RIGA TECHNICAL UNIVERSITY

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Doctoral Study Programme “Computerized Control of Electrical Technologies”

RESEARCH AND DEVELOPMENT OF OBSTACLE AVOIDANCE SYSTEMS FOR MOBILE ROBOTICS

Doctoral Thesis

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ABSTRACT

The presented Doctoral Thesis is devoted to the research and development of obstacle avoidance systems for autonomous mobile robotics applications and in particular to the development of a mobile robotic vehicle to enable further investigative research into passive or read only sensory systems in autonomous robotics.

The avoidance system primarily described includes pyroelectric, modified pyroelectric and infra-red sensors and includes photodiodes in a reverse biased configuration, all of which represent a passive Rx system reliant only upon external electromagnetic spectral stimulation. There exist significant drawbacks in the development of a system which effectively flies in the face of existing methods and in particular, reference is made to the more commonly utilized systems for robotic maneuvering and mobility. Such systems will be briefly covered within this thesis, however those systems almost exclusively involve emitter/receiver configuration and rarely rely upon read only configuration. The creation of a read only system allows the investigation of various methods to assimilate received data from the environment and specifically in relation to the dynamic changes which are inevitable within those environments. With the emergence of higher level robotics systems comes the need for the enhancement of existing systems, adaption of older systems and the development of new systems capable of an acceptable result. Autonomous robotics requires modules with freedom and independence from external control themselves in order to fulfill the requirement of a fully autonomous system. However, fully autonomous systems also have significant drawbacks being that after manufacture and programming they are effectively free to succeed or fail without external interference. The measure of success and failure is therefore in the hands of the engineer or programmer and at the extremes of the environment chosen as the exploratory field. Initial costs should be offset by lower system maintenance costs and far less energy consumption within environments where energy sources are scarce and received also from limited resources. The service life of the system must also form a part of the equation, especially in scenarios where extreme distance environments are concerned such as interplanetary exploration. In this scenario the system may be partially autonomous and partial remotely controlled and a hybrid involving both systems seems more than appropriate when deciding to deal with one or the other as when if method fails a legacy system may prevail. There are a few problematic elements to examine. The first being the variable nature of light itself and secondly obtaining this data for processing in a way that provides sufficient and suitable reactive response from the mobile robot. Due to the dynamic nature of a given environment the issues related to

obstacle avoidance can be very complicated, therefore the main focus of this research is aimed at the problems relating to passive detection of objects and obstacles and applications to properly address these.

A summary of conventional obstacle avoidance techniques are described within the introduction chapters of the Doctoral Thesis and include an outline of possible benefits and disadvantages of existing systems. The main objectives and hypotheses of the research and development have been defined.

Parts of the Doctoral Thesis are included as proposals to issues both in parallel or direct subsidiaries to the proposed system. The primary benefits of utilizing a read only sensory system are exceptionally low energy consumption, extreme longevity or product life and a large sensor variant and programming method range, constrained only by the imagination of the researcher or developer.

The Doctoral thesis has been written in English. All summaries and conclusions and the results of the research relate to the hypothesis and the relationship between them. Some of the research has evolved into other projects consisting of various methodologies extracted from the investigations.

The thesis consists of 7 chapters inclusive of the introduction and the subsequent conclusions.
The bibliography contains 55 reference sources and 14 appendices.
The volume of the present Doctoral Thesis is 125 pages. It has been illustrated with 77 figures, 22 formula and 10 tables.

Anotācija

Šīs promocijas darbs ir veltīts robotu šķēršļu apiešanas sekošanas sistēmas izpētei un izstrādei, lai pielietotu autonomajās mobilajās robotizētajās sistēmās un īpaši mobilu robotizētu transporta līdzekļa izstrādē ar mērķi veikt tālākos pētījumus pasīvajās vai tikai nolasāmās robotu sensoru sistēmās.

Šķēršļu apiešanas sekošanas sistēma pirmkārt ietver sevī piroelektriskos, modificēti piroelektriskos un infra-sarkanos sensorus, kā arī fotodiodes sprostvirziena konfigurācijā, kas veido pasīvu Rx sistēmu, kuras darbība balstās tikai uz ārējā elektromagnētiskā lauka iedarbības.

Tādas sistēmas attīstībai ir būtiski trūkumi, kuri ir saistīti ar esošajām metodēm, kas tiek pieņemtas par etalonu un visur izmantotas sistēmu manevrēšanai un kustībai. Šādas sistēmas tiks īsi aplūkotas šajā darbā, tomēr tās izmanto tikai raidītāja/uztvērēja konfigurāciju un reti izmanto nolasāmās sistēmas konfigurāciju. Nolasāmo sistēmu izveidošana ļauj izpētīt dažādas metodes, lai izmantotu iegūtos datus no vides un īpaši no dinamiskajām izmaiņām, kuras ir neizbēgamas šādās vidēs. Augsta līmeņa robotizēto sistēmu rašanās prasa esošo sistēmu uzlabošanu, veco sistēmu adaptāciju un jauno sistēmu attīstīšanu ar pieņemamiem rezultātiem. Autonoma robotizēta tehnoloģija prasa moduļus ar brīvību un neatkarību no ārējās vadības, lai izpildītu pilnīgi autonomas sistēmas prasības. Tomēr pilnīgi autonomām sistēmām ir tāds nopietns trūkums, ka pēc izgatavošanas un ieprogrammēšanas tās var gan sekmīgi strādāt, gan nedaroties bez iejaukšanās no ārpuses. Veiksmes un trūkumi ir tomēr inženieru un programmētāju rokās un apkārtējā vidē, kura ir izvēlēta, kā darbības vieta. Sākuma kapitālieguldījumus ir jākompensē ar zemākiem ekspluatācijas izdevumiem un mazāku enerģijas patērēšanu ierobežoto enerģijas avotu gadījumos. Sistēmas kalpošanas laikam arī ir jābūt aprēķina daļai, īpaši tādos pielietojumos, kur vides ekstremāla distance attiecas uz starpplanetāro izpēti. Te sistēma var būt daļēji autonoma un daļēji attālināti vadīta, tas ir kā hibrīds, kurš ietver sevī abas sistēmas un ir piemērots darboties ar vienu vai otru vadību, jo, kad viena vadības sistēma nedarbojas, otra sistēma var veikt uzdevumu. Izpētes laikā tika atklāti daži problemātiski elementi. Pirmkārt, tā ir gaismas mainīgā daba un, otrkārt, datu iegūšana nodrošinot pietiekamu un piemērotu reaktīvu atsauci no mobilā robota.

Tradicionālās robotu brīva ceļa sekošanas metodes izpētītas Promocijas darba sākuma sadaļās un ietver esošo sistēmu priekšrocības un trūkumus. Pētījumu galvenie uzdevumi un hipotēze tika noteikti.

Dažās darba daļās tika izpētītas robotizētās sistēmas papildus iekārtas paralēlai vai tiešai izmantošanai. Pierādīts, ka nolasāmas sensoru sistēmas pielietošanas galvenie ieguvumi ir ārkārtīgi zemais enerģijas patēriņš, augsta izturība un plašs sensoru izvēles un programmēšanas metožu diapazons, kas ir atkarīgs no pētnieka izdomas.

Promocijas darbs ir uzrakstīts angļu valodā. Visi pētījumi, rezultāti un secinājumi ir saistīti ar hipotēzes pierādījumu, mērķu un uzdevumu izpildi. Daļa no pētījuma tika iekļauta arī citos projektos, ņemot vērā pētījuma rezultātu plašās pielietošanas iespējas.

Darbs sastāv no ievada, 7 nodaļām un secinājumiem. Bibliogrāfijas saraksts sastāv no 55 informācijas avotiem. Promocijas darbs ir uzrakstīts uz 125 lapaspusēm. Tas ir ilustrēts ar 77 attēliem, 22 formulām un 10 tabulām, ir 14 pielikumi.

CONTENTS

1. Introduction

1.1 Obstacle Avoidance - Inside the Envelope

As long as a robot is functioning within a controlled environment, such as a manufacturing plant, it is possible to use programming techniques to make sure that the robot functions within a known portion of its vicinity. This region is known as the robot's workspace or the *workspace envelope* (WE), which is governed by specific spacial algorithms. After the workspace is defined and known, it is possible to avoid placing obstacles within that region of space. This eliminates the requirement for the robot to be capable of sensing the environment to make decisions regarding obstacle avoidance (OA). However, the addition of non-static items to this envelope can lead to catastrophes in the workspace and workplace. Robots that function outside of controlled environments obviously require the ability to move around in the presence of a myriad of obstacles. These robots include robotic toys, unmanned vehicles, unmanned aviation vehicles and some industrial robots to name a few.

Some part of this work though not specifically referred at each point is to define the (WE) which is accomplished through sensitivity adjustments to the various sensors used. As stated above this is usually referenced as the spacial envelope (SE) of a stationary factory type robot, the authors premise is that a mobile robot should also have the benefit of a (WE), albeit mobile. This would be analogous to the idea of a person having their own personal space or an area within which they feel comfortable and in this regard we can look to the space suits worn by astronauts which may also be referred to as a mobile (WE). Refer to Fig.1. This premise also gives rise to the requirement for a sensory system that has a sensory range which is versatile or able to be decoded for accurate response. Obstacle avoidance is, at its core based upon suitable or programmed reactions and responses to external stimuli.

1.2 Topicality

When we discuss the topicality of obstacle avoidance we are discussing the topicality of robots, essentially due to OA being only one part of the many processes involved in successful robotic application. Likewise when we discuss robots with complete autonomy obstacle avoidance is elevated to the primary system of the device. OA is one of the most important aspects of mobile robotics. Without it robot movement would be very restrictive and fragile.

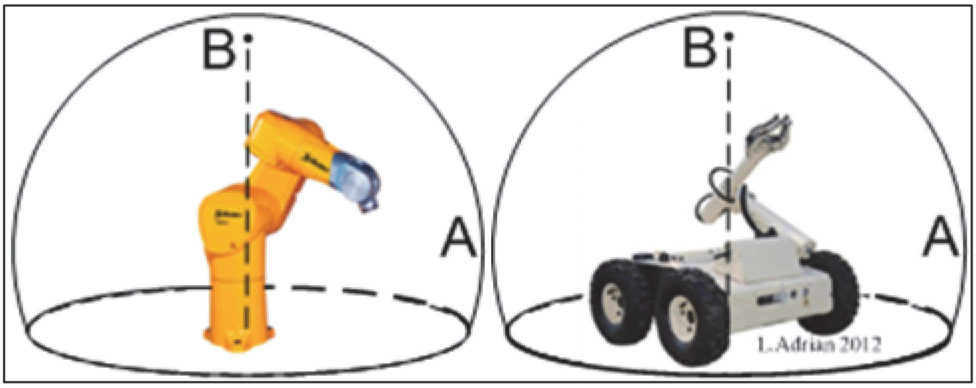


Fig.1. Immobile and mobile robots both require workspace envelopes. (Authors' assertion)

There are many articles and tutorials written explaining ways to accomplish the task of OA within the home environment and outside or far away exploration of foreign and dynamic environments and the subject of the thesis investigates a passive sensor array which relies only on available ambient light sources. In its most simplified schematic, Fig.2, the array represents a 360° workspace envelope view of the environment which must be analysed and logical reactions programmed. The model represented within Fig.2, shows the digital/analogue sensors and how they relate to the 4 motor drives of the vehicle for a better understanding of how the array is constructed. The model at this intersection of the thesis does not show the Fuzzification/defuzzification and Guided Learning algorithm which forms the neural net as represented in the model.

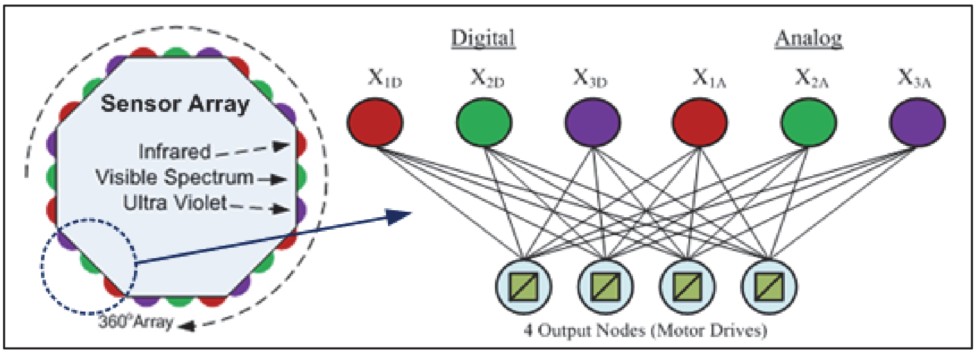


Fig.2. Consists of 3 sensors each within 8 banks forming 1 array of 24 sensors, each performing the dual function of analogue and digital ambient light receivers.

To understand the relevance of what we attempt to accomplish today we must also delve into the histories of what are now considered to be matters very relevant to the subject of OA and in this I look to five distinct figures in the field. Grey Walter, W. Braitenberg, V. Brooks, R. A. W. Ross Ashby and Lotfi A. Zadeh (*Refer Section 5*), all of whom, among many others have laid or continue to lay the foundations for the robotics that we utilize today.

The author's long standing intrigue with robotics possibly began or was enhanced with the teachings of these scientists.

By 1950, Grey Walter, W. (1910–1977), had completed a three wheeled, turtle like, mobile robotic vehicle. The vehicles included a *light sensor*, *touch sensor*, *propulsion motor*, *steering motor*, and *a two vacuum tube analogue computer*. See Fig.4.and Fig.5. Even with this simple design, Grey was able to demonstrate that his robots exhibited highly complex behaviours, able even to recharge themselves. He named his creations as "*Machina Speculatrix*" after their speculative tendency to explore their' environment, the Adam and Eve of his robots were named Elmer and Elsie (ELectro MEchanical Robots, Light Sensitive.) His robots were unique because, unlike the robotic creations that preceded them, they did not display a fixed behaviour. These robots had reflexes or were reactive and when combined with their environment, caused them to never exactly repeat the same actions twice. This emergent life-like behaviour was an early form of what we now call Artificial Life (AL) [1].

With his published works, V. Braitenberg, has influenced the thought of many researchers in the fields of artificial intelligence, cognitive psychology and Neuro-anatomy. The book conveys that many, complex behaviours, may result from apparently simple structures. The book is subtitled "Experiments in Synthetic Psychology" and represents increasingly complex thought experiments based on the simple rewiring of small vehicles.

The vehicles in Fig.3, are in the main a connection between light sensors and motors, and could result in apparently complex behaviour. A vehicle would move toward light due to the sensor on the left front of the vehicle being attached to the effectors (motor) on the diagonally opposite corner. In simplistic terms an increase in sensed light relates to an increase in speed on the opposite motor, turning the vehicle toward the light. Many combinations could be achieved dependent only upon configuration with each vehicle displaying varying complexity of behaviours as witnessed in part in the insect world.

It was an idea that would demonstrate that complex and apparently purposive behaviour did not need to depend on complex representations of the environment inside a creature or agents brain. It demonstrated that reaction to an environment in a consistent manner was more than enough to explain the low level reactive behaviours exhibited by many animals. The ideas' of Braitenberg, for his vehicles resulted from the unique perspective of a psychologist, he subsequently developed a wide range of vehicles which used inhibitory and excitatory influences, with a direct coupling of sensors to motors, which exhibited behaviour characteristics that appeared to indicate cowardice, aggression, love and a variety of other "emotions". Although his systems were inflexible and non-reprogrammable they were compelling in there overt behaviour and achieved seemingly complex behaviour from simple sensory-motor transformations.

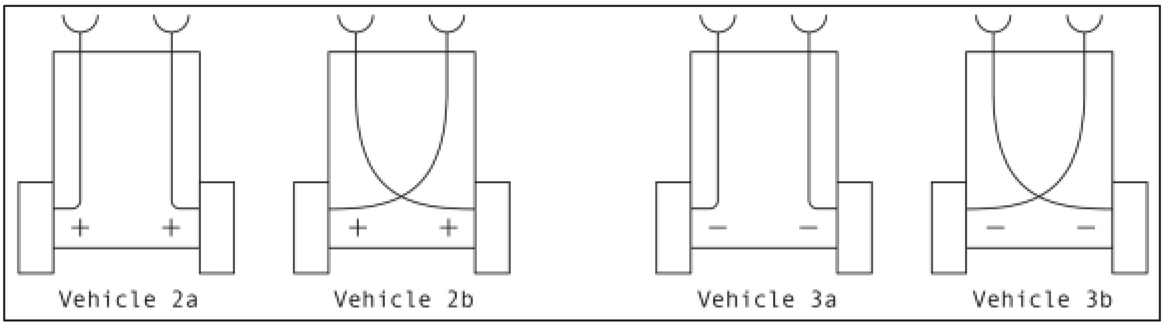


Fig.3. The basic Braitenberg vehicle models [49].

A cursory glance at the sensory/motor configuration gives an idea as to the behaviour of the vehicles given a light source to track. For example, vehicle "3a" motors will reduce speed in an oscillatory manner until finally coming to a stop at a light source.

At first glance these vehicles appear little more than the object of mild interest however upon deeper investigation and a delving into mobile robotic manoeuvrability it becomes very clear that Braitenberg was indeed correct in his assumptions and hypotheses. Robots of most sorts if programmed logically do follow these chaotic yet defined sequences, whether it is a photovore (PV) that is constantly attracted to or avoids light or a robot designed to be attracted to a remote signal, they all operate essentially in the same manner. The only difference being that Braitenberg's inclinations were toward psychology, but the robots do exhibit low level reactive behaviour which may be predictive. Alternatively, chaotic behaviour may be witnessed when combining various combinations of sensor/motor configurations which in many respects can lead to a more lifelike behaviour in the robotic device. This of course is not intelligence by any means but is indicative the varying response may be beneficial to some extent and opposite to that expected.

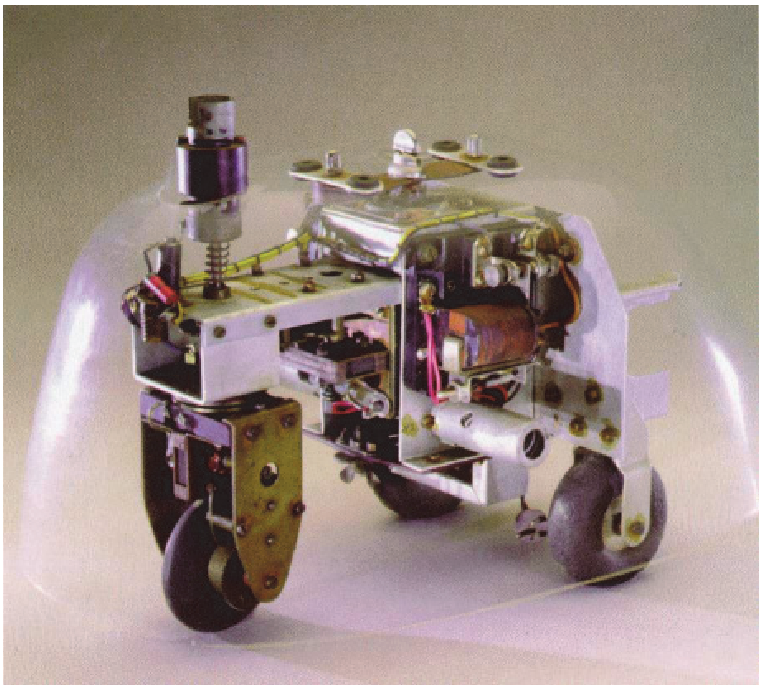


Fig.4. Walter Grey's "Tortoise".

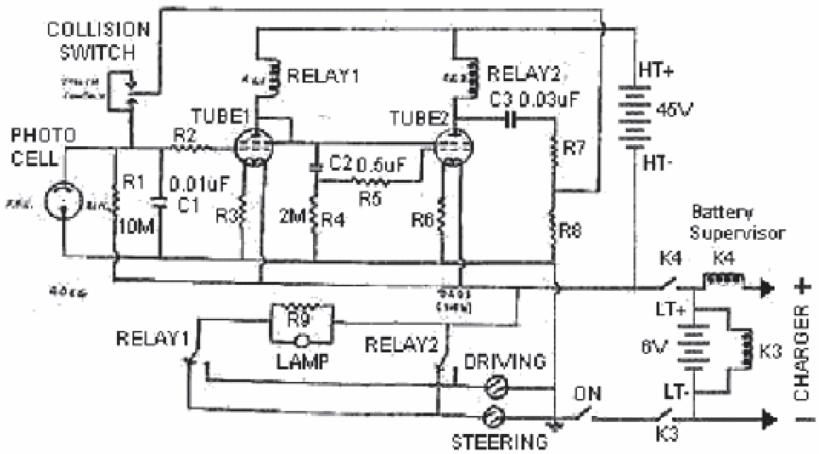


Fig.5. Original "Tortoise" circuit diagram.

So when we look to the topicality of OA it is not difficult to foresee a future with increasing numbers of robots, toy robots, carer robots, service robots, industrial robots and the need for efficient simple solutions is now more than ever a priority in robotics.

Even more astounding is that, according to the International Federation of Robotics (IFR), projections for the period 2011-2014, about 14.4 million units of service robots for personal use to be sold and it is estimated that the worldwide stock of operational industrial robots (OIR) will increase from about 1,035,000 units at the end of 2010 to 1,308,000 units by the end of 2014 with one third as mobile manufacturing robots [2].

1.3 Primary Hypothesis and Intention

Hypotheses:

a) The accuracy of electromagnetic spectrum detection and the subsequent analysis of received sensory data may be sufficient for a truly autonomous mobile robotic platform able to negotiate distant and dynamic terrains without need of human remote interface, providing a more substantive and more rapid investigation of unexplored areas.
b) The inclusion of other passive (read-only) type sensors may enhance the learning processes of a proposed Analogue Neural Network (ANN) or Software based Neural Networking system and instantaneous regulation of an analogue and/or digital weighting system could prove beneficial.

Intention:

a) To design appropriate sensor/circuit topology to enable both analogue and digital detection methods in an adjustable closed feedback system and construct associated printed circuit board for the purpose.
b) To design appropriate microprocessor controller board capable of evaluating received data, analyze controllability parameters and efficiently respond to this data in a controlled and purposeful manner. To construct the board according to design specifications.
c) The inclusion of a barebones neural fuzzy logic solution for example purposes and to enable appropriate research capability.
d) To develop the mobile robot AMBOA Ver.3, purpose built for internal or external research and development, inclusive of hardware structure and control mechanisms.

1.4 Method of Research and Development

Many of the processes of theoretical calculations and graphical representation of results have been obtained utilizing a menagerie of software systems including

- *fuzzy*TECH Fuzzy/Neural Studio- fuzzy logic modeling and programming algorithms;

- Excell- tables and spreadsheets;
- LT Spice- component selection;
- Pspice- Circuit modeling and analysis;
- Orcad- PCB design,
- Eagle- PCB design.
- Visio- 2D parts design
- Blender- 3D parts design
- Matrix2PNG- color modeling of matrix sensor input;
- Neural.NET- neural guided learning software.
- Aforge.net- C# (C Sharp programming framework for .NET applications).
- Matrix2PNG- conversion of matrix data to PNG color charts.

Other results required hands on test-bed approaches to verify the accuracy of software obtained data or reported data. The primary method of research fell to the earlier versions of AMBOA, therefore providing a mobile laboratory of sorts.

Some results were beyond the resources of the author and therefore some reliance of referenced material result was required.

1.5 Scientific Novelty

1. A single multi-sensor photovoltaic array has been used as a primarily read-only passive system for the negotiation of dynamic environments, thus improving self-controlling parameters of the autonomous mobile robotic rover.
2. The sensor array is not restricted to any particular type of sensor (having removable sensors) and can be easily fitted with many photovoltaic analogue or digital devices dependent only on the requirements of the user and within design constrictions non-passive sensors may also be utilized if required.
3. A Neuro-Fuzzy control algorithm has been partially developed for the adjustment, weighting and learning system of the sensor array.

