intermittent control algorithms.

As a further study of trajectory following with speed control, a polynomial path from 6th order is thought to be used to fit any given trajectory optimally. To achieve a desired path tracking primarily the radius of curvatures are calculated so that the centre point of the rear axe can be hold on the given path.

For further studies laser sensors can be added to detect obstacles and mapping the environment. Also a GPS system can be integrated to the vehicle for perfect indoor and outdoor combined applications.

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# APPENDIX A

**PIC Program:**

```
#include <16F877.H>
#fuses XT, NOWDT, NOPROTECT, BROWNOUT, PUT, NOLVP
#use delay(clock=4000000)
#use
rs232(baud=9600,parity=N,xmit=PIN_C6,rcv=PIN_C7,bits=8)
#use i2c(Master,fast,sda=PIN_C4,scl=PIN_C3,force_hw)
#use fast_io(a)
#use fast_io(b)
#include <stdlib.h>
#BIT T0IF = 0x0B.2
#define HMC6352_GET_DATA_COMMAND 0x41
#define HMC6352_I2C_WRITE_ADDRESS 0x42
#define HMC6352_I2C_READ_ADDRESS  0x43
   int8 girdi;
   int1 timeout_error;
   int16 aci;   int16 adim;   int16 hedef;
   int16 s[9]; int16 n;
#INT_rtcc
clock_isr() {IF (T0IF) {adim++;}}

char timed_getc()
{long timeout; timeout_error=FALSE; timeout=0;
 while(!kbhit()&&(++timeout>10000))
 delay_us(10);
 if(kbhit())return(getc());
```

```
 else { timeout_error=TRUE;return(0);}
}



int16 HMC6352_oku(void)
{int8 lsb;  int8 msb;
 i2c_start();
 i2c_write(HMC6352_I2C_WRITE_ADDRESS);
 i2c_write(HMC6352_GET_DATA_COMMAND);
 i2c_stop();

 delay_ms(10);  // Allow 1 ms extra for safety

 i2c_start();
 i2c_write(HMC6352_I2C_READ_ADDRESS);
 msb = i2c_read();
 lsb = i2c_read(0);
 i2c_stop();
 return((int16)lsb | ((int16)msb << 8));
}

void main()
{  int16 aci;
   aci=0;
   setup_psp(PSP_DISABLED);
   setup_timer_2(T2_DISABLED,0,1);
   setup_adc_ports(NO_ANALOGS);
   setup_adc(ADC_OFF);
   setup_CCP1(CCP_OFF);
   setup_CCP2(CCP_OFF);
        set_tris_a(0b00000000);
        set_tris_b(0b11111111);
        output_a(0b00000000);
```

```
    set_timer1(0);
    setup_timer_1(T1_EXTERNAL);
    enable_interrupts(INT_rtcc);
    enable_interrupts(GLOBAL);
    ext_int_edge (1, H_TO_L);
    n=0;hedef=0;
while(1)
   {girdi=timed_getc();
    if
(girdi==46){n=0;s[0]=0;s[1]=0;s[2]=0;s[3]=0;s[4]=0;}
    if (girdi>47){s[n]=girdi-48;n=n+1;}

    if (n>4)
    {if (s[0]==1){output_a(0b011);}
     if (s[0]==2){output_a(0b110);}
     if (s[0]==3){output_a(0b111);}
     if (s[0]==4){output_a(0b010);}
     if (s[0]==0){output_a(0b000);adim=0;set_timer1(0);}

     n=0;hedef=0;
     hedef=(s[2]*100+s[3]*10+s[4]+(s[1]*1000));
    }
    adim=get_timer1();
    aci = HMC6352_oku()/10;
    printf("<A=%3LU K=%5LU H=%5LU>",aci,adim,hedef);
    }
}
```