1.6 Practical Novelties

1. The generic wafer has been designed in four tiers: Tier one comprises the sensor array and associated comparator control circuit. ***Refer Appendix D***.
2. Tier two comprises microcontroller based control system with input connection for both analogue (photovoltaic) and digital array outputs. ***Refer Appendix E***.

3. Tier three comprises the DC-DC power conversion circuitry for energy considerations of motors, servos, camera apparatus, touch sensors, modified PIR sensors, lights and wafer controller boards. Tier four will not be constructed and is a future inclusion in the project, however comprises an experimental ANN, designed by the author and is not strictly a part of the doctoral work. ***Refer Appendix F***.

4. The less energy efficient transimpedence amplification of sensory input as originally designed for AMBOA Ver.1 and Ver.2, has been abandoned in favor of tuned comparator only arrays with three 360^0 arrays and a total of 24 independent measurement sensors capable of detecting the electromagnetic spectrum from the Ultra-violet range @ λ = 150nm to the Near Infrared range @ λ = 1150nm on tier one of the wafer board.

5. Cameras have been fitted, and though not specifically necessary for this particular method of obstacle avoidance, gain primary importance to the programmer when with the use of still images, where variances of the sensor responses may be better understood to allow for correct weighting of the decision model of the machine during the "Guided Learning" algorithm or ANN adjustment.

6. The final experimental model mobile chassis is outlined in ***Appendix C***, of this paper and has been:

   Purpose built to serve no other function than that of obstacle avoidance. The chassis is complete with a robust metal framework, four powerful DC motors (obviously relative to size) and four independent three hub wheel tracks capable of traversing rougher than normal terrains. Designed with two additional smaller "scout" robots to enable future investigations within the field of swarm robotics yet although included, do not strictly form part of this paper. Wireless interface has also been included for remote observation requirements.

1.7 Practical Application of Research Results

The completed research model (Ver.3) of the AMBOA (**Amb**ient **O**bstacle **A**voidance) robot presents an ideal test-bed for a large variety of research projects. The generic design is capable of utilizing a wide assortment of sensors (passive and non-passive) and is fitted with a very powerful microprocessor, wireless capability, *prototype ANN (future proposal)*, Wi-Fi vision capabilities, self-charging capability and many other features. These features allow for a test-bed that is limited only by the imagination of the researcher.

The fundamental application or purpose of the author in the creation of AMBOA has been that of an investigative research into remote, isolated destinations and even extraterrestrial exploration in the most dynamic of environments. It is apparent from investigations of our Solar System that using various robotics systems has been thwarted by difficulties due to robotics limitations on mobility and in the future the problems will only increase with distance. The author believes a good starting point is to embed within the robots' sub-systems at the very least an ability to move through dynamic terrains free of the limitations of ultra long distance remote control and forwarding instead constant imagery or video of the chosen environment. This of course does not detract from the controller's ability to override the robot's basic function however the more inbuilt systems which do not constantly require attention from a very distant controller the more area can be covered and discovered with optimistically greater result.

1.8 Dissemination of Research Results

The following 11 publications are presented in the Doctoral Thesis:

1. **L. Adrian**, I. Galkin "Clear Path Sensors for Robotics (The Autonomy-Based Model)", 7th International Conference, Compatibility and Power Electronics CPE'2011 Forum, Tallinn (Estonia) June 3rd, 2011. http://egdk.ttu.ee /files/sf2011/CPE2011_Student_Forum_062-067.pdf
2. **Leslie R. Adrian**, I.Galkin. "Preliminary Circuit Design for Robotics Environment Mapping Utilizing Ambient Light, Reflected Light and Stationary Infrared Radiation", Scientific Journal of Riga Technical University. 29th International

Conference,Power and Electrical Engineering. Volume 29, Issue 1, Pages 123–128, ISSN (Print) 1407-7345, DOI: 10.2478/v10144-011-0021-y, October 2011.

3. **L. R. Adrian** and L. Ribickis, «Fuzzy Logic Control of Photo-voltaic Sensors for Obstacle Avoidance or Mapping Robot», (IJAS) International Conference for Academic Disciplines in Gottenheim, Germany. Academic Journal of Science, Vol. 1, No. 2 Dec 29, 2012.
4. **L. R. Adrian** and L. Ribickis, «Fuzzy Logic Analysis of Photovoltaic Data for Obstacle Avoidance or Mapping Robot», The 16th International Conference ELECTRONICS'2012, Palanga, Lithuania ,18th – 20th June 2012. No. 1(127) Vol 19, Jan 2013.
5. **Leslie R. Adrian**, An Autonomy-Based Model for Obstacle Avoidance in Robotics, (IJAS) International Conference for Academic Disciplines in Rome, Italy. Published May 19, 2013. http://universitypublications.net/ijas/0601/html/ SPQ788.xml
6. **Adrian, L.R.**; Ribickis, L., "Design of human tracking robot utilizing pyroelectric sensor and analogue circuitry, "*EUROCON, 2013 IEEE* , vol., no., pp.1927, 1931,1–4 July, 2013.doi:10.1109/EUROCON. 2013.6625242
7. **L. Adrian**, D. Repole and L. Ribickis. Passive Human Tracking Robot Utilizing PIR and Four Band Multispectral Snapshot, Electronic Proceedings (RTUCON2013) 54th International Scientific Conference of Riga Technical University, Page 32.
8. **Adrian, L.R.**; Ribickis, L., "Proposed Piezoelectric Energy Harvesting in Mobile Robotic Devices," Power and Electrical Engineering of Riga Technical University (RTUCON), 2014 55th International Scientific Conference on , vol., no., pp.63,66, 14–14 Oct. 2014.
9. **Adrian, L.R.**; Ribickis, L., "Intelligent power management device for street lighting control incorporating long range static and non-static hybrid infrared detection system," (EPE'14-ECCE Europe), 2014 16th European Conference on Power Electronics and Applications, vol., no., pp.1,5, 26–28 Aug. 2014.
10. A. Patlins, N. Kunicina, **L.R. Adrian**, Sensor Networking and signal Processing in City Transport Systems. Proceedings of the18th International Conference, Lietuva, Kaunas, 23.–24. oktobris, 2014. Kaunas: Technologija, 2014, 355.–359.lpp.
11. **L. Adrian**, D. Repole, Ribickis, L., "Proposed neuro-guided learning for obstacle avoidance in AMBO a robotic device," in Power and Electrical Engineering of Riga Technical University (RTUCON), 2015 56th International Scientific Conference on , vol., no., pp.1–5, 14–14 Oct. 2015

2. Sensor Technologies

2.1 Conventional Sensor Technologies

In recent decades, the field of robotics has grown beyond all expectations. Authors of science fiction have always placed robots at the zenith of their creative work, although it is doubtful that robots in the near future will acquire the intellectual function of the human mind it is indeed likely that many of the skill sets of the human being in the form of basic tasks could indeed be within reach. Due to a robots ability to repeat tasks without sacrificing accuracy and efficiency, the manufacturing industry has greatly benefited from the ongoing innovation. In addition to industrial robots that essentially repeat the same task once their programming is complete, a new genre of robots are also quickly gaining fame. These robots appear more intelligent and have the ability to respond to external stimuli based in part on a variety of sensory attachments and in part on past experience by way of learning algorithms from many types of advanced programming languages and advanced Analogue Neural Network (ANN) hardware configurations. This could be classed as similar in many respects to the abilities that humans and some animals possess.

Many developments in the field of engineering are directly responsible for this extraordinary growth. The advancements in the fields of analogue and digital electronics have greatly improved the ability to automate and control tasks. In fact, since the introduction of programmable integrated circuits, the development of robots, which was once categorized as an extreme task, has become a hobby for electronic enthusiasts. While these robots have limited capabilities, with creative designing and programming, hobbyists have been able to achieve many versatile objectives, ranging from line-following to obstacle avoidance to smart navigation and even treasure hunting [3]. One of the key components that developed with analogue electronics is the sensing technology. Human beings, animals and insects have the ability to sense the world around them and based on many cues and excitations received, it is possible to deliver or perform appropriate responses. In fact very few humans, animals or insect emit any type of projected radiation and rely for the most part on received stimuli.

Robots, in order to function in the real world or as it is often referred the grounded world, require the same capability and the development of various sensors therefore directly contribute to the development of the field. Another field of engineering that has directly contributed towards this growth is human level machine intelligence. While HLMI is not vital for industrial robots, in attempts to create humanoid robots proponents of the field attempt to create HLMI in order for the robot to make sophisticated decisions, however to date most attempts are not more than reactive responses to algorithmic programming and have little to do with intelligence. The field of machine vision and image processing is also a key player that has contributed to robotics, and this combined with very sophisticated programming is promising but still a long way from actual intelligence but does give the robot some ability to respond to visual cues.

2.2 Methods of Obstacle Avoidance

Obstacle avoidance methods are of a varied and diversified nature. A complete discussion of all methods is simply not realistic however the simplest form of obstacle avoidance is based on negative feedback. What this means is that a sensor will detect an obstacle at a particular location and the "programmed" controller, be that of an analogue or digital nature and dependent on the trajectory of the robot, will determine whether a collision is eminent. If a collision is eminent, a new path (detour) will be decided by the controller. The determination of this detour path is a complicated mathematical process and has to be individually modelled depending on the application. For instance, for a robot travelling in a grid, the optimum path will be to turn left or right at the obstacle, depending on the shortest path from the current location to the destination. The determination of the shortest path is once again a mathematical task, often requiring an algorithm such as Dijkstra's. Robots that do not travel in a grid have to turn while cautiously monitoring the obstacle's dimensions while doing so, once the obstacle is avoided the robot can continue on its shortest path to the destination [4].

For highly efficient tasks, the algorithm needs to be tuned considerably. For instance, turning exactly at the right point in time is vital to remain safe while saving time. This would require even more complex mathematical modelling depending on the obstacle dimensions. Furthermore, the possibility of dynamic obstacles makes this task even more complicated [5].

Obstacle avoidance in robotics is still a largely unsolved problem and a considerable amount of effort is being applied to the problem at leading universities and within the private sector to advancement the field.

2.3 Sensors Used in Obstacle Avoidance

There are numerous sensor types available which may deliver adequate feedback information to a mobile robot regarding the presence of obstacles within an environment. All of these however have their individual pros and cons [6].

In order to successfully avoid obstacles it is necessary to strategically position the sensors on the robot in order to adequately avoid obstacles. Obstacle detection is thereafter followed by a pre-programmed or reactive response by the robot initiating a change to its original trajectory. Reactive response is the basis of the doctoral thesis and based upon the authors assumptions that this passive responsiveness is the fundamental basis for mobility. Depending on the application, trajectory planning can be performed either dynamically or by observing the operating environment prior to mobilization. Usually dynamic trajectory planning is more complicated and versatile algorithms are required for functionality. Should algorithms be a preferred method, they should be carefully selected depending on the application. For instance, if the environment is highly dynamic, the algorithm must have a quick response time, and usually this requires a much larger processing power. The selected algorithm will also have a direct impact on the power consumption of the robot which may be detrimental to the operating duration of the robot, especially in environments where the robot is reliant on external energy sources such as solar recharging.

The subsequent section of this article will give a brief outline and present information about the various types of sensors and their uses, pros and cons. [6],[7].

2.4 Ultrasonic Proximity Sensors

(Not Utilized in AMBOA)

These sensors operate in a similar fashion to the infrared (IR) proximity sensor. Instead of bursting IR waves, these sensors emit ultrasonic sound waves. These waves are then detected by an ultrasonic detector. Depending on the characteristics and timing of the return signal it is possible to measure the distance to the object. Ultrasonic sensors are available in a wide array of characteristics, ranging from sound frequency used, electronic circuitry used and the exterior mounting methods. Depending on the application being designed, the designer has to choose the best type of proximity sensor required. Furthermore, the designer must also take into account the properties of the sound waves used in the sensor. The speed of sound varies from medium to medium and therefore, the sensor will require calibration if the working environment changes. For instance, a robot designed to work in the ambient environment using an ultrasonic sensor will be feeding wrong readings if the air density is changed, for an example, near a highly congested road. The sound characteristics of the working environment can have an impact on the reading as well.

These sensors usually can perform well over a wider range (1-500 cm), resulting in a more versatile obstacle detection characteristic. However, these sensors fail when the obstacle has a high sound absorbing capability, such as clothing or sponges. The general accuracy as well as the price of ultrasonic proximity sensors is higher than IR sensors.

More sophisticated ultrasonic sensors that can identify the frequency shift due to the movement of the obstacle are also available in the market. This shift in frequency is known as the Doppler Effect and these sensors usually have the ability to perform tasks with high precision requirements, such as hand gesture detection.

Proximity sensors have the ability to detect objects that are in the vicinity prior to making contact. These are the most popular type of sensors used in the industry at the present. While there are many types of proximity sensors in use, the IR and the ultrasonic sensors are the most commonly used types in robotics. Laser range finders are also discussed for the sake of completeness.

The formula (1) for calculations relating to ultrasonic sensors became invaluable for estimating distances and receptivity of wavelengths as discussed in Appendix H.

When ultrasonic waves are projected on an object, subtle reflection of the energy takes place in the form of echoes. Thus some fraction of the emitted energy is reflected back to the transducer and is detected. The speed of the ultrasonic wave (v), allows a calculation of distance (L) to the object by (1):

$$L = \frac{vt\cos\theta}{2} \qquad (1)$$

where:

t = the time taken for the ultrasonic wave to return to the sensor and cosΘ represents the angle between the horizontal and the course of the wave as in Fig.6. However in the instance where either the object or the sensor (robot) is in motion Doppler Effect equipment or algorithms must be used.

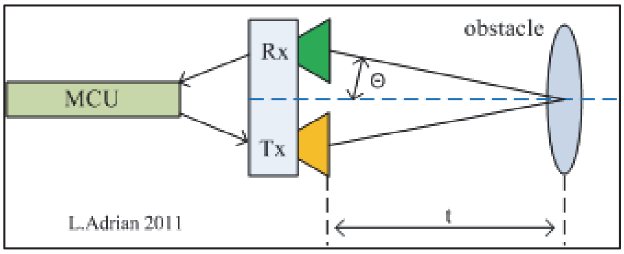


Fig.6. Typical ultrasonic sensor.

Moreover, in overly obtuse angle situations, Fig.7, this type of sensor has much less reliability due to the fact that when dealing with sound, "*the angle of incidence equals the angle of reflection*", as defined for light.

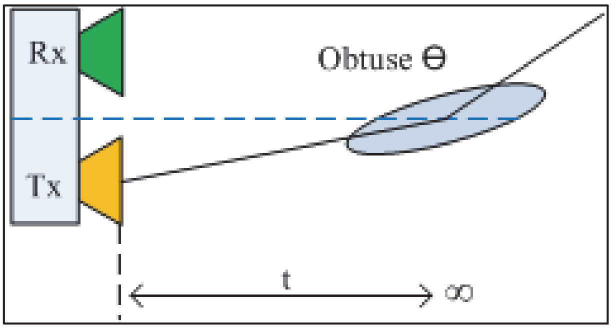


Fig.7. Overly obtuse angles may considerably affect results.

2.5 *Infrared Proximity Sensors*

(Not Utilized in AMBOA) Infrared proximity sensors are used in the AMBOA system only whilst Guided Learning is performed, as a backup system to avoid damage to the robot.

These sensors comprise of an emitter that emits (IR) light and a sensor that observes the return signal. The emitter may emit a specific frequency say 38 kHz though more often than not simple emitters are used with no thought as to ambient interference, which is the main issue with random sensor selection. A frequency tuned emitter is slightly more accurate however with matching receiver becomes quite expensive with little additional benefit. The sensors are also dependant on whether or not the signal is actually returned and the time taken for the signal to be received and thereafter the sensor has the ability to produce an analogue or digital reading, which can be interfaced with a main controller to make a decision regarding the distance between the sensor and the obstacle. The binary type IR sensor can be used to detect the presence of the obstacle however lacks the ability to give useful information about the distance from the obstacle.

By varying the design of the sensor, it is possible to sense the presence of various types of objects with various colours at various distances. However, due to the absorption, IR sensors usually perform poorly when the obstacle is dark in colour. IR sensors often need to be recalibrated when the sunlight conditions change, therefore, are not suitable for outdoor use unless specific measures are taken to adjust ambient light levels on the fly (which is covered in ***Appendix G*** of the paper).

IR sensors are usually used for either short range (4 – 35cm) or long range (100 – 500cm) and often provide incorrect readings when the obstacle is out of range. IR sensors are inexpensive and available for hobbyists who may design their own if required due the simplicity of the design.

2.6 Passive Infrared Proximity/Motion Sensors

(Moderately Utilized in AMBOA)

Another type of IR sensor, known as the passive infrared (PIR) is used for motion detection. These sensors do not have an emitter and rely only on received Infrared Radiation impinging on the receiver. These sensors are usually sensitive enough to detect even fast moving objects. PIR sensor readings usually do not convey distance information however through specific measures taken approximations of distance may be formulated as can be seen in ***Appendix O***, of the paper. An obstacle avoidance robot will thoroughly benefit from the information received through the PIR to make swift decisions in path planning.

2.7 Laser Rangefinder

(Not Utilized in AMBOA)

These devices perform using the same theory as the IR proximity sensor. A laser light is emitted from the emitter end and a sensor is used to detect the reflected wave. In general applications, laser rangefinders are used to determine the distance to objects that are far away. While highly sophisticated laser rangefinders can detect objects that are several kilometres away, general robots do not have a requirement to make such measurements. However, robots deployed in military applications may have applications for such long distance rangefinders. Typical robotic rangefinders can work for longer distances than ultrasonic rangefinders, typically ranging from around 10cm – 5000m.

These rangefinders usually require a camera sensor to detect the presence of laser light and can fail in bright environments. However, in sufficiently dark conditions, laser rangefinders are far more accurate than IR proximity sensors. However, in dynamic lighting environments, laser rangefinders require multiple calibrations. Furthermore, using laser light in robotic applications can be risky to the user, especially considering the risk of retinal damage by direct exposure to laser light.

2.8 Camera Sensors

(Utilized in AMBOA for Programming and Area Image Retrieval Purposes)

Due to recent reductions in pricing, cameras are gaining great popularity within the robotics field, also reducing weight and increases in image quality make them ideal for remote visual sensing. A camera installed on a mobile robotics device has no ability or capability of detecting the presence of an object and therefore, if a camera sensor is used, it is often used for the purpose of image reporting to the user and for any other operation it is necessary to include a digital signal processing (DSP) unit along with it. Unless sophisticated obstacle detection is required, using a camera sensor is often a disadvantage. Image processing is a highly processor intensive task and therefore, requires a processor along with considerable amounts of memory, extremely large algorithms and the ability to store massive quantities of redundant images. The main problems associated with such visual system is the high energy requirement needed cameras including processors and storage will often perform poorly when the robot is reliant on a battery only system.

If correctly implemented and augmented with well programmed routines these sensors have the highest capability of successful trajectory planning in complicated environments. Unfortunately, the responses of cameras and their associated algorithms are too slow for real time dynamic obstacle avoidance. For example, you cannot expect that a camera, regardless of its program will detect a fast moving object in sufficient time to avoid a collision.

Unlike analogue sensors, camera sensors operate based on visual cues, and by utilizing powerful algorithms, it is possible to detect the object, understand the direction of movement, and calculate the distance to the obstacle. Even with all this information, the camera sensor is relatively slow to respond in dynamic environments. A popular application of obstacle detection and avoidance using camera sensors is in robot football games. The robot must distinguish between other robots and the ball then shoot the ball to the net while avoiding contact with the goalie robot. However anyone having witnessed a robot football game will attest to the slow action of the robots however in more recent times these actions have increased in speed in accordance with faster processing power. Vision systems regardless of their drawbacks, are becoming quite popular in many areas of robotics albeit mostly in the factory environment with recognition systems.

Of the most common types of camera sensors available, two are most commonly used in the robotics field being the charged coupled device (CCD) sensor which is rarely used in photographic applications due to poor performance however, may be used in robotics if the price is a design consideration. The complementary metal oxide semiconductor (CMOS) type device is many times more expensive, yet can deliver better image quality, even when subjected to lower lighting conditions at a faster rate. When designing a robot relying on visual cues, it is important to consider the resolution of the camera. Higher resolution images in proper lighting conditions may deliver more information, however, the processing time, energy consumption and hardware costs can increase tremendously. It is vital that the resolution is selected such that it is at the minimum required level to conserve all three.

AMBOA Ver.3, is fitted with camera utilities, however these cameras are primarily for neural fuzzy logic algorithm weighting purposes as will be further explained in ***Appendix C*** of the paper.

2.9 Sound Sensors

(Mildly Utilized in AMBOA)

Essentially microphones incorporating an analogue comparator circuit in combination with a low power amplifier, sound sensors may be used for obstacle avoidance in certain applications or where the environment involves signal analysis. The output from the sensor due to the comparator arrangement and amplifier can be operated as either a digital or analogue device. When obstacles emit known sound waves with a certain distinguishable pattern, the use of microphones is a possibility. At first glance this may appear strange as most object do not, to our range of senses usually emit any sound, however upon investigation one can find that many substances are emitting sound waves which are usually caused by vibration similar to that of a tuning fork though most are in the higher order of Hertz and out of our audible range. Their use however, due to the requirement of preamplifiers and current amplifiers can complicate the process considerably. Usually for signal pattern analysis, it is essential to convert the analogue sound signal into a digital signal and is quite similar to how camera sensors operate and often requires the addition of a DSP or ADC unit though the processing requirements of an audio signal is considerably less than that of video or image analysis.

Processing of the audio signal makes it is possible to make several observations about the obstacle including the distance to the object which can be approximated using multiple microphones and it is also possible to capture the direction of movement of mobile obstacles. However, microphone based systems perform extremely poorly in noisy environments and therefore as a rule are not well suited to obstacle avoidance.

The most advantageous use so far realized by the author is the location of other robots in a swarm robotics scenario, where each robot is producing its own specific sound and all members of the swarm maintain a memory allocation to identify that particular member.

2.10 Light Sensors

(Heavily Utilized in AMBOA)

Light sensors form the primary functional envelope of AMBOA. These include the family of sensors which are designed with a responsivity to many wavelengths (λ) of the electromagnetic spectrum from low nano-meter through visible spectrum to much higher wavelengths dependent on the type of band-pass filter used. Many types of detectors exist, such as photo resistors, photo-transistors, photo-diodes and sensors able to detect colour and some with near human eye receptivity. It is also possible to use more complicated devices such as photo-multiplier tubes (PMTs) however these are not commonly used in practice.

Incident light sensing based devices can read the quantity of light falling upon the sensor surface or substrate. The λ of the wavelength sensed may or may not be visible to the human eye. Notwithstanding, depending on the level of luminance, the microprocessor or analogue controller should be able to select a proper trajectory for the robotic device. These devices are well suited for navigating within darker environments, especially if the obstacles are illuminated. Cameras of course may be used however the photo sensitive sensor can be utilized and perform the same task without additional processor requirement or in fact through a fixed analogue hardware device. In addition, photo sensitive devices have a minimal energy impact on the robot systems, unlike cameras which can create a huge impact on the energy reserves of the robot.

Obviously, photo sensors can perform inadequately in highly illuminated environments and are subject to saturation if those light levels are not constantly adjusted. Therefore a simpler technology is utilized to adjust the sensitivity of the sensor array. ***Refer Appendix G***.

It is true to a certain extent that the use of variable resistors to maintain controls upon sensor calibration is not strictly suitable for devices that are not designed to perform in both poorly and highly illuminated environments, it is possible using the LDR potential divider to obtain an appropriate average solution.

2.11 Push Buttons, Pressure and Force Sensors

(Utilized in AMBOA for Programming Information and System Safety)

Certainly nowhere near as elegant and not usually classified as a high tech solution, the reliability of push buttons, pressure and force sensors are much higher than that of proximity sensors. The sensors require some form of physical contact which no doubt, in the eyes of many makes them appear a crude and outdated device. Nothing could be further from the truth. From office printers, to factory robots, to vehicles, toys and a large assortment of machinery produced today, many are equipped with some form of pressure sensor.

It is necessary to have the sensor come into direct contact with the obstacle in order to detect its presence. These devices usually consume negligible amounts of power and are absolutely essential to be used to assure safety. A very simple application example is of a ground robot navigating at a certain speed. At an obstacle, such as a wall, by using proximity sensors it is possible to totally avoid the collision. However, regardless of the type, all proximity sensors can fail to work under certain environmental conditions. In such an occasion, if a force sensor or a push button is not available, the robot will hit the obstacle, and will try to continue propagating in the same path. The initial hit, if the robot is carefully designed, will result in negligible damage to the robot, however, if the robot does not immediately stop at the impact point, the damage may increase to disastrous levels.

Push Buttons or Whiskers

Whiskers are used in the AMBOA system only a backup system to avoid damage to the robot while Guided Learning is performed.

While physical contact may sound ill-suited for navigation purposes, push buttons are highly used in robotics for detecting stopping criteria. The push button is a tactile device with a single button. When it is powered, a pulse will be generated at every button push. This pulse needs to be processed in the robot’s controller. As it was mentioned before, these buttons are usually used for safety mechanisms and therefore, the controller should take immediate action if the button is pressed to avoid the robot from harming itself and the obstacle.

The now quite common robotic vacuum cleaners available still utilise the whisker (push button) reactive system fall movement close to walls etc.

Pressure Sensors

The pressure sensor has a similar application. In robotics, the usual practice is to use strain gauge type pressure sensors. The strain gauge is a simple metallic coil which is printed on a flexible plastic. When the plastic is pressurized, it will bend and the coil will deform, resulting in a change of resistance at the two ends of the coil. This change is proportional to the amount of pressure on the flexible plastic.

Force Sensors

A force sensor is usually made of a material that changes resistance when a force is applied upon it. Usually, conductive polymers are used for this purpose. These polymers essentially comprise of particles that conduct electricity and particle that do not. When a force is applied, due to the physical deformation, the density of conducting particles will increase and the resistance will drop.

Sensors - Ancillary

<u>Encoders</u> *(Encoders will be added to the AMBOA system at a later date or when the mapping of areas or distance measurement becomes a necessity)*

These devices are not designed to capture readings from the external environment of the robot rather these devices precisely measure the position of the robot by measuring the movement of actuators. The human body has a very advanced encoder system which is capable of detecting the positioning of the body without any other cues. For instance, even if there is total darkness, the human body is capable of walking without falling onto the ground. A robot must have a similar capability to navigate in the environment while successfully avoiding obstacles. Furthermore, in robotics, most applications require the actuators to move a certain distance or a certain angle in order to perform the task. While proximity and tactile sensors can give a very good feedback regarding the distance, the actuator itself needs to be carefully controlled to stop at the precise location. This is especially true for high speed applications. The exact point to start applying a brake on a high speed actuator (e.g. motor) cannot be calculated using the proximity reading. The encoder exactly measures the current position of the actuator and feeds the controller with the information to make a more accurate decision.

Linear Encoders

These encoders are used with linear actuators to measure the position. A scale is attached to the linear actuator which moves along with the motion of the actuator. This scale is usually made up of small stripes, and a sensor is properly aligned with the scale to count the number of stripes that pass directly next to it. Depending on the thickness of the stripe, it is possible to achieve a variable level of resolution to the movement. In order to improve the accuracy, some encoders have an emitter that emits light from the other side of the sensor. The scale moves in between the emitter and the sensor and the stripes are counted with extremely high accuracies in this method.

Rotary Encoders

These encoders measure the angle of rotation of a motor. The operating principle of a rotary encoder is the same as a linear encoder. A disc with layered stripes is used as the scale. A stationary sensor is used to count the number of stripes as the stripe disc rotates next to it. Similarly, an emitter of some sorts may also be used to improve accuracy.

Both these measurements are digital measurements, and therefore, can be directly coupled with the robotic controller and the number of stripe counts are usually received in the form of a binary signal and can be counted. Once counted, it is necessary to perform a simple calculation to convert the reading to a linear or an angular reading. As mentioned, once the controller knows how much further the actuator has to travel and how far it has travelled so far, it can carefully control the power applied to the actuator such that it will stop exactly where it is required without overshooting.

Other Types of Sensors

Besides the ones discussed so far, many sensors are available and are used in the field of robotics for obstacle avoidance purposes. For instance, the Hall Effect sensor is a type of magnetic device that can be used to take measurements about the magnetic field around the robot. Besides the Hall Effect sensor, there are specific magnetic proximity sensors that can perform the same tasks however, magnetic measurements are generally not used in robotic applications.

2.13 *Conclusions Section 2*

In the creation of the AMBOA robots, the author deliberately had a specific goal in mind. That goal being to evaluate the possibility of an autonomous robot to move unhindered in a dynamic environment without the use of emitter or non-passive electronics, some of which are described in the preceding sub-categories. With this in mind and subsequent investigation of a large assortment of readily available sensors it has become evident that almost all of the described sensors fall short of a complete solution and yet are frequently used due to their ease of installation or ease of programming. An OA sensor with a ninety percent reliability (infrared proximity sensor), will collide with an object 10% of the time. Given the value of some robotic devices this is an extraordinarily unsatisfactory solution.

3. Obstacle Avoidance

3.1 *Common Applications*

What first comes to mind when robotics applications are mentioned to most people are extraterrestrial vehicles operating on mars, landing upon asteroids and flying across the solar system at incredible speeds, military robots or even drones. These vehicles with their various applications of robotics are for all their features and amazing results still far from the true meanings of autonomy and may be better suited to the name of simply remotely operated machines (ROM) or remotely operated vehicle (ROV). Very little of the processes they perform have much to do with autonomy at all, in that they are driven remotely with most experiments performed from pre-programmed sequences activated by the controllers but this does not take away from the incredible engineering feats performed.

OA methods and applications are required for (but not limited to):

- Safety for people working alongside robots.
- Safety for animals in the vicinity of robots.
- Safety in respect of damage to surrounding equipment.
- Prevention of damage to the robot and possible failure or expensive repair.
- Environmental or other research in areas inaccessible to humans.
- Exploration of terrestrial, undersea and extraterrestrial environments.
- Ensuring full autonomy for remote vehicle exploration.
- Enabling researchers to concentrate on exploration instead of vehicle guidance.

3.2 *Obstacle Avoidance or Recognition*

It is believed by some that a prerequisite for true OA systems is a certain level of artificial intelligence (AI) or at least human level machine intelligence (HLMI), however the author disagrees with the assumption for the following reasons. It has been shown in research across the globe that many OA methods do work and work adequately for most tasks (refer section 1.4), dependent on the task required. Some problems arise when OA is confused with obstacle recognition (OR). Analysis of OR is far more intricate and requires heavy data processing in association with sophisticated algorithmic methods with associated losses in efficiency and higher energy costs and does not form a part of this thesis.

Let us take for an example a ROM traversing a particularly rocky area of Mars. The robot has been programmed to travel from a point A to a point B. This may be achieved using various methods, for example radio beacon technologies or even following high frequency sound emitted from a previously landed device. Irrespective of the method used, the area is an unknown and so the number of obstacles unknown. Therefore the shortest path between A and B is variable.

The robot AIBO by Sony is one of the most sophisticated robots of the past few decades. Although a financial failure due to costs and selling prices, it incorporated sophisticated engineering principles and if affordable would have been one of the favourite toys of this generation. This robot relies on a proximity sensor mounted on the chest and cameras mounted in the eyes. Based on the readings from these devices, AIBO can safely work in the environment with children without causing harm. While the toy robot may not seem to be of much importance for scientific development, the technology opens a myriad of ways to develop robots suitable for home use. Caring for the elderly, in particular, is rapidly becoming a leading problem and, researchers with these types of robots are now looking to that end [7]. The ASIMO robot by Honda is another example [8].

The latest parking assistant technology in the BMW 5 series is another fine example of robotics and obstacle avoidance. A video feed from a camera along with strategically placed proximity sensors are used to guide the car to a parallel parking without the requirement of human interaction [9]. The Google car, which can drive entirely on its own, is another fine example of obstacle avoidance in application. Although no obstacle avoidance was performed, even the older cars that had proximity sensors to sound an alarm, gave the driver helpful information regarding the proximity of objects to the blind spots sides of the vehicle.

Self-navigating robots are still in developmental stages and some time away from appearing on the streets, however the technology that is being developed today in terms of obstacle avoidance will definitely be a cornerstone in the development of those next generation robots.

3.3 Advantages of Reverse Biasing

During the construction of the AMBOA system and specifically the sensor array, investigations and research led to the conclusions that for practical purposes, the use of biasing dramatically improves the response of all photodiodes. The responsivity of the photodiodes increases and more readable results have been obtained. In this configuration, where analogue measurements are an amplification of the received signal, it is necessary to obtain the greatest degree of receptivity possible from the photodiodes.

The following is an extract from the white paper of "National Instruments" regarding the advantages of Reverse Biasing;

Without incident light, the depletion region of a photodiode does not contain free charge carriers (all electrons and holes are recombined, which is why we have a depletion region), whereas the n and p regions of a semiconductor have mobile charge carriers that are ready to flow. Hence, nearly all the bias voltage drops across the depletion region because this zone does not conduct. As soon as the incident photon creates electron-hole pairs, this voltage helps to separate these free charge carriers and quickly removes them from the depletion region, thus generating photocurrent. This is the first and major advantage of using reverse biasing.

In the situation where the incident photon does not strike a depletion region but, rather, the n or p regions of a semiconductor? This can also create a free charge carrier, but the electric forces in these regions are weak so they will remove the electrons and holes there very slowly. Thus, a photo-generated electron-hole pair is separated by reverse voltage quickly and efficiently in the depletion region, but this separation occurs very slowly and inefficiently in the p or n regions because of the weakness there of electric forces. This is the second advantage of using reverse biasing. Incidentally, the photocurrent created in the depletion region is called drift current.

Photocurrent created in the n or p regions is called diffusion current.

A puzzling thought may cross your mind at this point: "If electrons and holes created by the incident photons and separated by reverse voltage have to drift through the depletion region before they reach the wire to flow to the battery, why don't they recombine again and radiate a photon?" Good question. Theoretically, electrons and holes can recombine again but, in *reality, the loss of charge carriers due to secondary recombination is negligibly low. This is because the reverse voltage sweeps them from the depletion region faster than they can recombine again. In other words, the separation time of these carriers due to applied voltage is much less than their recombination lifetime. Thus, we have the third advantage of using reverse biasing.*

The last, but not the least, advantage of reverse biasing is its ability to eliminate what's called dark current. Without incident light, some free charges in the depletion region can be created mostly by external thermal energy (temperature). The flow of these charges creates dark current, I_d. In other words, dark current is current generated by a photodiode without light. Clearly, dark current is a detrimental phenomenon because it eventually determines the minimum light power that can be detected, that is, a photodiode's sensitivity. How does reverse biasing help here? Since all voltage is applied across the depletion region, any free charge carriers that are occasionally created without light will be swept away by the reverse-bias voltage. This means that reverse biasing controls dark current.

So, from a practical standpoint, reverse biasing improves a photodiode's linearity, increases its speed and efficiency of operation, and reduces its dark current [10].

3.4 Conclusions Section 3

Taking consideration of the preceding paragraphs it becomes clear that possibly the most effective solution for obstacle avoidance is a redesign of the system to exclude systems that attempt to recognize and also avoid obstacles. The authors premise is that these two structures should remain exclusive. In effect the recognition of an object is not specifically necessary in order to avoid that object. The OA system does have some ability in the areas of recognition due to its ability to recognize specific spectral wavelength λ however those areas have not been tested to a large extent and this is a priority for future research. As in paragraph 3.3, the use of photoconductive mode with the selected AMBOA sensor array, makes the most logical sense from the perspective of hardware design (smaller form factor) and also the energy efficiency which may be expected from that mode of operation. The matters of obstacle recognition are the subject of other research however the writer should point out that objects which are known to emit specific wavelength, be it color or temperature or other invisible spectral characteristics have proven to be identifiable, yet due to the varying degrees of ambient light and temperature would still require algorithmic analysis, of which many programmers have previously designed which may be incorporated into the AMBOA system if required. It has been previously stated that as a whole the AMBOA system, where possible has been designed specifically to be utilized as a test bed for other approaches be they OA, OR, and many other applications.

4. Preliminary Stages of the AMBOA System

The Ambient Obstacle Avoidance Robot (AMBOA) has developed through three stages. The first of which was in effect a very clever toy AMBOA Ver.1, Fig.8, capable of very remedial navigation within a dynamic environment yet very capable of detection of infrared wavelength in a 360^{o} radius and using a completely analogue system combined with a modified PIR system, was able to react in various ways to hand commands such as stop, come and back away and included an absolute "avoid" reactive system when approaching or being approached by a human. The system was highly chaotic yet many of the systems were refined to perform the tasks mention above.

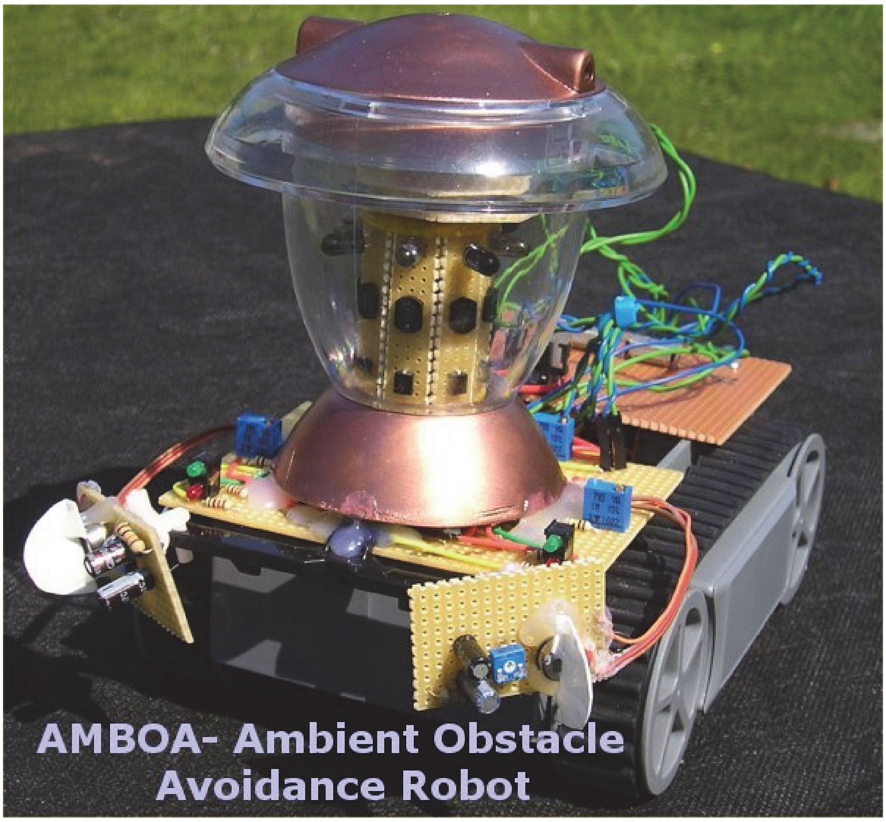


Fig.8. AMBOA Ver.1, a completely analogue system.

In effect the system was the initial proof of concept in the use of read only sensory devices such as PIR, Low visible, mid-range visible and near infrared photodiodes. This initial prototype relied on the temperature variation across the pyroelectric sensors to react to hand movement and to indicate human movement direction. The sensor array was used to control directional movement away from high and low temperature objects and always directing towards the middle range readings.

AMBOA Ver.2, Fig.9, was dedicated only to a redesign of the sensor array, utilizing more sensitive photodiodes in an attempt to alleviate problems occurring with transimpedence amplification across the 24 PD array as mentioned within ***Appendix D***. The redesign allowed recognition of a greater degree of incident light but was plagued by external noise affecting the transimpedence amplifiers. Noise reduction, especially in a read only system is a critical aspect for light sensor based obstacle avoidance [11] as the author has previously concluded within earlier work and subsequently witnessed within the project.

Thereafter AMBOA Ver.2b, Fig.10, was enabled with a digital system only to enable cross references of the adaptability of the system to a programmed system as is further detailed in *Section 5*. Irrespective, both systems were dropped in favor of a Hybrid Analogue & Digital AMBOA Ver.3.

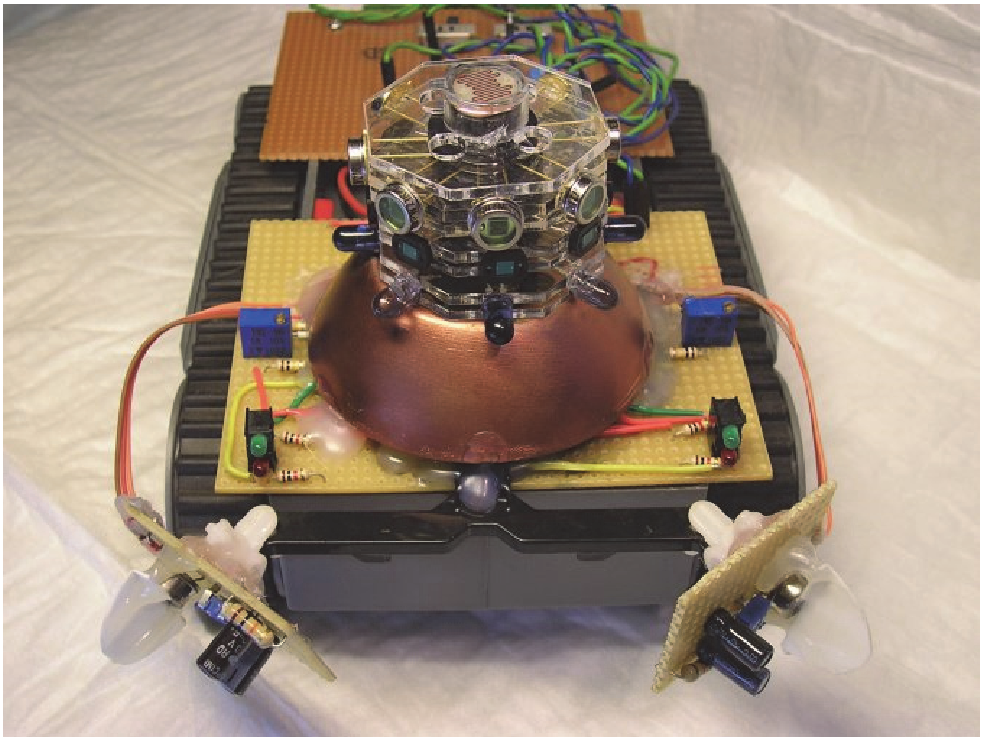


Fig.9. AMBOA Ver.2a, with new sensor array.

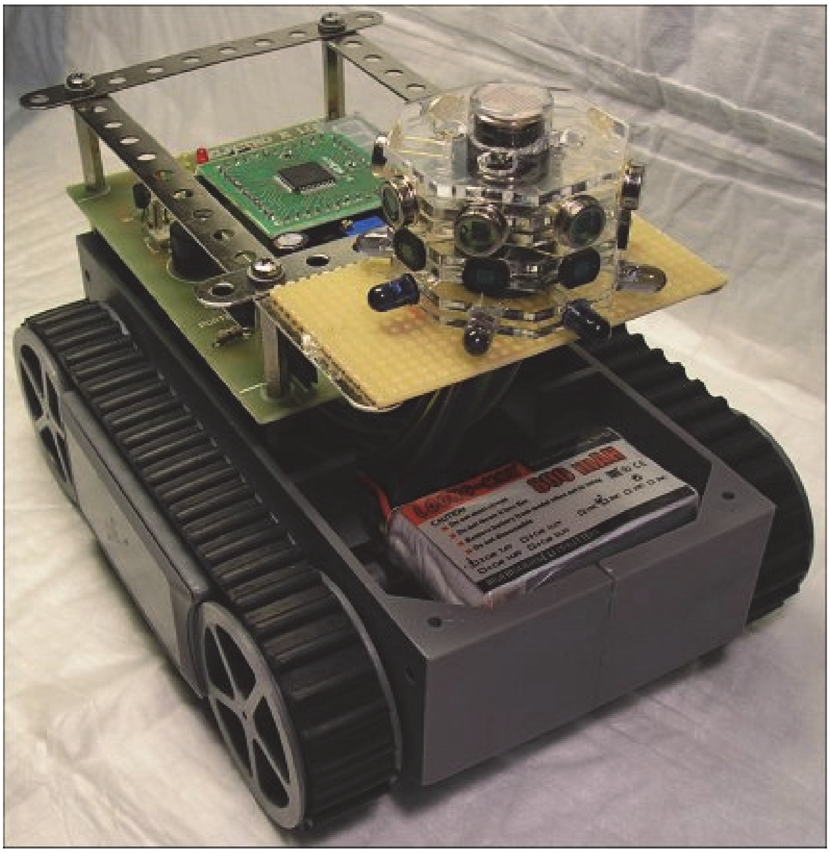


Fig.10. AMBOA Ver.2b, experimentation with fully digital system.

5. Fuzzy Logics Introduced to AMBOA

5.1 Introduction

For Lotfi A. Zadeh, the author of the fuzzy logic system, it was quite normal to describe his work as, "computing with words", and with that definition of fuzzy logic was enabled a new way of thinking about logical systems. The use of qualitative inferences in the design of artificial systems whether it be in decision or control support, if the mathematical model is not known or simply does not exist or is too complex to run properly in real time the target of fuzzy logic has been to unearth solutions to problems, through the use of empirical and qualitative rules that affect a world of unclear or fuzzy actions, instead of the logic of either black or white [12].

In actual practice, traditional bivalent logic is characterized by associating each element with a value that can be only "0" or "1", so that the method of belonging to a set is only ever true or false. In contrast, fuzzy logic is designed to be "polyvalent", where a degree of membership "M_I (X)" of an element "X" to a fuzzy set "I" can assume any value in the range between 0 and 1. Membership Function may be defined as the relationship that represents this kind of membership. Those functions are designed as a result of expert recommendations or in the most elementary case witch use easy empirical functions dictated by common sense. These functions could take many forms, but in less complex cases is preferable to use only triangles and or trapezoids.

The design of fuzzy algorithms is achieved in 3 steps, Fuzzification, Fuzzy hedges and Defuzzification. ***Refer Appendix I***.

5.2 Fuzzy Logic Applications

Nowadays there are endless applications for fuzzy logic in as many fields, due to the fact that this approach is providing very good feedback, especially for applications upon which the process is not available or not yet modeled or is affected by disturbances due to external variables that can influence the model. In fact, in order to achieve an accurate, reliable and stable control for complex system, the mathematical model (P(s)) that describes the physical system process may not be appropriate, because it is based on a specific hypothesis and usually is calculated with approximations under specific environmental conditions. Therefore the control design process should be obtained utilizing formula (2):

This means that what should be used for the control to design the process is:

$$P_{D(s)} = \left\{ \widetilde{P}_{(s)} = P_{(s)}\left(1 + \Pi_{(s)}\Delta_{(S)}\right), \left\|\Delta_{(S)}\right\|_{\infty} \leq 1 \right\} \qquad (2)$$

Where the weight function: $\Pi_{(s)}$

and: $\Delta_{(S)}$ an adaptive function that has a resonance peak of ≤ 1, so that both functions could only have negative poles and zeros. It is therefore easy to understand how useful fuzzy logic can be when: $1 + \Pi_{(s)}\Delta_{(S)}$ is not very small.

The control theory and stability theory are based on LTI hypothesis, in other words, fuzzy logic is a very good choice when looking to Lyapunovs' Theorem (***Refer Appendix J***). Also in this case Fuzzy Logic is very useful for values of ε that are not extremely small.

Some interesting examples of Fuzzy logic applications are:

- Fuzzy control design for gas absorber systems.
- Large scale fuzzy controllers for appliances.
- Power factor correction.
- Trending and prediction.
- Biomedical applications.
- Ground Vehicle Engineering.

- Smart Modeled Fuzzy Logic Maximum Power Point Tracker for photovoltaic applications.
- Application of Fuzzy Logic in Smart Distributed Power Systems or Micro-grids with a High Penetration of Renewable Energy.
- Application of Self-tuning fuzzy PID controller on industrial hydraulic actuator using system identification approach.

5.3 Introduction to Neuro-Fuzzy

Artificial neural systems can be considered as simplified mathematical models of brain-like systems and they function as parallel distributed computing networks. However, in contrast to conventional computers, which are programmed to perform specific task, most neural networks must be taught, or trained. They can learn new associations, new functional dependencies and new patterns. Although computers outperform both biological and artificial neural systems for tasks based on precise and fast arithmetic operations, artificial neural systems represent the promising new generation of information processing networks. ***Refer Appendix J***.

The modern techniques of artificial intelligence have found applications in almost all the fields of human knowledge. However, a great emphasis is given to the accurate science areas. Perhaps the biggest expression of the success of these techniques is in the engineering field. These two techniques, neural networks and fuzzy logic are many times applied together for solving engineering problems where the classic techniques do not supply an easy and accurate solution. The neuro-fuzzy term was born by the fusing of these two techniques. As each researcher combines these two tools in different ways, then, some confusion was created on the exact meaning of the term. Still there is no absolute consensus but in general, the neuro-fuzzy term means a type of system characterized for a similar structure of a fuzzy controller where the fuzzy sets and rules are adjusted using neural networks tuning techniques in an iterative way with data vectors (input and output system data). Such systems show two distinct ways of behavior. In the first phase, called the learning phase it behaves similar to neural networks, that learns internal parameters off-line. Later, in the execution phase, it behaves like a fuzzy logic system. Separately, each one of these techniques possess advantages and disadvantages that, when mixed together, theirs cooperage provides better results than the ones achieved with the use of each isolated technique.

Since the moment that fuzzy systems become popular in industrial application, the community perceived that the development of a fuzzy system with good performance is not an easy task. The problem of finding membership functions and appropriate rules is frequently a tiring process of attempt and error which lead to the idea of applying learning algorithms to the fuzzy systems. The neural networks, that have efficient learning algorithms, had been presented as an alternative to automate or to support the development of tuning fuzzy systems. The first studies of the neuro-fuzzy systems date of the beginning of the 1990s, with Jang, Lin and Lee in 1991, Berenji in 1992 and Nauck from 1993. The majority of the first applications were in process control. Gradually, its application spread for all the areas of the knowledge like, data analysis, data classification, imperfections detection and support to decision-making, etc. Neural networks and fuzzy systems can be combined to join its advantages and to cure its individual illness. Neural networks introduce its computational characteristics of learning in the fuzzy systems and receive from them the interpretation and clarity of systems representation. Thus, the disadvantages of the fuzzy systems are compensated by the capacities of the neural networks. These techniques are complementary, which justifies their use together. [15], [16], [17], [18].

5.4 Neuro Fuzzy Systems

In general, all the combinations of techniques based on neural networks and fuzzy logic can be called neuro-fuzzy systems [17]. The different combinations of these techniques can be divided, in accordance with in the following classes:

- *Cooperative Neuro-Fuzzy System:* In the cooperative systems there is a pre-processing phase where the neural networks mechanisms of learning determine some sub-blocks of the fuzzy system. For instance, the fuzzy sets and/or fuzzy rules fuzzy associative memories or the use of clustering algorithms to determine the rules and fuzzy sets position. After the fuzzy sub-blocks are calculated the neural network learning methods are taken away, executing only the fuzzy system [19], [20].
- *Concurrent Neuro-Fuzzy System:* In the concurrent systems the neural network and the fuzzy system work continuously together. In general, the neural networks pre-processes the inputs (or pos-processes the outputs) of the fuzzy system [17].
- *Hybrid Neuro-Fuzzy System:* In this category, a neural network is used to learn some parameters of the fuzzy system (parameters of the fuzzy sets, fuzzy rules and the weights of the rules) of a fuzzy system in an iterative way. The majority of the researchers utilize the neuro-fuzzy term to refer only to hybrid neuro-fuzzy system [17]. ***Refer Appendix K***.

5.5 *Author Preferred Fuzzy Logic Software*

Many software solutions are available such as MatLab, and are able to manage fuzzy logic programming and provide the necessary tools to evaluate ideas. Of particular interest to the author is software expressively designed for elaborating fuzzy logic algorithms called *fuzzy*Tech. This software is able to simulate and also to generate algorithms in C code, Java ST code and M code. Obviously, dedicated software has higher performance than general purpose computational software.

The software allows the generation of many types of fuzzy membership functions Fig. 12, and once a declaration of hedges is made through the rules editor, Fig. 13, is it possible to develop simulations Fig. 11 and to generate the necessary codes.

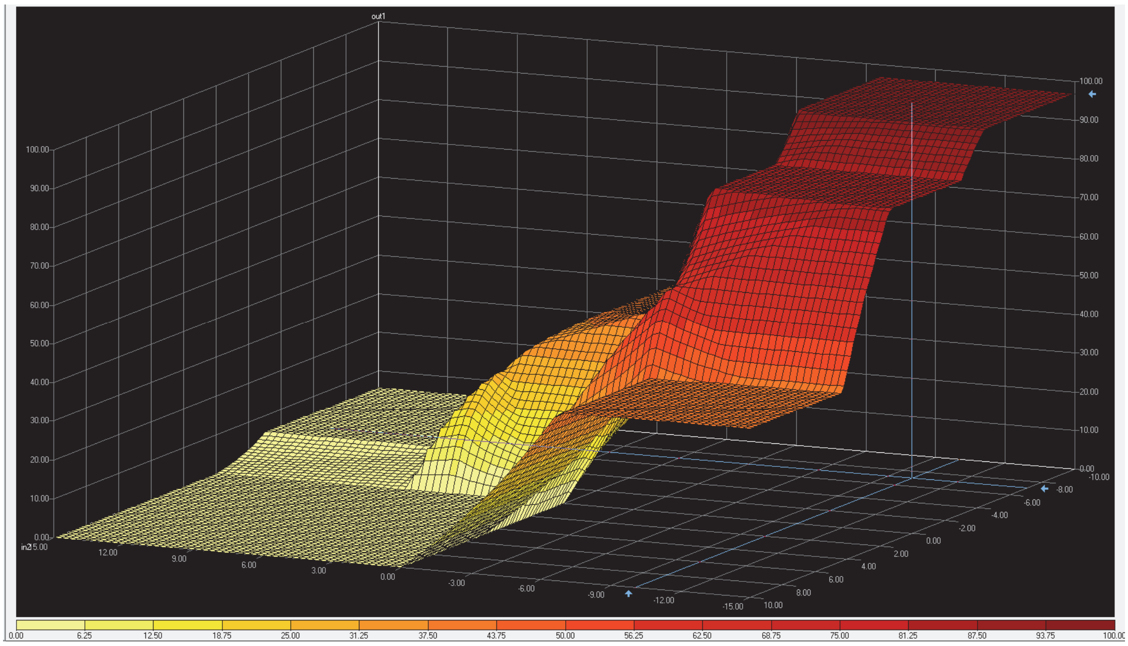


Fig.11. FuzzyTech 3D system simulation example.

Of course the software offers endless numbers of solutions for varying configurations and with the project of the thesis it was not necessary to utilize in any great way the 3D aspect of the software, however it should be noted that should a 3D representation of the acquired date be needed then this particular feature would prove itself very useful. Within the AMBOA system, fuzzy logic is used as a simplification method to filter the data, essentially minimizing the amount of data which is thereafter fed to the guided learning algorithm. As an example, if the robot is moving forward, and this is the only direction the operator is interested in, then only 12 of the 24 sensor array is actually needed to be delivered to the guided learning algorithm essentially reducing processing time by one half.

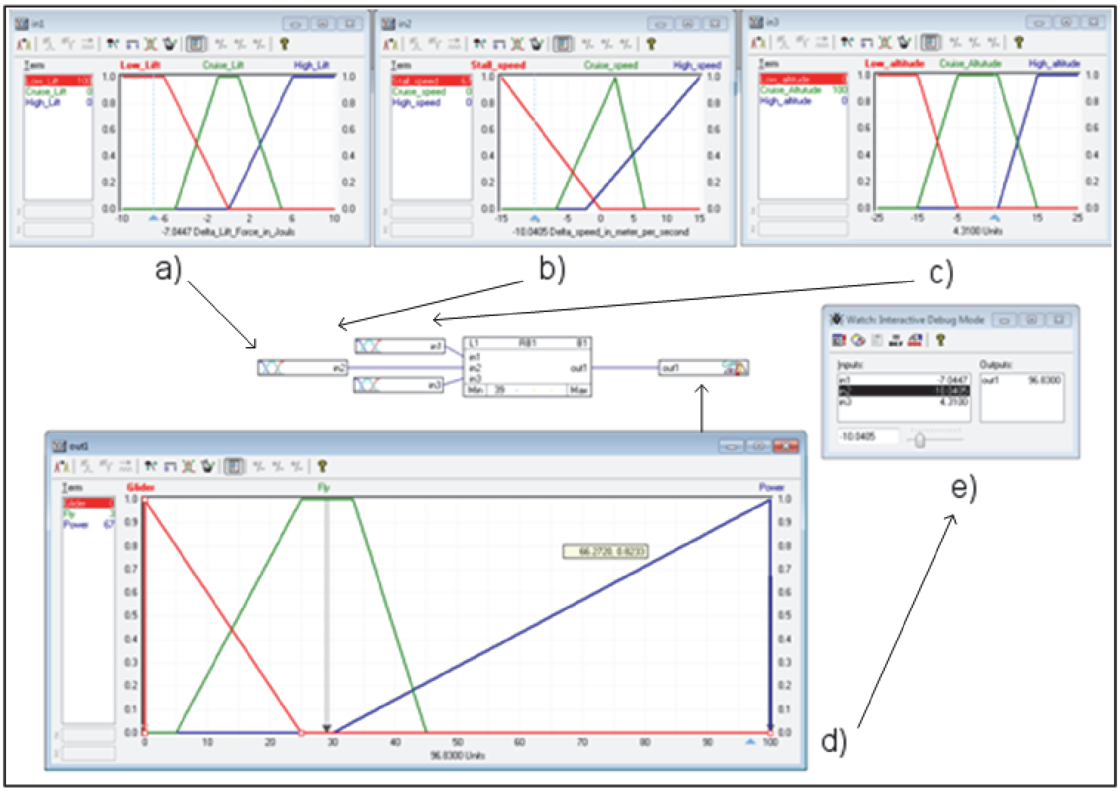
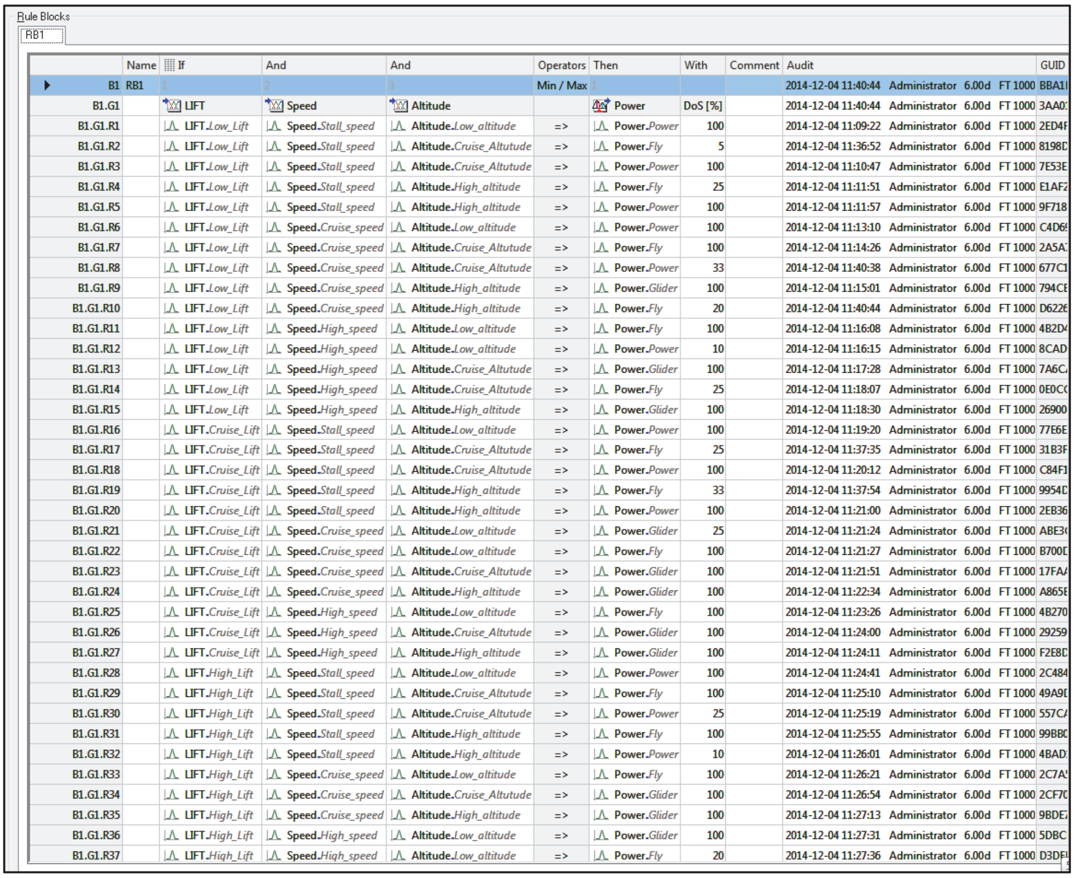


Fig.12. *fuzzy*Tech input membership functions (a,b,c), output block (d) and simulation output result (e).



Rule Blocks

RB1

	Name	If	And	And	Operators	Then	With	Comment	Audit	GUID
B1	RB1	1	2	3	Min / Max	1			2014-12-04 11:40:44 Administrator 6.00d FT 1000	BBA1
B1.G1		LIFT	Speed	Altitude		Power	DoS [%]		2014-12-04 11:40:44 Administrator 6.00d FT 1000	3AA0
B1.G1.R1		LIFT.*Low_Lift*	Speed.*Stall_speed*	Altitude.*Low_altitude*	=>	Power.*Power*	100		2014-12-04 11:09:22 Administrator 6.00d FT 1000	2ED4F
B1.G1.R2		LIFT.*Low_Lift*	Speed.*Stall_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Fly*	5		2014-12-04 11:36:52 Administrator 6.00d FT 1000	8198D
B1.G1.R3		LIFT.*Low_Lift*	Speed.*Stall_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Power*	100		2014-12-04 11:10:47 Administrator 6.00d FT 1000	7E53E
B1.G1.R4		LIFT.*Low_Lift*	Speed.*Stall_speed*	Altitude.*High_altitude*	=>	Power.*Fly*	25		2014-12-04 11:11:51 Administrator 6.00d FT 1000	E1AF2
B1.G1.R5		LIFT.*Low_Lift*	Speed.*Stall_speed*	Altitude.*High_altitude*	=>	Power.*Power*	100		2014-12-04 11:11:57 Administrator 6.00d FT 1000	9F718
B1.G1.R6		LIFT.*Low_Lift*	Speed.*Cruise_speed*	Altitude.*Low_altitude*	=>	Power.*Power*	100		2014-12-04 11:13:10 Administrator 6.00d FT 1000	C4D6
B1.G1.R7		LIFT.*Low_Lift*	Speed.*Cruise_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Fly*	100		2014-12-04 11:14:26 Administrator 6.00d FT 1000	2A5A
B1.G1.R8		LIFT.*Low_Lift*	Speed.*Cruise_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Power*	33		2014-12-04 11:40:38 Administrator 6.00d FT 1000	677C1
B1.G1.R9		LIFT.*Low_Lift*	Speed.*Cruise_speed*	Altitude.*High_altitude*	=>	Power.*Glider*	100		2014-12-04 11:15:01 Administrator 6.00d FT 1000	794CE
B1.G1.R10		LIFT.*Low_Lift*	Speed.*Cruise_speed*	Altitude.*High_altitude*	=>	Power.*Fly*	20		2014-12-04 11:40:44 Administrator 6.00d FT 1000	D6226
B1.G1.R11		LIFT.*Low_Lift*	Speed.*High_speed*	Altitude.*Low_altitude*	=>	Power.*Fly*	100		2014-12-04 11:16:08 Administrator 6.00d FT 1000	4B2D4
B1.G1.R12		LIFT.*Low_Lift*	Speed.*High_speed*	Altitude.*Low_altitude*	=>	Power.*Power*	10		2014-12-04 11:16:15 Administrator 6.00d FT 1000	8CAD
B1.G1.R13		LIFT.*Low_Lift*	Speed.*High_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Glider*	100		2014-12-04 11:17:28 Administrator 6.00d FT 1000	7A6C
B1.G1.R14		LIFT.*Low_Lift*	Speed.*High_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Fly*	25		2014-12-04 11:18:07 Administrator 6.00d FT 1000	0E0C
B1.G1.R15		LIFT.*Low_Lift*	Speed.*High_speed*	Altitude.*High_altitude*	=>	Power.*Glider*	100		2014-12-04 11:18:30 Administrator 6.00d FT 1000	26900
B1.G1.R16		LIFT.*Cruise_Lift*	Speed.*Stall_speed*	Altitude.*Low_altitude*	=>	Power.*Power*	100		2014-12-04 11:19:20 Administrator 6.00d FT 1000	77E6E
B1.G1.R17		LIFT.*Cruise_Lift*	Speed.*Stall_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Fly*	25		2014-12-04 11:37:35 Administrator 6.00d FT 1000	31B3F
B1.G1.R18		LIFT.*Cruise_Lift*	Speed.*Stall_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Power*	100		2014-12-04 11:20:12 Administrator 6.00d FT 1000	C84F1
B1.G1.R19		LIFT.*Cruise_Lift*	Speed.*Stall_speed*	Altitude.*High_altitude*	=>	Power.*Fly*	33		2014-12-04 11:37:54 Administrator 6.00d FT 1000	9954D
B1.G1.R20		LIFT.*Cruise_Lift*	Speed.*Stall_speed*	Altitude.*High_altitude*	=>	Power.*Power*	100		2014-12-04 11:21:00 Administrator 6.00d FT 1000	2EB36
B1.G1.R21		LIFT.*Cruise_Lift*	Speed.*Cruise_speed*	Altitude.*Low_altitude*	=>	Power.*Glider*	25		2014-12-04 11:21:24 Administrator 6.00d FT 1000	ABE3
B1.G1.R22		LIFT.*Cruise_Lift*	Speed.*Cruise_speed*	Altitude.*Low_altitude*	=>	Power.*Fly*	100		2014-12-04 11:21:27 Administrator 6.00d FT 1000	B700D
B1.G1.R23		LIFT.*Cruise_Lift*	Speed.*Cruise_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Glider*	100		2014-12-04 11:21:51 Administrator 6.00d FT 1000	17FA
B1.G1.R24		LIFT.*Cruise_Lift*	Speed.*Cruise_speed*	Altitude.*High_altitude*	=>	Power.*Glider*	100		2014-12-04 11:22:34 Administrator 6.00d FT 1000	A865E
B1.G1.R25		LIFT.*Cruise_Lift*	Speed.*High_speed*	Altitude.*Low_altitude*	=>	Power.*Fly*	100		2014-12-04 11:23:26 Administrator 6.00d FT 1000	4B270
B1.G1.R26		LIFT.*Cruise_Lift*	Speed.*High_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Glider*	100		2014-12-04 11:24:00 Administrator 6.00d FT 1000	29259
B1.G1.R27		LIFT.*Cruise_Lift*	Speed.*High_speed*	Altitude.*High_altitude*	=>	Power.*Glider*	100		2014-12-04 11:24:11 Administrator 6.00d FT 1000	F2E8D
B1.G1.R28		LIFT.*High_Lift*	Speed.*Stall_speed*	Altitude.*Low_altitude*	=>	Power.*Power*	100		2014-12-04 11:24:41 Administrator 6.00d FT 1000	2C484
B1.G1.R29		LIFT.*High_Lift*	Speed.*Stall_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Fly*	100		2014-12-04 11:25:10 Administrator 6.00d FT 1000	49A9D
B1.G1.R30		LIFT.*High_Lift*	Speed.*Stall_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Power*	25		2014-12-04 11:25:19 Administrator 6.00d FT 1000	557C
B1.G1.R31		LIFT.*High_Lift*	Speed.*Stall_speed*	Altitude.*High_altitude*	=>	Power.*Fly*	100		2014-12-04 11:25:55 Administrator 6.00d FT 1000	99BB
B1.G1.R32		LIFT.*High_Lift*	Speed.*Stall_speed*	Altitude.*High_altitude*	=>	Power.*Power*	10		2014-12-04 11:26:01 Administrator 6.00d FT 1000	4BAD
B1.G1.R33		LIFT.*High_Lift*	Speed.*Cruise_speed*	Altitude.*Low_altitude*	=>	Power.*Fly*	100		2014-12-04 11:26:21 Administrator 6.00d FT 1000	2C7A
B1.G1.R34		LIFT.*High_Lift*	Speed.*Cruise_speed*	Altitude.*Cruise_Altutude*	=>	Power.*Glider*	100		2014-12-04 11:26:54 Administrator 6.00d FT 1000	2CF70
B1.G1.R35		LIFT.*High_Lift*	Speed.*Cruise_speed*	Altitude.*High_altitude*	=>	Power.*Glider*	100		2014-12-04 11:27:13 Administrator 6.00d FT 1000	9BDE
B1.G1.R36		LIFT.*High_Lift*	Speed.*High_speed*	Altitude.*Low_altitude*	=>	Power.*Glider*	100		2014-12-04 11:27:31 Administrator 6.00d FT 1000	5DBC
B1.G1.R37		LIFT.*High_Lift*	Speed.*High_speed*	Altitude.*Low_altitude*	=>	Power.*Fly*	20		2014-12-04 11:27:36 Administrator 6.00d FT 1000	D3DF

Fig.13. FuzzyTech rule editor.

6. Autonomous Vehicle Motor Control

6.1 Hardware configurations

This section of the paper is dedicated to the Autonomous Vehicle Motor Controller developed for AMBOA Ver.2. The idea was to design a general purpose and very robust control system that could be used in many applications by the changing of some parameters within the algorithm.

In order that the system remains robust the control algorithm should not overload the MCU, in fact it should be remembered that although utilizing more powerful processing, we are usually working with assembly language and designers usually write algorithms in embedded C. What this means is that the compiler will translate from one programming language to the other, often with some command or information generating a conflict or more often than not the translation uses much more commands to solve those unstable states.

In the case of large and complex algorithms, microprocessors could very easily overload and thereafter operate at a less efficient rate with a higher probability to jump in an unstable state. In order to use lighter control algorithms to achieve a more robust control system, we use a Decentralized Control System, a powerful microprocessor unit that controls the process and that communicate, through some specific protocols, with smaller microcontrollers (usually DSP) specifically designed to control peripherals.

The system designed initially for AMBOA Ver.2 used as its “brain”, a PIC32 microchip and as a peripheral control a DsPic33. The idea is that once the “brain” processes the information it will communicate through I2C protocol, providing the information that will activate the dedicated function of the DsPIC33.

6.2 DC Motor Hardware Control

What was required was that no matter what motor topology was chosen it would be necessary to change only a few parameters on the algorithm of the PIC32 or of the DsPIC33. In fact is possible to control a 3ph brushless motor or 3ph DC brushless motor through an A3930 or A3931, “Automotive 3-Phase BLDC Controller and MOSFET Driver” or the DC motor Drive through the same DsPic33 (Figs.14, 15, 16, 17) outputs, such as:
The Motor Direction by a digital pin (A3930 or A3931 pin 9; M1 DIR, M2 DIR).

Motor Enable by digital outputs (A3930 Pin 2 for sleep mode and 39 for Enable stop on fault input; E1 and E2 for the DC controller) and power of the engine through a PWM signal (A3930 or A3931 pin 14 ; M1 PWM, M2 PWM).

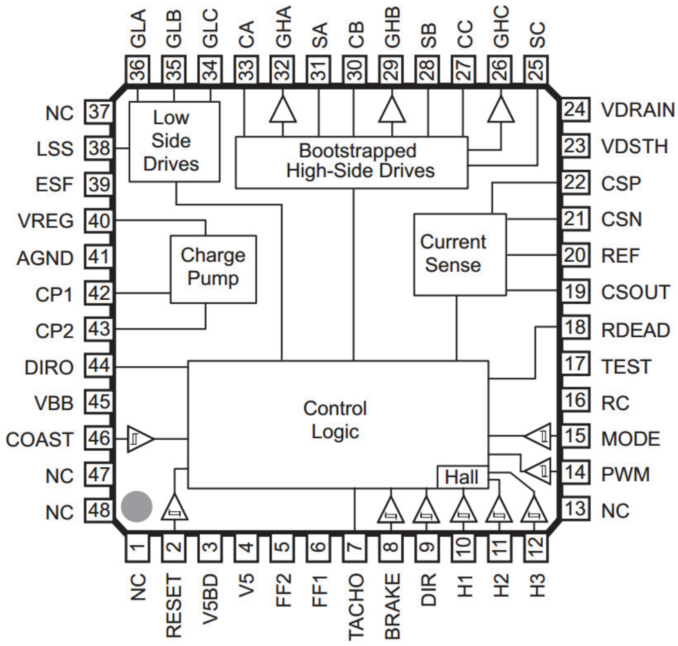


Fig.14. A3930 Pin Out.

The motor controller using the L293 chip and driver design in Fig.15, was selected for the AMBOA drive system due to its higher current rating, small form factor and ease of use and a quite cost effective solution.

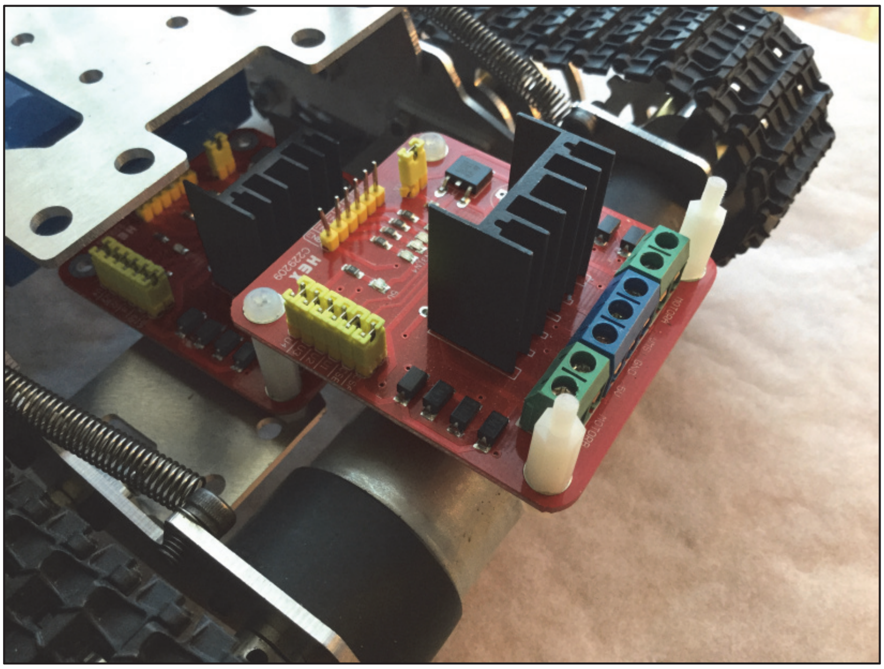


Fig.15. AMBOA Dual L293 Drivers

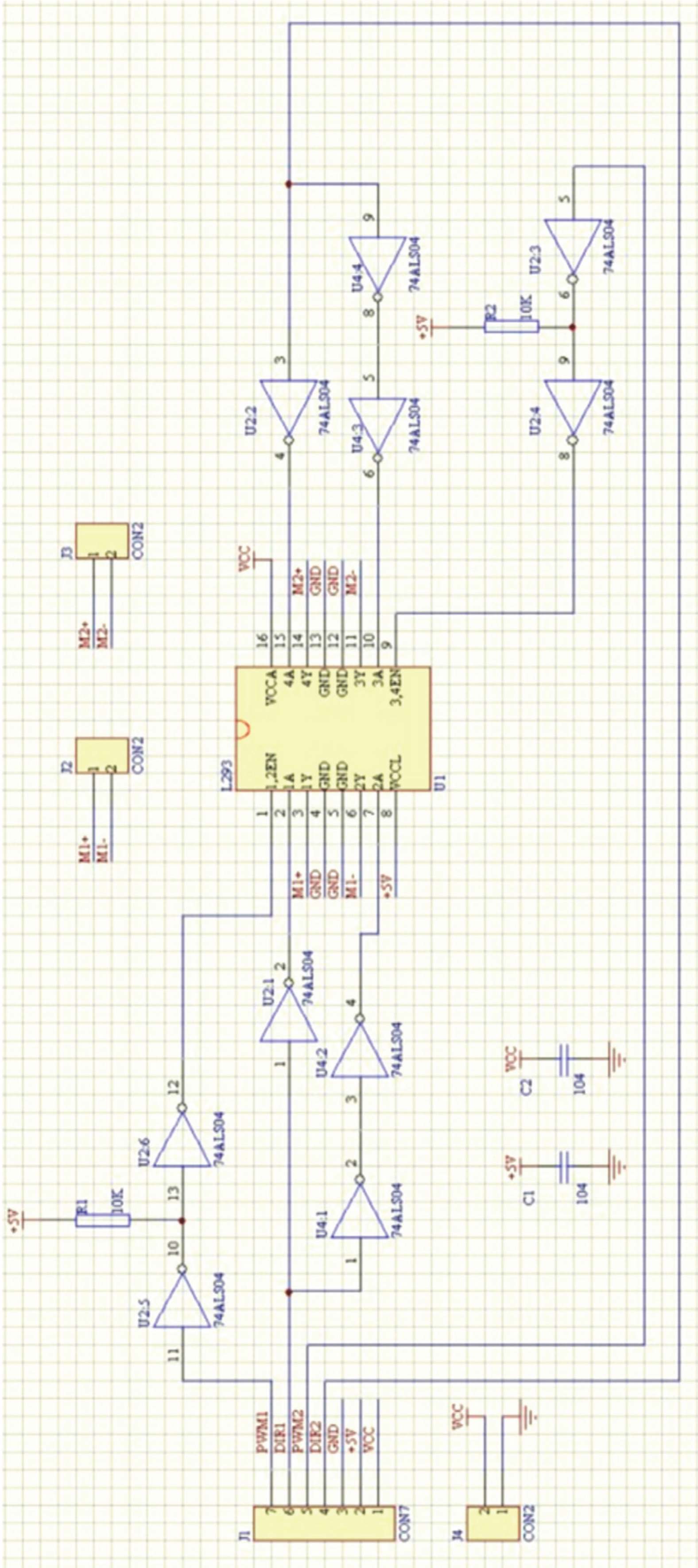


Fig.16 Common scheme of dual motor control based on L292 and L293 motor Driver [21]

To enable proper operation of the system the PIC32 at the end of is algorithm cycle should transfer to the “DsPic33”, 4 registers for each motor that should be controlled, 2 registers are 16bits integer that represent the motor power, 1 register is the enable register and 1 register is the direction register. From this information the DsPIC33 will generate a control PWM signal and all the digital pins described before, in order to drive the motor driver unit that will supply the motors.

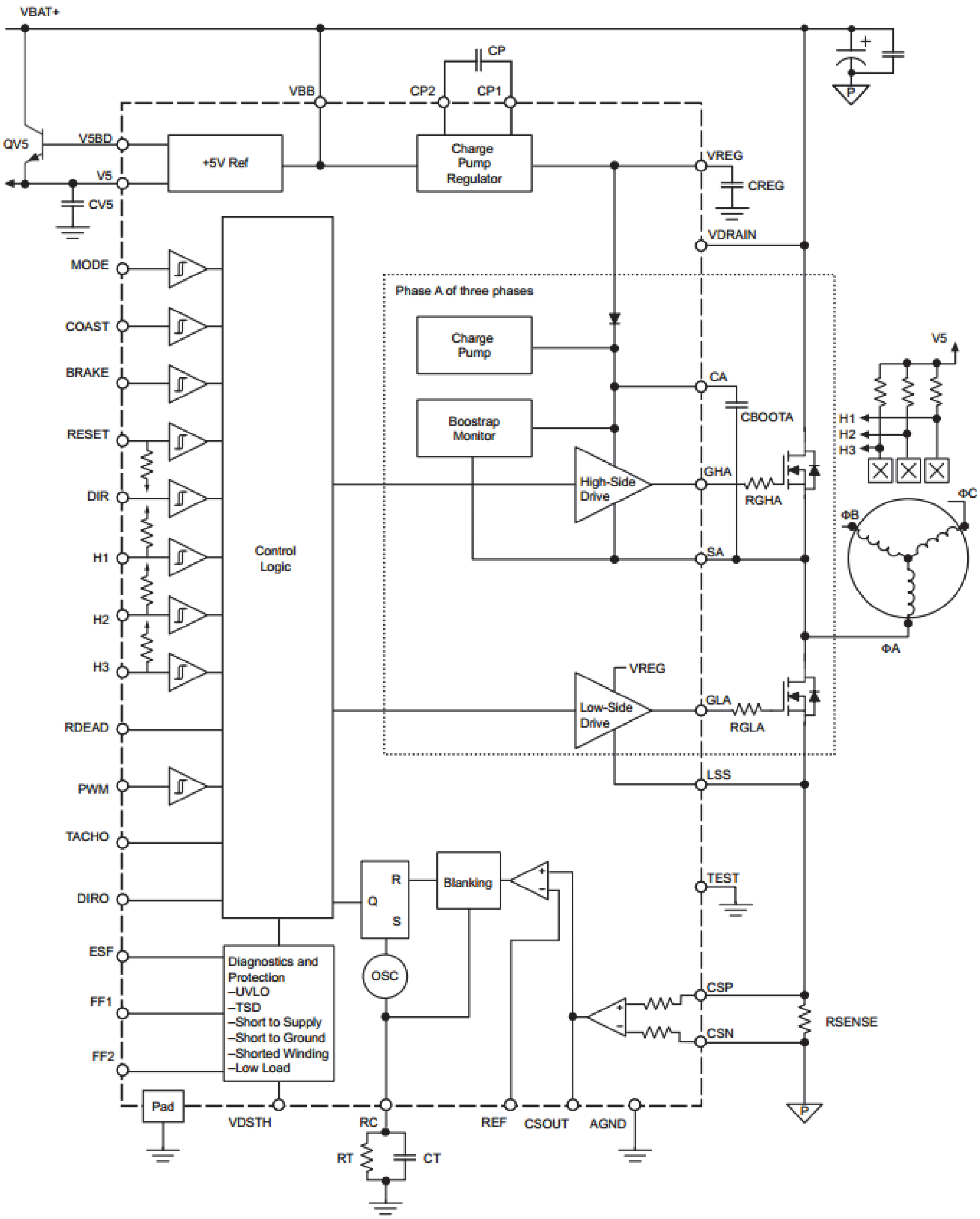


Fig.17 Motor Driver connections with the power electronics unit and the 3ph Brushless motor

It is possible to use also one other configuration for higher power on which the system controls the motor power through a DC/DC converter that supplies the motor driver (DC/AC converter) using a PWM signal. The motor driver (A3930 or A3931) could use its self PWM frequency (as is described in A3930 or A3931 datasheet or any other motor driver with internal fixed PWM generator). This configuration uses almost the same control, but could be more efficient and increase the maximum power controlled. Obviously this system is more expensive.

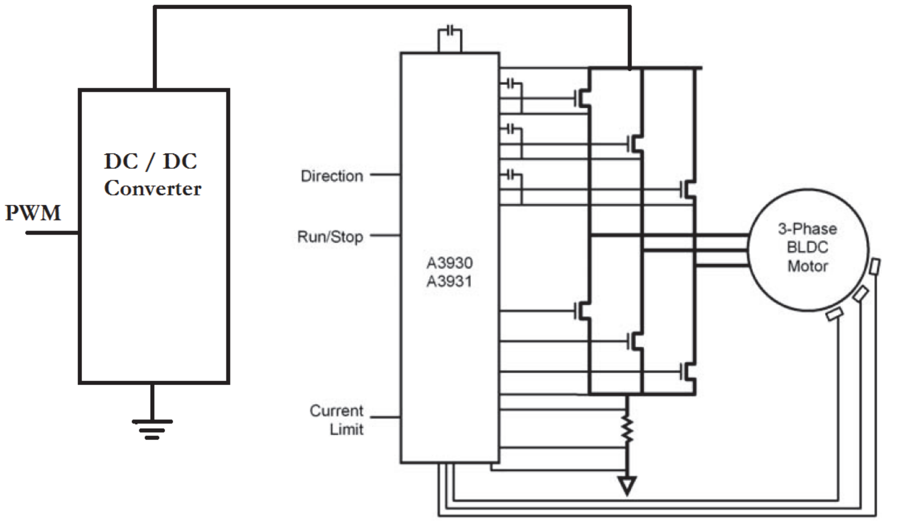


Fig.18. Motor Driver with DC/DC converter unit.

6.3 *Servo Hardware control*

Controlling a servo in this DCS is similar to what was previously described. In fact, a common servo engine has a dedicated input for the control and is achieved by a PWM signal. Also in this case of the PIC32 at the end of his cycle will transfer 4 registers to the DsPIC33; those 4 registers contain only 32 bits float information that represents the servo angle. The DsPIC33 will use this information to generate the appropriate PWM that will trigger the servo to such angle position. Each servo motor, although they have similar function, require an appropriate function that will convert the angle with the PWM signal, for example the servo shown in Fig. 18, could expect an algorithm accuracy of: ± 0.1265 deg.

- HS-322HD

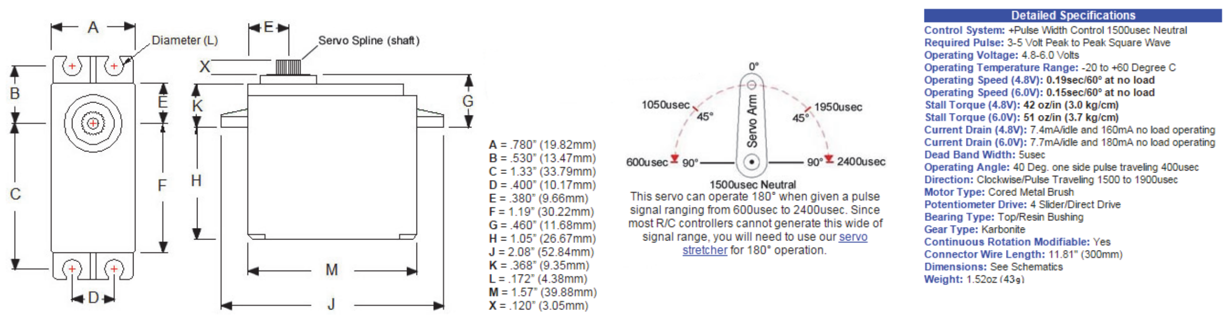


Fig.19. HS-322HD overview

6.4 Application for Simple Motor Control

The system goal is to prevent any robot impact with any obstacle and to achieve an appropriate level of safety which is essential for the system. Appropriate observations were needed before designing a function that will properly manage the Infrared Diffuse Reflectance Infrared Sensor Module Fig.20. A common and reliable configuration for a robot uses two proximity sensors installed one on the left side and one on the right side of the robot in such way it possible to detect any obstacle that can obstruct the robot's path. In developing the system, the fuzzy logic solution that is shown Fig 21, was used.

At this intersection it must be pointed out that the completed AMBOA Ver.3, does NOT utilize any sensor that is not specifically of a read only nature. Only passive sensors are installed. However, the test bed AMBOA is fitted with IR Proximity sensors and Analogue Whiskers (push button) and an onboard Camera. These are fitted to aid the operator during the "Guided Learning Process" and to investigate the robots abilities to avoid obstacles after the learning process. In effect they constitute a safeguard for the robot and a method to determine the accuracy of the robots movements. To better understand this method Fig.20, and refer to Appendix B.

Each Proximity sensor unit is the input of a Fuzzy Membership Function, Fig. 21, and the combination of the fuzzy membership functions, (hedges) is described in the fuzzyTech Rule Block in Fig.22. Activation of this specific fuzzy membership function results in the system simulation as seen in the fuzzyTech 3D simulation in Fig.23.

Although the AMBOA robots are primarily passive sensor based the following IR detector was used as a base platform for the testing of an algorithm using the FuzzyTech system. Some parameters of the device are included for reference only.

"Infrared Diffuse Reflectance Infrared Sensor Module" uses a "74HC00 Quad 2-input NAND gate". The main characteristics of the device are:

- Operating voltage: DC 3.3V-5V (ideal voltage 5V); (*high sensitivity at this voltage*)
- Working current: ≥ 10mA; (*Test bench indicated >15mA*)
- Operating Temperature: -10 ℃ - +50 ℃;
- Detection distance: from 2cm to 40cm; (*ultra fine tuning is required to adjust parameters*)
- Output interface: 4 wire interface ;

- Output signal: TTL level (*can be directly connected to the microcontroller I/0, an obstacle causes a LOW level and no obstruction causes a HIGH level output*).

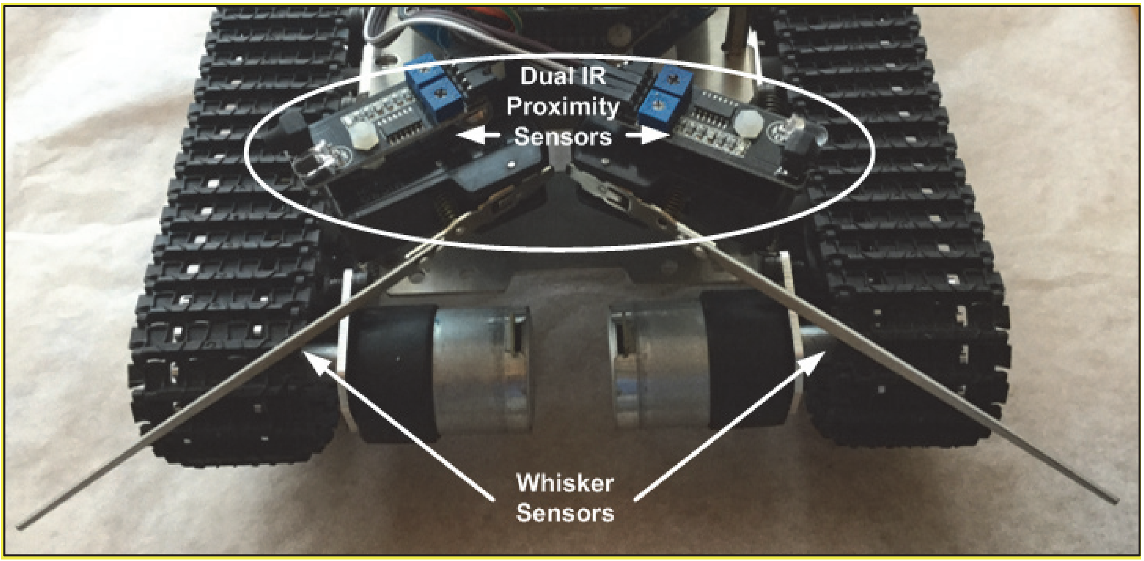


Fig.20. Diffuse reflectance sensors and whisker sensors fitted to AMBOA during Guided Learning process.

It was found that the sensors used are very sensitive to those obstacles displaying a less than obtuse angle, changing their output as a function of the obstacle and distance. Thus is easy to receive a false signal that could be not 0 or 1 but could be both within a very short period. To increase the average speed of the robot the system was designed so that in some instances the robot would alter course without stopping and at others can stop the robot prior to turning.

The simulations made using the fuzzyTech system indicated that the robot was able to alter direction (go round) an object without stopping if there was a high probability of some obstacle is in the way. When the system generates a duty cycle lower than 20% for both engines it indicates that the probability that an obstacle is in the robot`s path is high, thus a stop command is generated for both engines which can thereafter initialize a reverse, turn or spin reaction. Obviously the logical step would be that once the robot has stopped it will be diverted in the direction of the motor that has the highest duty cycle, after that the motors will be enabled again and the system will work as usual until at least one engine will receive a duty cycle higher than 20% from the algorithm. After this fuzzyTech simulation, it was expected that an adequate performance would be had once the robot was fully programmed.

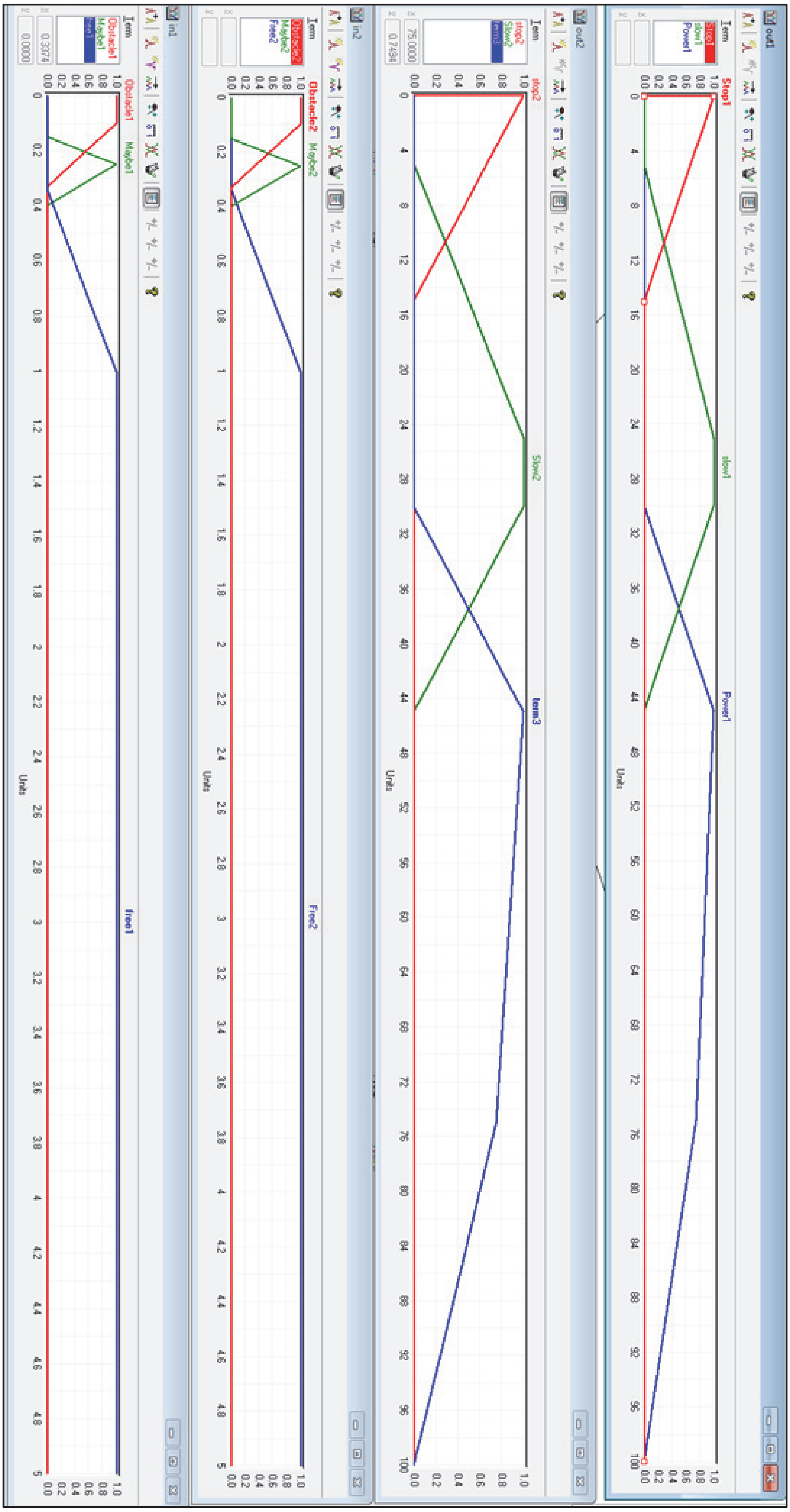
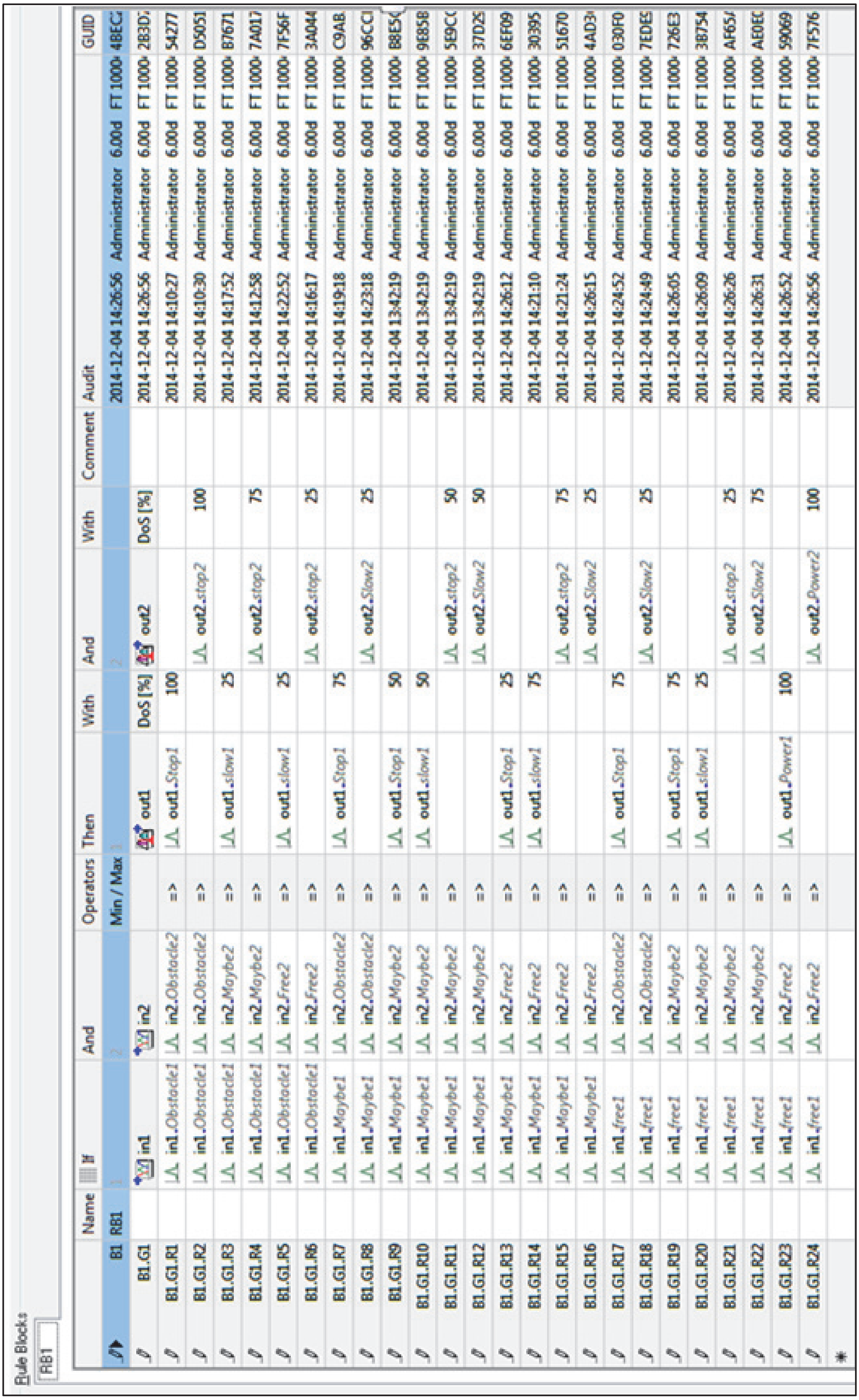


Fig.21. Fuzzy Membership Functions for Swarm Robot motor control.


Rule Blocks

RB1

	Name	If	And	Operators	Then	With	And	With	Comment	Audit	GUID
B1	RB1	1	2	Min / Max	1		2			2014-12-04 14:26:56 Administrator 6.00d FT 1000·	4BEC:
B1.G1		in1	in2		out1	DoS [%]	out2	DoS [%]		2014-12-04 14:26:56 Administrator 6.00d FT 1000·	2B3D7
B1.G1.R1		in1.Obstacle1	in2.Obstacle2	=>	out1.Stop1	100				2014-12-04 14:10:27 Administrator 6.00d FT 1000·	54277
B1.G1.R2		in1.Obstacle1	in2.Obstacle2	=>			out2.stop2	100		2014-12-04 14:10:30 Administrator 6.00d FT 1000·	D5051
B1.G1.R3		in1.Obstacle1	in2.Maybe2	=>	out1.slow1	25				2014-12-04 14:17:52 Administrator 6.00d FT 1000·	B7671
B1.G1.R4		in1.Obstacle1	in2.Maybe2	=>			out2.stop2	75		2014-12-04 14:12:58 Administrator 6.00d FT 1000·	7A017
B1.G1.R5		in1.Obstacle1	in2.Free2	=>	out1.slow1	25				2014-12-04 14:22:52 Administrator 6.00d FT 1000·	7F56F
B1.G1.R6		in1.Obstacle1	in2.Free2	=>			out2.stop2	25		2014-12-04 14:16:17 Administrator 6.00d FT 1000·	3A044
B1.G1.R7		in1.Maybe1	in2.Obstacle2	=>	out1.Stop1	75				2014-12-04 14:19:18 Administrator 6.00d FT 1000·	C9AB
B1.G1.R8		in1.Maybe1	in2.Obstacle2	=>			out2.Slow2	25		2014-12-04 14:23:18 Administrator 6.00d FT 1000·	96CCI
B1.G1.R9		in1.Maybe1	in2.Maybe2	=>	out1.Stop1	50				2014-12-04 13:42:19 Administrator 6.00d FT 1000·	B8E5(
B1.G1.R10		in1.Maybe1	in2.Maybe2	=>	out1.slow1	50				2014-12-04 13:42:19 Administrator 6.00d FT 1000·	9E85B
B1.G1.R11		in1.Maybe1	in2.Maybe2	=>			out2.stop2	50		2014-12-04 13:42:19 Administrator 6.00d FT 1000·	5E9CC
B1.G1.R12		in1.Maybe1	in2.Maybe2	=>			out2.Slow2	50		2014-12-04 13:42:19 Administrator 6.00d FT 1000·	37D2S
B1.G1.R13		in1.Maybe1	in2.Free2	=>	out1.Stop1	25				2014-12-04 14:26:12 Administrator 6.00d FT 1000·	6EF09
B1.G1.R14		in1.Maybe1	in2.Free2	=>	out1.slow1	75				2014-12-04 14:21:10 Administrator 6.00d FT 1000·	30395
B1.G1.R15		in1.Maybe1	in2.Free2	=>			out2.stop2	75		2014-12-04 14:21:24 Administrator 6.00d FT 1000·	51670
B1.G1.R16		in1.Maybe1	in2.Free2	=>			out2.Slow2	25		2014-12-04 14:26:15 Administrator 6.00d FT 1000·	4AD3
B1.G1.R17		in1.free1	in2.Obstacle2	=>	out1.Stop1	75				2014-12-04 14:24:52 Administrator 6.00d FT 1000·	030F0
B1.G1.R18		in1.free1	in2.Obstacle2	=>			out2.Slow2	25		2014-12-04 14:24:49 Administrator 6.00d FT 1000·	7EDES
B1.G1.R19		in1.free1	in2.Maybe2	=>	out1.Stop1	75				2014-12-04 14:26:05 Administrator 6.00d FT 1000·	726E3
B1.G1.R20		in1.free1	in2.Maybe2	=>	out1.slow1	25				2014-12-04 14:26:09 Administrator 6.00d FT 1000·	3B754
B1.G1.R21		in1.free1	in2.Maybe2	=>			out2.stop2	25		2014-12-04 14:26:26 Administrator 6.00d FT 1000·	AF65/
B1.G1.R22		in1.free1	in2.Maybe2	=>			out2.Slow2	75		2014-12-04 14:26:31 Administrator 6.00d FT 1000·	AE0EC
B1.G1.R23		in1.free1	in2.Free2	=>	out1.Power1	100				2014-12-04 14:26:52 Administrator 6.00d FT 1000·	59069
B1.G1.R24		in1.free1	in2.Free2	=>			out2.Power2	100		2014-12-04 14:26:56 Administrator 6.00d FT 1000·	7F576

Fig.22 FuzzyTech Rule Block for Swarm Robot Motor control.

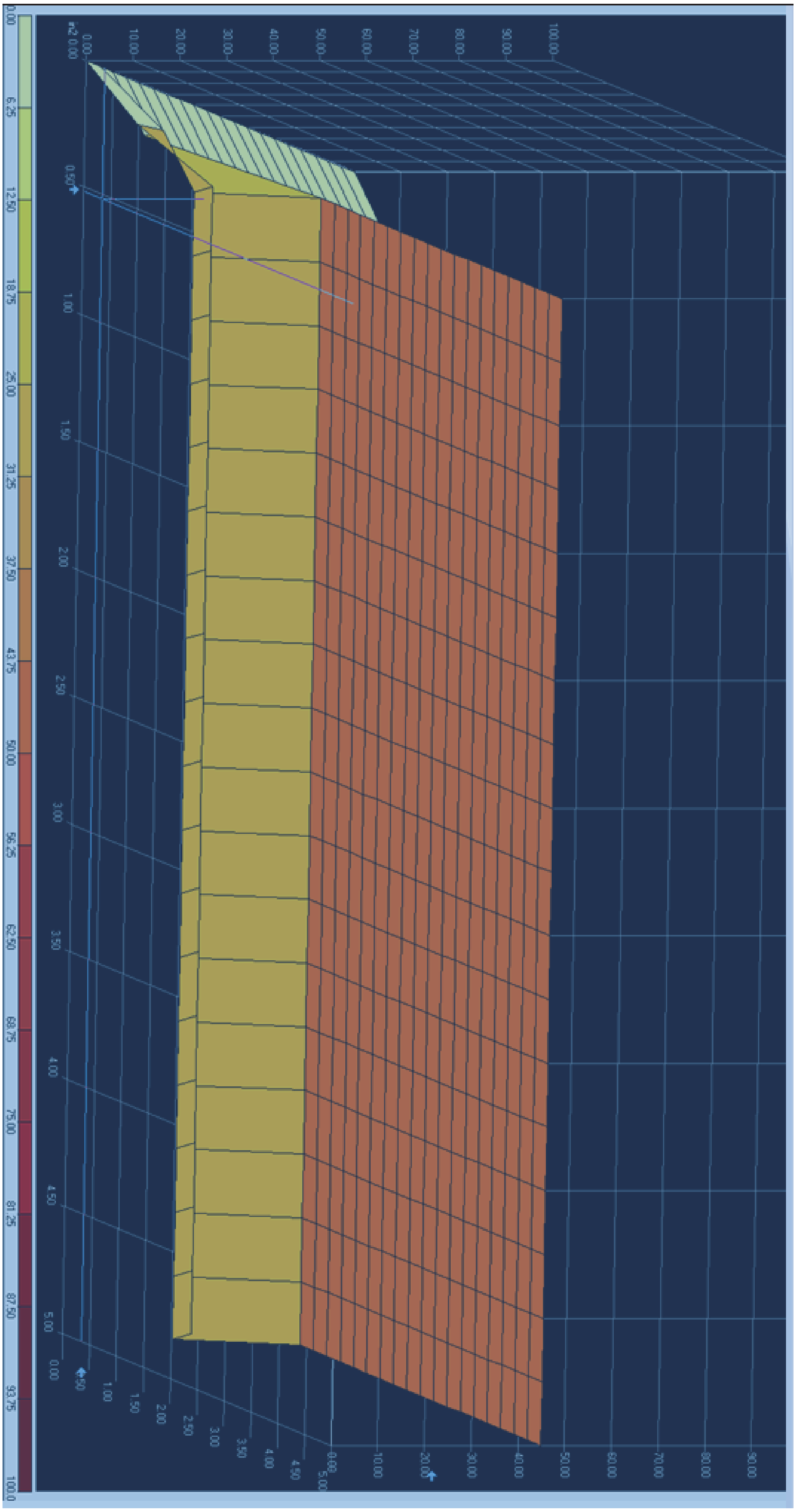


Fig.23. Fuzzytech 3D simulation

6.5 *Fuzzy Logic applications for power-trains*

In testing the applications for *fuzzy*Tech software package and to ensure suitability of such, various scenarios were applied. These systems were necessarily related to the doctoral work due to the resolve to incorporate fuzzy algorithms into the system. An energy mode saving fuzzy algorithm has been produced in order to fulfill certain requirements of any mobile robotics system, be that ground vehicle, submersible or flying vehicle as the Author has interests in both aqua and air robotics, so for example the control of the power used in the instance of a AUAV utilizing a gliding technique in order to sustain energy reserves.

Obviously the main task of the system is to follow a precise route, defined by the user. The system will use some differential parameters to understand how the system should behave, which is the input of a specific fuzzy membership function. For example in an AUAV:

For the purposes of evaluating the movement of our robot, the visualizing of UAV control has proven more than fruitful. At first glance it seems to require more parameters for control but becomes a more reliable method due to the fact that mobile robotics, whether on the ground, under water or in the air are subjected to the same variances in the directional vectors. It has been realized during the course of the thesis that we must not always assume that a robot is operating on a flat surface, therefore to program using only two dimensional methods is of itself a miscalculation.

For the lift force "L" we use the parameter:

$$\delta L = \frac{(L_{Read} - L_{Wanted})}{L_{Read}} * 100 \; ; \qquad (3)$$

For the speed "Δs" we use the parameter:

$$\Delta_S = S_{read} - S_{wanted} \qquad (4)$$

For the altitude "A" we use the parameter:

$$\delta A = \frac{(A_{read} - A_{wanted})}{A_{read}} * 100 \; ; \qquad (5)$$

It is possible to design some general membership function for δL, Δs and δA, as shown in 3a, 3b and 3c, and only change the trajectory parameter. When changing the trajectory and some variables that could personalize the membership functions for each specific UAV in this instance and where, each vehicle has a specific low speed, high range cruise speed, fast cruise speed and of course maximum allowable speed.

To control an airborne robot there are three commands required which are, aileron control, elevator control and rudder control, all of which may be converted to their ground mobile robot counterparts and further to their submersible robot counterparts. Usually, these commands are for small and mid-size robots and are mechanically generated by small servo motors. The selected controller, the PIC32 controls the processes and generates the angle for ailerons, elevator and rudder with that information thereafter transferred to the peripheral unit that will use the information to generate appropriate PWM signals in order to achieve the wanted angles or motor power.

To control such complex process as in the UAV, a very complex model is needed that can approximate the process in a feedback controlled system. The best way according to the author's research, is to utilize the fuzzy logic system for the power-train control in order to achieve the best efficiency and to save energy in order to increase the operating range and time of the system. With fuzzy logic to manipulate the system inputs offers more accurate parameters that take care of *noise* [11] or measurement failure.

The aim of this particular phase of work was to become accustomed to working with a high end software product which allows the creation of both, low, intermediate and high level algorithms and to enable the control of many kind of motors, vehicles etcetera without need to dramatically rewrite control systems. Changing very few parameter and activating (or deactivating) some part of the algorithm is possible to properly control one specific motor without problems. As it is possible to observe in the algorithm in ***Appendix M***, a proposal was attained that could reach that requirement. This method through reasoning can apply to all discussed methods above and inclusive of the OA System, the subject of the thesis.

Very interesting and productive were the simulations done for our Swarm Robots fuzzy dynamic motor control that manages to perform higher average turn speed of robots without need for the robot to stop.

Simulations show that this approach could work, but it is not possible to preview how well it could work until AMBOA Ver.3 is completed. Also very productive is the motor control for an AUAV the aim of this approach being in the realm of energy saving for increasing the AUAV range using the external forces to save or accumulate energy.

Energy requirements of the system may be greatly improved with a positive power balance, however this s a matter for further research. Simulation showed that the idea behind the system is positive.

7. Guided Learning Utilizing Delta Rule Method

The developed robot for evaluation purposes and the subject of the thesis is the Ambient Obstacle Avoidance (AMBOA) robot which is equipped with a purely passive sensing system [45], in other words it relies only on received spectral wavelength and does not emit radiation such as is the case with infrared or sonic devices. The sensor array registers only wavelengths from the spectral field from the ultraviolet to the near infrared in a combination digital and analogue array. The predominant manner of programming the robot has hitherto been the use of fuzzy logic algorithms which has proven quite satisfactory however given the research accomplished during the course of the thesis a theoretical and logical look at another method of obstacle avoidance has been included as a final solution to the system. The programming of the fuzzy algorithm for the task is quite comprehensive as can be seen in the line drawing network in Fig.24.

7.1 Permutations

Remembering of course, that permutations within the sensor array may become exponentially greater when account is taken to the duplication or repetition of received signals, in other words, we can raise 24 sensors to the 24th power to calculate the number of combinations obtainable with repetition (6) of any received signal, or receiving the same signal more than once, we have a very large number indeed.

$$24^{24} = 1.3337358e + 33 \qquad (6)$$

This has been the main reason that the sensor array was divided into 8 quadrants, each of three primary sensors. The three sensors operate at within wide variation of wavelength and therefore there is a greatly reduced opportunity for repetitive signal. Using this quadrant principle the total permutation for each bank of three is lessened considerably and yet to be analysed.

The enormity of the number of (if-and-and-then statements)* required although quite doable is both a challenging task and would lead to many error adjustments with the number of network connections and combinations required for a 24 sensor input and 4 drive motor output. [52][53]. As such it was decided to investigate a neural learning network design as an option. After evaluation by the author it was decided to utilize the Delta rule and an associated guided learning method as an entry level investigation.

* *The standard statement used in fuzzy logic programming.*

7.2 *Network Training Method*

Data collection is achieved as the robot is guided via remote control (RC), through an area defined as the “selected environment”, which is either the actual environment in which the robot will operate or is a near facsimile of that environment. Therefore appropriate hardware is required to provide the RC aspect of the learning process. The operator guides the robot through a series of obstacles, approaching as many as possible obstacles from all possible angles to establish a base and bias pattern for the algorithm. The onboard data collection algorithm as described in ***Appendix B***, has been designed to capture both digital and analogue readings from each of the 8 banks in the 24 sensor array, during the allocated learning period T_{learn}, during which time the received data is stored within the onboard memory chip. T_{learn} must not exceed MOB maximum as in formula (7).

$$T_{learn} < \left(\frac{(\text{MOB in Mb})\times 2e20}{\left((Sen_d\times 1)+(Sen_a\times 2)\right)\times S_{ps}\times S}\right) \quad , \qquad (7)$$

where:

T_{learn} = maximum run time,

Sen_d = digital sensors @ 1 byte per sample,

Sen_a = analog sensors @ 2 bytes per sample,

S_{ps} = samples per second,

S = number of seconds,

MOB = onboard memory in Mbytes.

In our configuration the robot will read the sensor array 10 times per second for 30 minutes of RC driving. Therefore, 24 sensors @ 1 byte per sample plus 24 sensors @ 2 bytes per sample multiplied by 10 samples per second multiplied by 60 seconds, represents data capture per minute approximating 43,2Kb per minute of RC navigation. With an onboard Memory of 2Mbit a maximum data collection time of around 45 minutes may be expected, though varying T_{learn} periods can be performed to determine results, the example illustrates the method by which the $T_{learn} < MEM_{max}$ may be obtained.

7.3 *Delta Rule and Single Layer Propagation*

The raw sensor data from the 24 sensor array is thereafter processed through the selected neural algorithm which in our test case is the Aforge.net C# framework which is purpose designed for developers and researchers in the fields of Artificial Intelligence, neural networks, genetic algorithms, machine learning and robotics among other things. The process is referred to as batch learning because after the data has been collected it is analysed using the Delta Rule method. As shown in Fig.24, a single layer propagation network is used as a feed forward perceptron, and although many combinations exist, it still retains the classification of a basic neural network consisting of a single layer of four output nodes where the inputs are fed directly to the outputs via a series of ninety-six weights. It should be noted that there is no back propagation in the network and hidden layers if any may be generated within a given algorithm. The Delta Rule as seen in Formula (8), in its simplest form as described by [53].

$$\Delta_{W_{ij_x}} = -\varepsilon \frac{\delta E}{\delta_{W_{ij}}} = \varepsilon \delta_{\alpha_{i_x}} \qquad (8)$$

In its form from formula (8), it can be seen that the change in any particular weight is equal to the products of:

- the learning rate epsilon;
- the difference between the target and actual activation of the output node δ;
- the activation of the input node associated with the weight in question;

A higher value for ε will necessarily result in a greater magnitude of change. Because each weight update can reduce error only slightly, as many iterations are required in order to satisfactorily minimize error. In batch mode the value of (9),

$$\frac{\delta E_p}{\delta_{W_{ij}}} \qquad (9)$$

calculated after each sample is submitted to the network with the total derivative (10), calculated at the end of an iteration by summing the individual pattern derivatives. Only after this value is calculated are the weights updated. As long as the learning rate epsilon is small,

$$\frac{\delta E}{\delta_{W_{ij}}} \qquad (10)$$

batch mode approximates gradient descent [54].

The network represented in Fig.24, is not a complete representation of the sensor input system of the AMBOA robot. While the sensor array has 24 passive sensors divided into three sensor types, Infrared (IR), Visible Spectrum (MID) and Ultraviolet (UV), the circuitry has been designed to provide both digital and analogue data simultaneously for each sensor, providing a duality in the neural learning process as the Delta Rule method allows also for non-binary values.

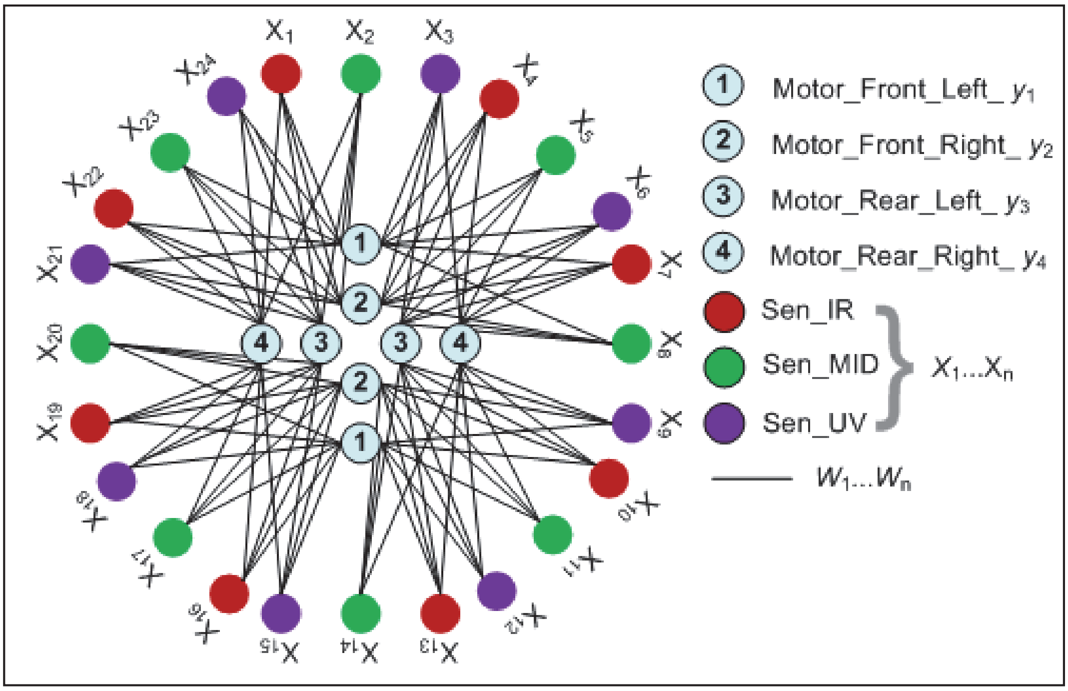


Fig.24. Network contains 96 weighted connections to 4 drive motors

As can be seen from formula (8) the Delta Rule is essentially a simple linear sum of products (which is represented by the symbol in the four output nodes in Fig. 25), and is used as the activation function at the output node of the network shown here.

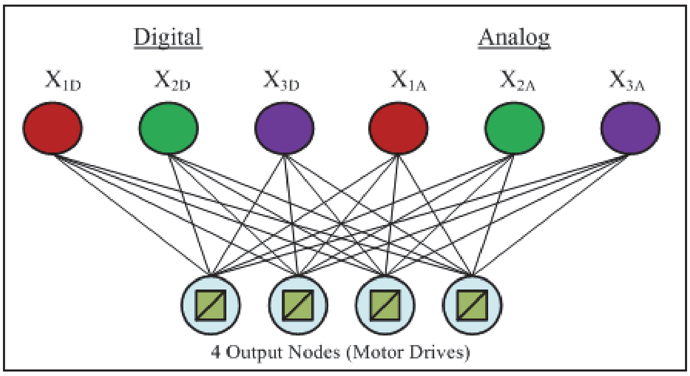


Fig.25. Three sensor input showing digital and analog inputs effectively doubling the efficiency of the network in its ability to adapt.

7.4 Error Reduction

This method to be utilized is referred to as *guided learning utilizing batch processing*, which is essentially the same as supervised learning except that in supervised learning the process results from sampling data strings one at a time and batch refers to the collection of all data and processing the samples all at once. According to examples as described by [53] which state. “With repeated presentation of the same training data to the network (with multiple iterations of training), it becomes clear that the network’s weights do indeed evolve to reduce classification error: error is eliminated altogether by the twentieth iteration. The network has learned to classify all training cases correctly, and is now ready to be used on new data whose relations between inputs and desired outputs generally match those of the training data”.

The example given within the thesis revolves around a four node and one output network, with original weights set to “0” with arbitrary weight progression set to 0.25 increments. When using the Delta Rule as in formula (8) this error free result is possible with the required condition that all solutions must be a linear function of the inputs.

7.5 Correlation Matrices

After the recorded batch data is trained within the algorithm the resultant connection strengths between the 24 input and 4 outputs are represented as a correlation matrix with associated values. Fig.26a is a sample screenshot of the Classifier Aforge.net framework. The test matrix is both complex and large and as such is not able to be included herein, however the representation of the working environment of the Delta Rule frontend gives a more rounded idea of the functions able to be generated. When allowing for a 4x24/1x4 matrix from 192 connections it was found preferable to set iterations to infinity. The results achieved from the new sensor array represent an extremely error resistant matrix.

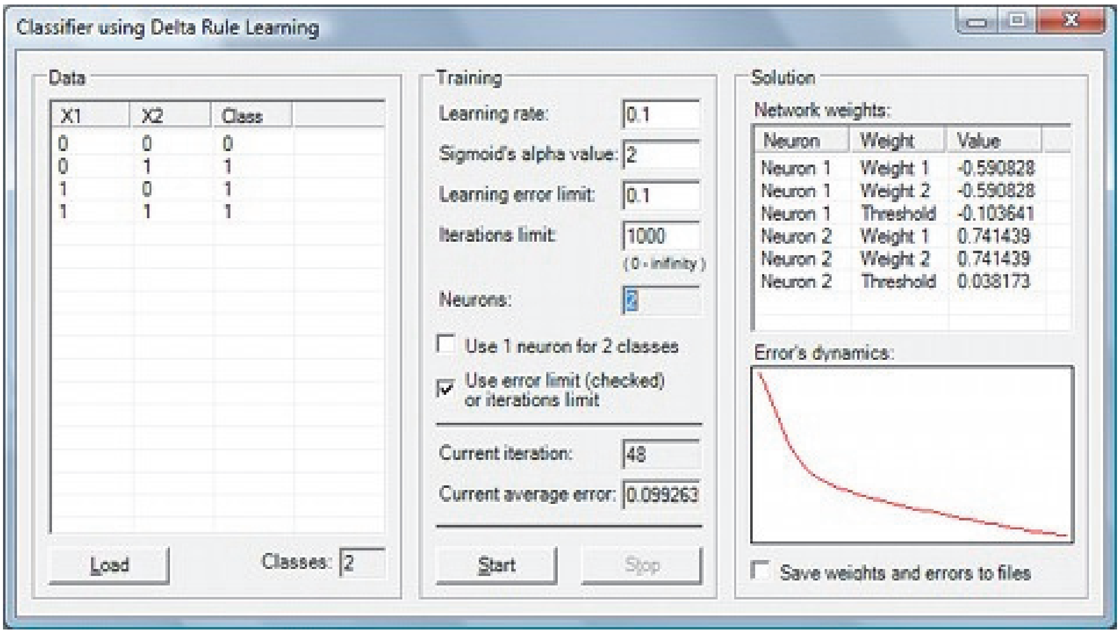


Fig.26a. Delta rule learning classifier screen.

7.6 *Visualizing Results*

During the course of the Guided Learning procedure it has become necessary to visualize what is occurring within the neural learning algorithm. After the robot has been guided via remote control, the data is fed through a fuzzy algorithm in order to reduce the high number of permutations involved and then subsequently relayed to the delta rule algorithm. After iteration, the result emerges as a matrix base and bias pattern. Utilizing the Matrix2PNG conversion program provided by [55] the operator is able to upload a tab delimited file and achieve a visual approximation of what the robot sees.

Table 1: Tab delimited file extracted from one data sample of 8 sensor array

Sensors	Infrared	Visible	Ultraviolet
Front	1.30	2.30	-0.43
Front Left	-0.90	2.10	-0.98
Front Right	1.10	2.50	-0.11
Left	-0.22	1.50	1.20
Right	-0.10	-0.80	0.76
Rear	-0.20	2.40	0.32
Left Rear	1.20	1.80	-0.76
Right Rear	-0.70	-0.90	1.10

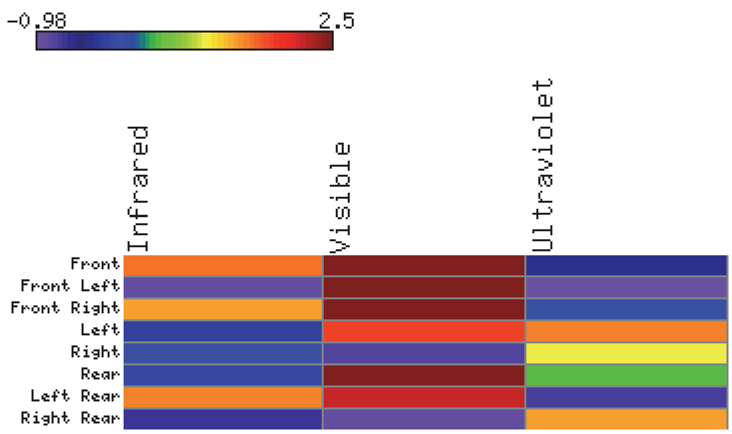


Fig.26b. Human visual representation of what the robot sees.

Therefore from a visual aspect Fig.26b, as an example, the front 8 sensor bank of the robot is seeing an object of lower infrared λ, high colour in the visible λ and virtually no ultraviolet λ. The resultant matrix from a lengthy T_{Learn} period, *Section 7.2*, produces an extremely more complicated matrix however this provides the general idea. A generated PNG image which shows a more intricate aspect of this method may be found in Fig.26c.

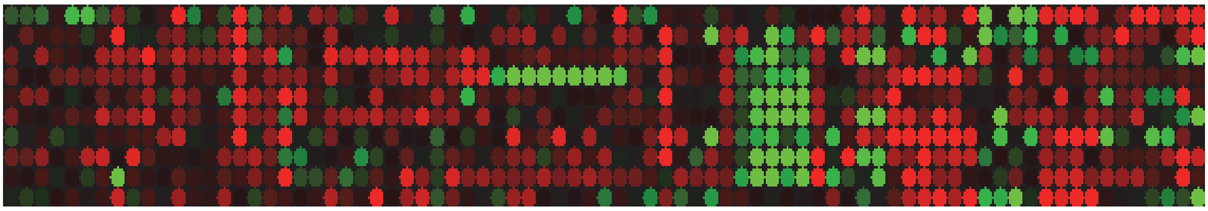


Fig.26c. Matrix2PNG conversion map as referenced in *Section 7.2*

Fig.26d. AMBOA final.

7.7 Conclusions Section 7

The utilization of the guided learning method as described within section 7 has been very successful and at the same time, daunting at the realization of the possibilities which emerging with the combination of a passive yet very sensitive sensor array, the guided learning approach and the neural processing of incoming data. The results are positive with the realization that many years of research will be required to investigate the many possibilities yet to be uncovered.

CONCLUSIONS AND FUTURE RESEARCH

It has been stated that in the creation of the AMBOA robots, the author had a specific goal in mind and that goal to a greater extent has been achieved.

Sensor systems have been selected and subjected to appropriate testing and where testing was not feasible, research was made to ensure the necessary responses where present within the sensors to be added to the array. The original system version was purely analogue and as such could be visually examined for chaotic, stable or unstable movement and avoidance of objects. The progression to version two with its wholly digital system was unable to function to expectations due to the analogue nature of the PIR sensors which remained a separate and analogue part of the system. In evaluating the possibility of an autonomous robot to move unhindered in a dynamic environment without the use of emitter or non-passive electronics, there were many errors detected which cannot yet be fully understood yet will become the subject of further research. The author believes this stems from frequency variations in the incident light, which is the primary need (input) of the robot. Evaluating the available light sources and applying an action to those signals is the main function of the device. From the research have evolved other ancillary devices which given time will be fully investigated by the author, one of which being the Passive Long Range Infrared Sensor outlined in Appendix N. The AMBOA Ver.3 is now production ready. The device is first and foremost a research and development tool which will be predominantly produced for Universities and should prove a worthwhile tool for those interested in robotics, sensory systems, programming, mechatronics and most importantly the author's further investigation in the field of Obstacle Avoidance. The bare-bones AMBOA system is capable of multiple programming language choices, able to adapt for most available sensor types (passive and non-passive), carries an impressive MCU capable of extended memory device addition and has been designed for fairly rugged terrain. Video cameras and wireless transmitter devices including intra-robot communication ability for swarm robotics adaption has been added, including the preliminary prototypes of two more AMBOA worker robots.

Analysis and Conclusions of Efficiencies

The question of efficiency in the field of autonomous robotics obstacle avoidance is both varied and subjective. Many claims are made regarding the efficiency of individual sensors in so far as relates to their ability to detect obstacles, though more often than not the claims are made based on "known global environmental information". In other words the landscape is known, obstacle dimensions are known and the spacial location of objects is known. In these instances it is not uncommon to see efficiencies ranging from low to a high of 95 percent with the effectiveness relating specifically to a particular type of sensor, for example infrared proximity sensors or ultrasonic sensors, the pros and cons of which may be reviewed within Section 2 of the thesis.

The AMBOA system on the other hand is not easily comparable to stand alone sensors, nor has it been designed to be so. The system is an array of sensors which, given their broadband characteristics are capable of an extreme range of sensory data collection combined with a very large number of available permutations. In truth, considering that readings of all sensors of the array may be duplicated, the number "permutations with repetition" may be seen to be exceeding $24^{24} \approx 1{,}3337*10^{33}$ (analogue) and this precludes the calculation for the digital side of the sensors. These factors in combination with the guided or unguided learning algorithm methods referred to in Section 7 give AMBOA the advantage of being a system where:

- efficiency becomes a function of time (T_{learn} as defined in Section 7.2)
- and T_{learn} becomes a function of available MOB (memory on board)

So, in the end result the longer the training period, the more efficient the system within the limits of the available memory.

Future Research

Future research will involve the addition of a fully analogue neural network now under design by the author. Further plans are to utilise reverse kinematic and feedback structures to allow the connection of other peripheral devices to the array which may not necessarily be sensors. Future research including but not limited to:

- Data collection for pseudo-memory applications.
- Practical applications for swarm robotics manipulation through memory harvesting.
- Long range exploration technologies for fully autonomous vehicles.
- Safety modelling for closed environment robotics.
- Investigation into appropriate control methods for data access including MOB, Cloud or other access methods for single robots, swarm robots or remote exploration robots.
- Full design of worker or swarm accessories to compliment the system.

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APPENDICES

A. ABREVIATIONS

ADC	- Analogue to Digital Converter
AL	- Artificial Life
AMBOA	- Ambient Obstacle Avoidance Robot as coined by the author.
AMC	- Autonomous Motor controller
ANN	- Analogue Neural Network
ARB	- Assessment Rule Block
AUAV	- Autonomous Unmanned Arial Vehicle
COG	- Centroid Method (Fuzzy Logic)
DC	- Direct Current
DES	- Decentralized Control System
DSP	- Digital Signal Processor
ELMER	- (ELectro MEchanical Robots, Light Sensitive)
ELSIE	- (Electro mechanical robots, LIght SEnsitive)
FOB	- Fuzzy Output Block
GBP	- Gain Bandwidth Product
HLMI	- Human Level Machine Intelligence
IFR	- International Federation of Robotics
iPM	- Intelligent Power Management
IR	- Infrared Radiation
LDR	- Light Dependant Resistor
MCU	- Microprocessor Control Unit
MOF	- Membership Output Function
NN	- Neural Network
OA	- Obstacle Avoidance
OIR	- operational Industrial Robots
OMF	- Output Membership function
OR	- Obstacle Recognition
PID	- proportional-integral-derivative controller
PIR	- Pyroelectric Infrared Radiation Sensor
PV	- PhotoVore (Light attracted Robot)
PWM	- Pulse Width Modulation

RB	- Reverse Biased
ROM	- Remotely Operated Machine
ROV	- Remotely Operated Vehicle
SE	- Spacial Envelope
TA	- Transimpedence Amplifier
UAV	- Unmanned Arial Vehicle
VAR	- Variable Resistor

B. GUIDED LEARNING FOR AMBOA VER.3

In order to achieve a robust system at low cost, certain sacrifices have been made relating to the computational speed of the algorithm. The primary initiative is based upon shifting the load weight from the algorithm and placing reliance on the results achieved from the Delta Rule neural trainer. In other words reduce the processing cycles with respect to controllers based on conventional approaches and give to each cycle more importance upon the information processed through the use of analogue based neural networks. The importance of those neural networks comes from the training on which it is developed. Training neural fuzzy algorithms means tuning the behaviour function of what it is able to learn. This means it is possible to change main robot task by changing the neural fuzzy logic weights without change of algorithm. As can be seen in the flow chart of Fig.27 algorithm, except for the neural fuzzy controller block, there is no need to develop any unconventional function, it is necessary to correctly adapt for the proposed algorithm with many auxiliary functions readily available from the manufacturer such as, PWM function, SPI function, digital sensing function, analogue sensing function and digital outputs.

Table 2: Data storage algorithm.

```
Main {
System Init_ ;
_delay32(16) ;
While (1)
{
Cycle = Cycle + 1;
Void Analog_Sensing_Function_(void) ;
_delay32(16);
Void Digital_Sensing_Function_ (void);
```

```
_delay32(16);
Void SPI_CH2_data_Storage_ ;
_delay_ (32000);
If (cycle > 16 000 000 ){
While(1){
};
};
};
```

Table 3: Autonomous driving algorithm.

```
Main {
System Init_;
_delay32(16);
While (1)
{
Void Analog_Sensing_Function_( void);
_delay32(16);
Void Digital_Sensing_Function_(void);
_delay32(16);
Void Neuro_Fuzzy_Control_Funct_(void);
_delay32(16);
Void Robot_Motor_Control(Void);
_delay32(16);
Void Robot_Operations(void);
_delay32(16)
Void SPI_CH1_WiFi__Communication_
(void);
_delay32(16);
Void SPI_CH2_data_Storage_(void);
_delay32(32000);
};
};
```

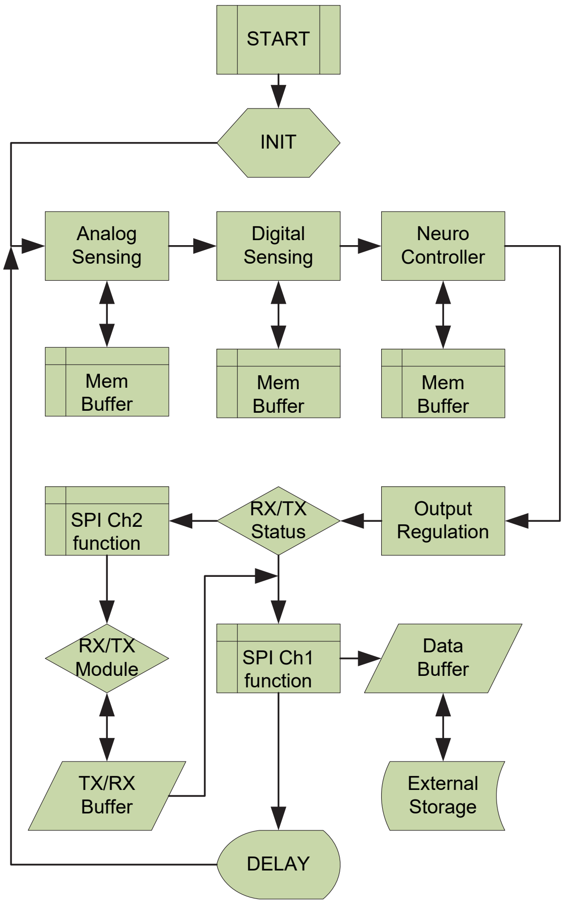


Fig.27. System flow chart

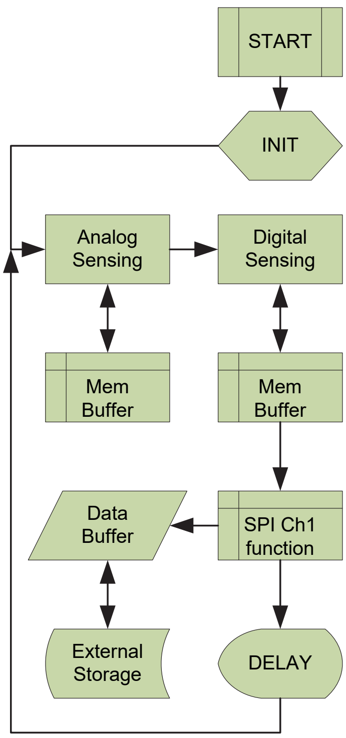


Fig.28. Guided learning flow chart

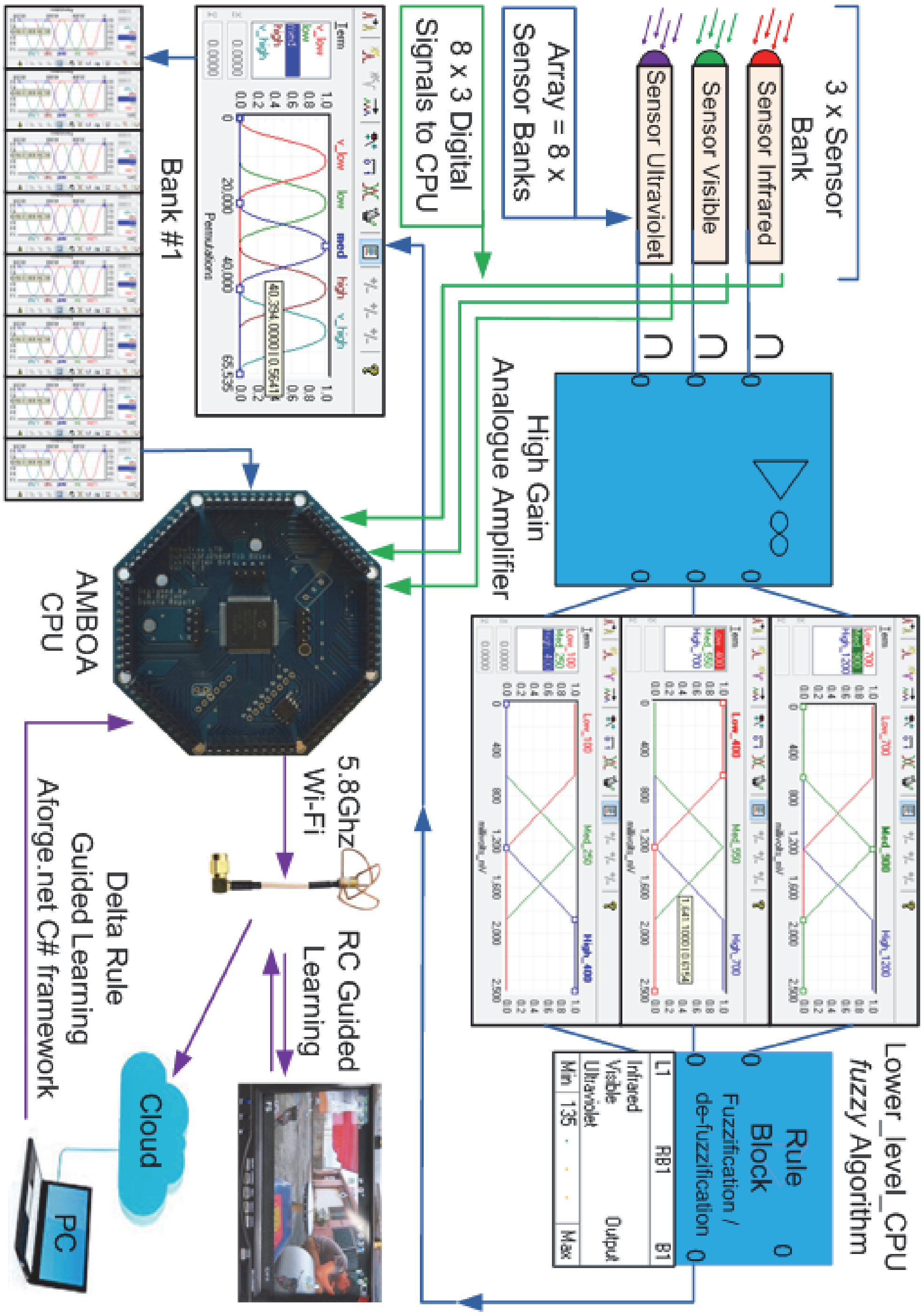


Fig.29. Guided fuzzy/neural learning model

C. CHASSIS ENGINEERING CONSIDERATIONS

The design and engineering of the mobile robot chassis was of prime importance to the thesis. Established features included:

- Size
- Robustness.

- Ease of portability.
- Ease of usability.
- Ability to fit and research a variety of sensors at the requirement of the user.
- Relative autonomy relating to battery recharging.
- Wireless communications for transmitting of environment photography.
- Programming should be researcher specific. Unrestricted code choice.

Table 4: AMBOA features.

Element	Type	Technical information
Size	------------------------	383mm x 204mm x 84mm
Weight	kG	1.5
Wafer 1 (Sensor Array)	360º Passive	8 x BPW34F (Vishay)
	360º Passive	8 x BPW2IR (Vishay)
	360º Passive	8 x FGAP71 (ThorLab)
	LDR Potential Divider	3 x
Adjustment LEDs	Tuning	24 total 8 quadrants
Wafer 2 (Processor Board)	Microchip DSP, DSC	dsPIC33F
Memory on Chip	RAM / FLASH	30kB / 256kB
Interface	CAN/I2C/SPI/UART	-----------------
Memory on Wafer 2	Flash Memory	32M
Wafer 3 (Power Board)		
Chassis Components		
Motors		4 x 12V DC Gear
Motor Drivers	L298N	H-Bridge 5V – 35V @ 2A
On Board Camera	Dual Servo Pan/Tilt	Mobius 5.8gHz High Definition
Battery	Li-Ion	12V @ 9800mAh
Wheels	Track	3 wheel rubber track, independent
Velocity		Max: 60 cm/s
Programming	Researcher Specific	Neural Fuzzy Architecture
Human to Robot Communication	Wireless: RF 2.4GHz	Standard Serial Port (up to 38kbps) Number of Robot Dependant

Robot to Robot Communication	Wireless: RF 2.4GHz	2 x Slave (Swarm)

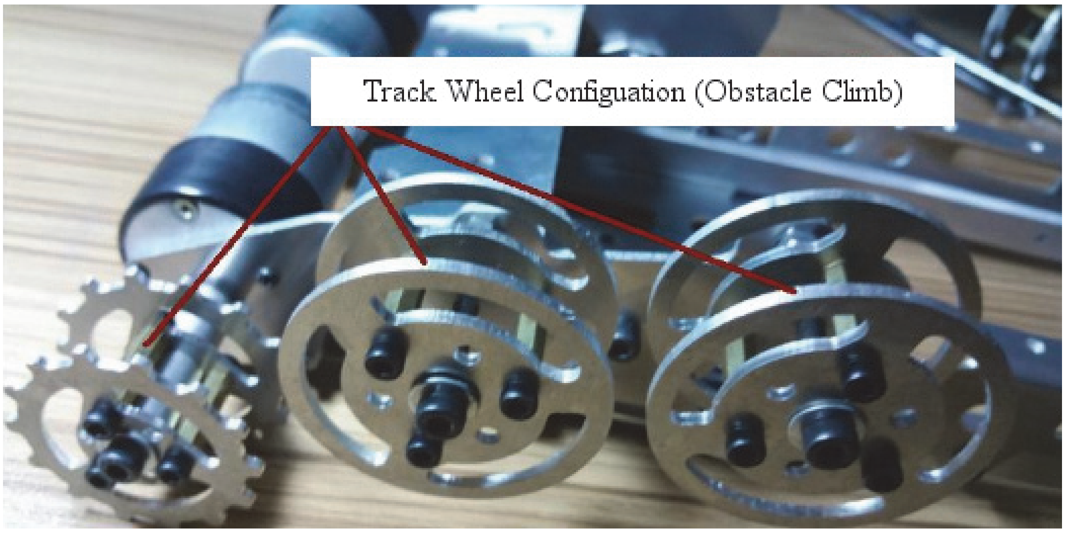


Fig.30.Each track set has one drive sprocket reducing clogging of track.
Open wheel rims reduce particle retention in tracks

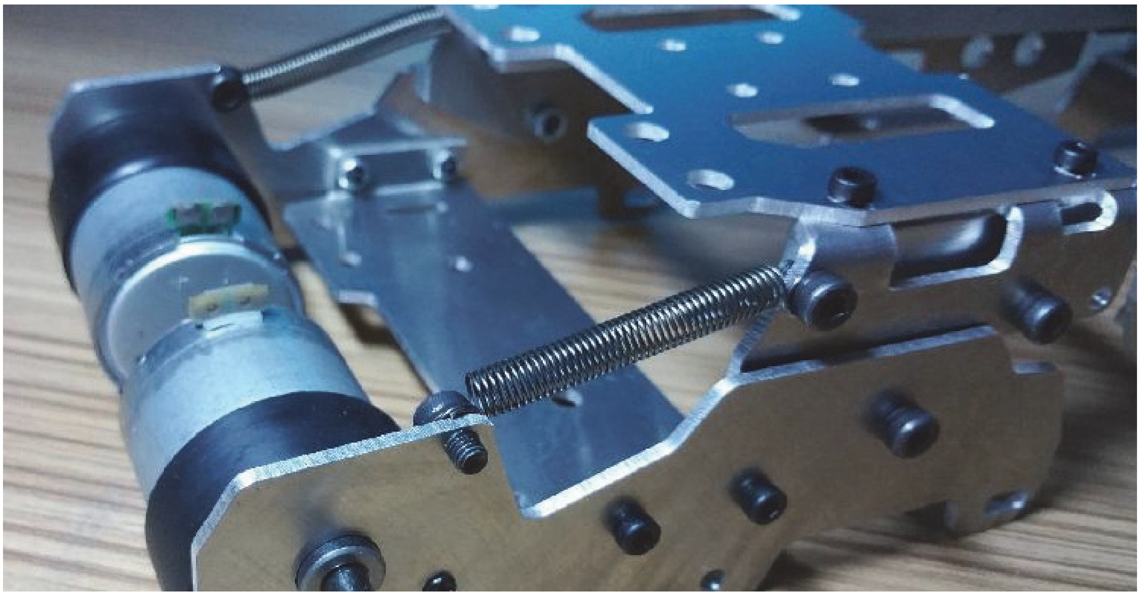


Fig.31. Track arms allow free movement of 35° with spring return mechanism

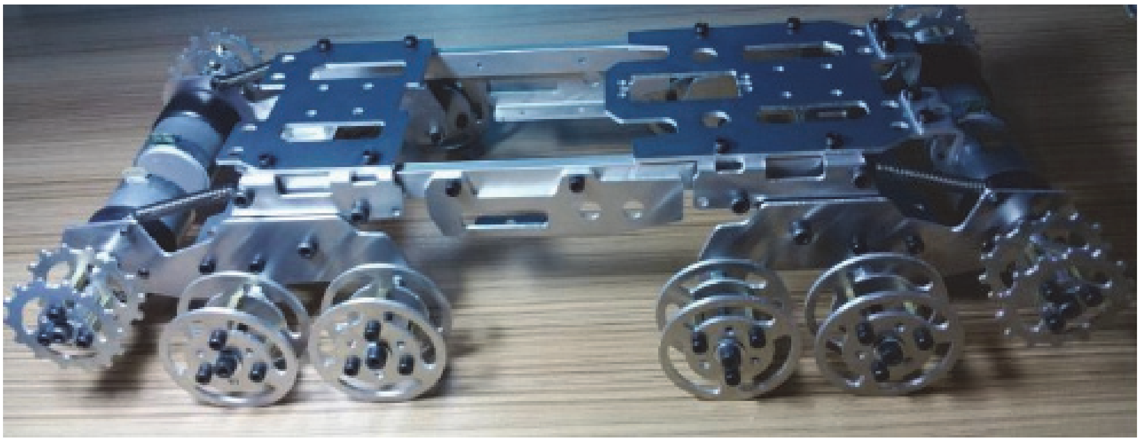


Fig.32. All metal construction including sealed DC Motors

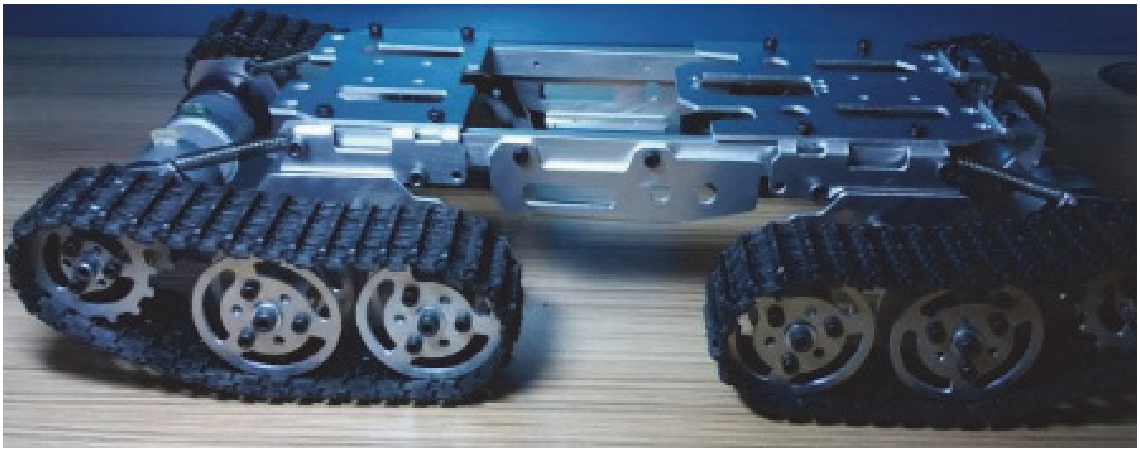


Fig.33. Raw chassis assembled.

D. PRINTED CIRCUIT DEVELOPMENT WAFER.1.SENSOR

AMBOA Ver.1a and Ver.1b and Ver.2 where configured with transimpedence amplification. Subsequent consideration of the original circuit led to decisive changes in the system. TA was only necessary only in a purely analogue system where higher or more amplified voltages were required to obtain suitable reactive response. TA, also had its' drawbacks in the instability of the amplifier gain. It was confirmed that across the board some 24 VAR's would be required for stabilization of the system to be sufficient for accurate readings from the photodiode arrays. This would inevitably lead to excessive time spent in sensor adjustment and an overburden of components on the PCB wafer (an additional 24 VARs and capacitors). As is often the case the simplest solution can be the best as in Fig.34.

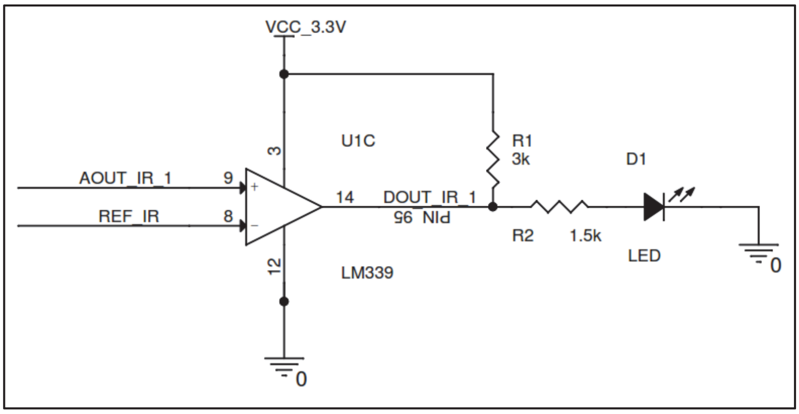


Fig.34. Simple comparator only circuit with $U_{ref,}$ controlled by LDR potential divider

As is shown the LM339 quad comparator is used due to its' outstanding stability in long term operation. The diagram represents only one of the eight sensors in the IR Array and so two quad comparators are required for each eight segment array, with U_{ref} for both LM339s' controlled by one LDR/VAR potential divider. Therefore the adjustment of the eight photodiodes in each array may be accomplished with one potentiometer (VAR). The only criteria to ensure the photodiodes are tuned (have an almost identical responsivity).

Adjustment is achieved through adjustment of the VAR until the LED_{D1} in Fig.35 illuminates, then backing off until the LED goes out. In this manner the LED will illuminate yet will not change in intensity due to the current limiting resistor at R2 but at this trigger point voltage from the photodiode at A_{out} will trigger the override the inverting input of the comparator causing logic 1 output at D_{out}. Both A_{out} and D_{out} are connected to the MCU.

The author has found that a distinct advantage of this configuration is the illumination of the LEDs and the subsequent visual representation of the system during operation and program development.

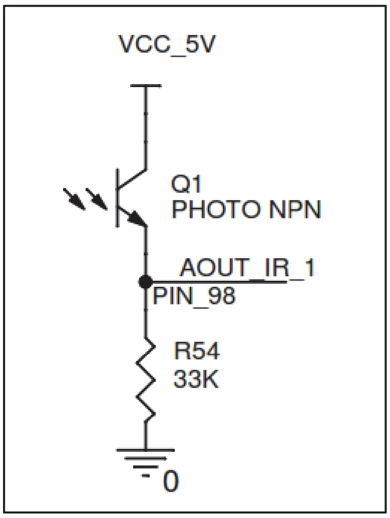


Fig.35. Photodiode RB held at 5V

The LM339 quad comparator was selected due to its' outstanding stability in long term operation when V_{CC} is kept at minimum. The diagram represents only one of the eight sensors in the IR Array and so two quad comparators are required for each eight segment array, with U_{ref} for both LM339s' controlled by the LDR/VAR potential divider in Fig.36.

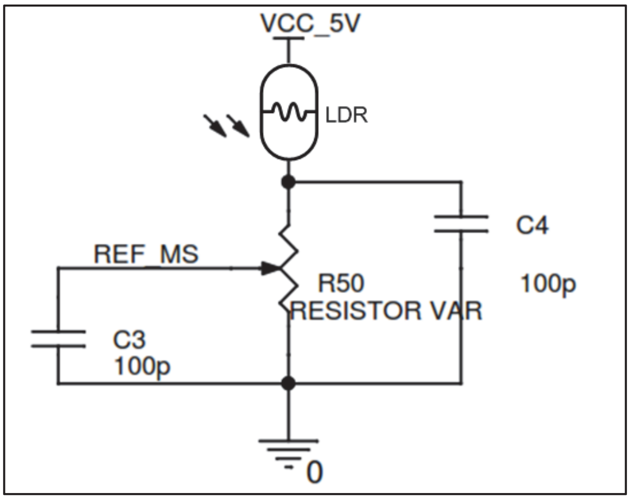


Fig.36. LDR/VAR controlled potential divider

The operation and purpose of the LDR/VAR controlled potential divider has been discussed in ***Appendix G***.

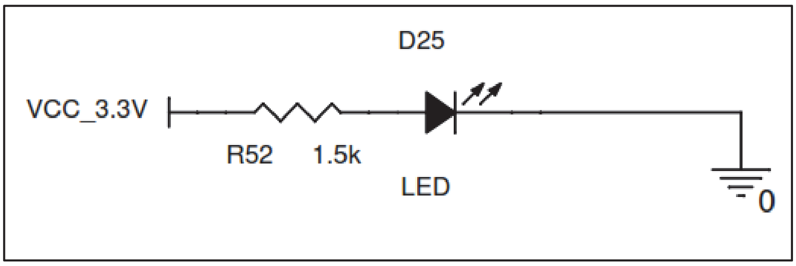
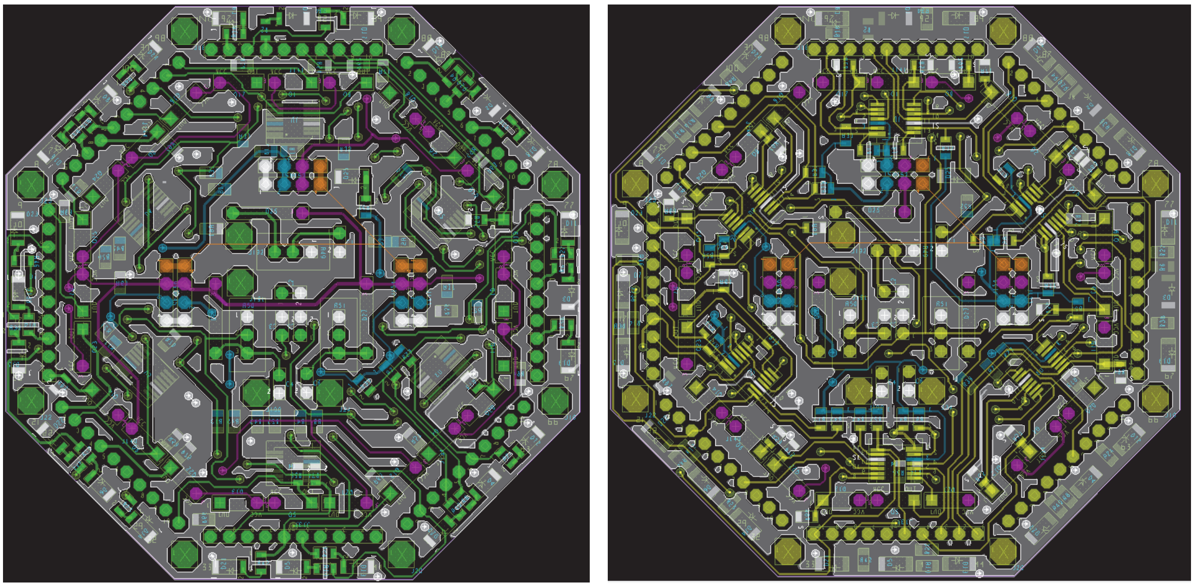


Fig.37. On-off indicator for Sensor Board

The PCBs shown in Fig.38 and Fig.39 have been designed in a octagonal geometry s that each of the 24 sensors faces a particular quadrant. Those quadrants are specifically named for the purpose of programming references and are: Front, F, Rear, R, Left L, Right R, LF, LR, RF and RR respectively.



a. b.

Fig.38. Sensor Wafer PCB, a. board front b. board back

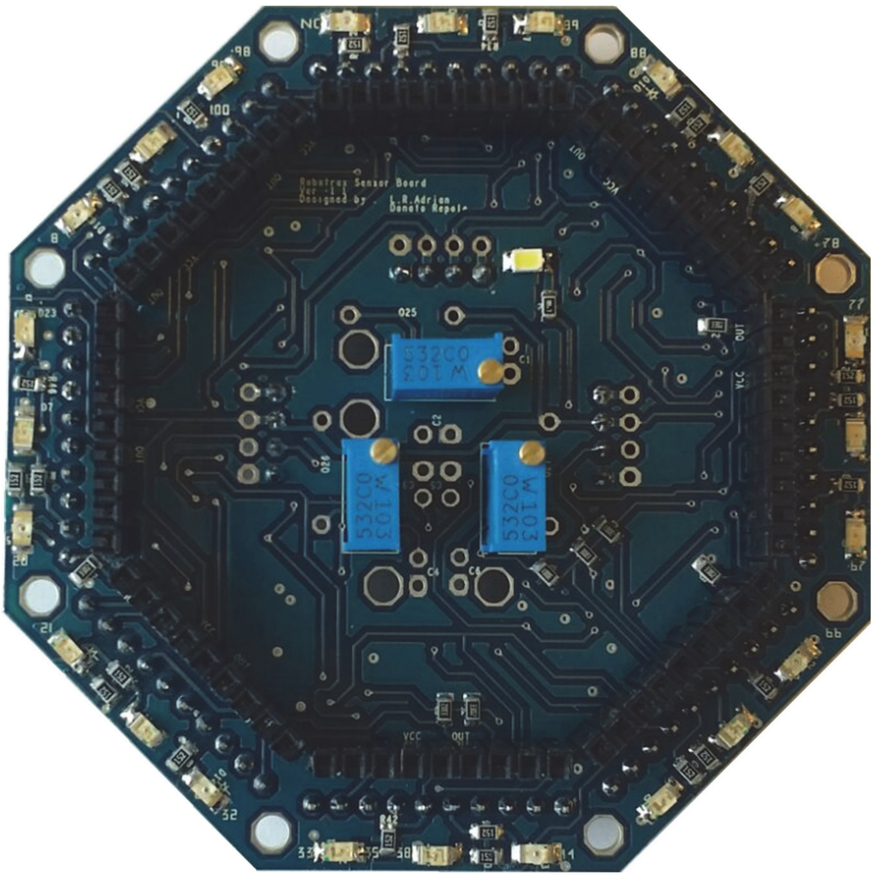


Fig.39. Sensor board

E. PRINTED CIRCUIT DEVELOPMENT WAFER.2.MCU

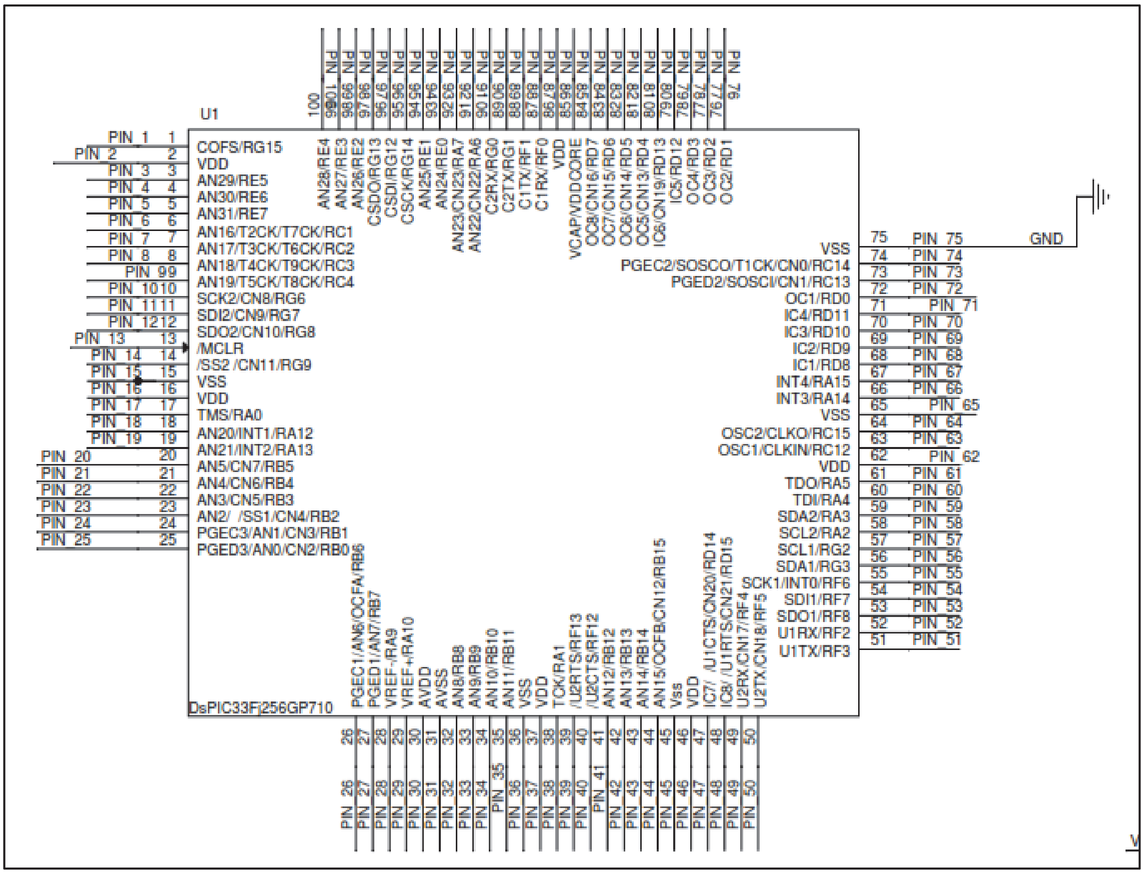


Fig.40. Sensor board print screen.

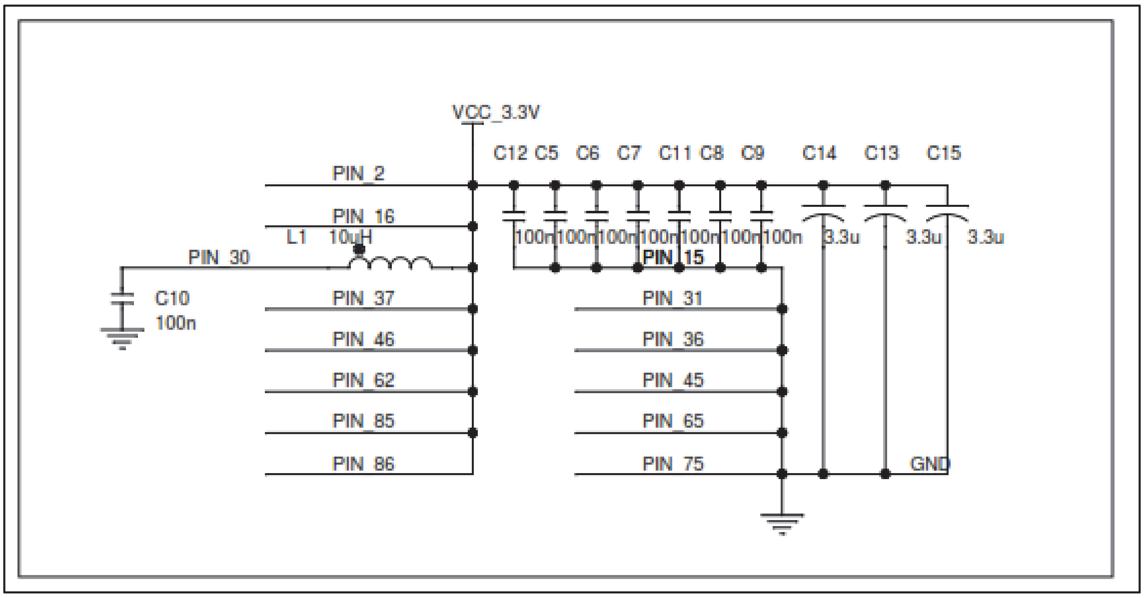


Fig.41. Sensor board print screen.

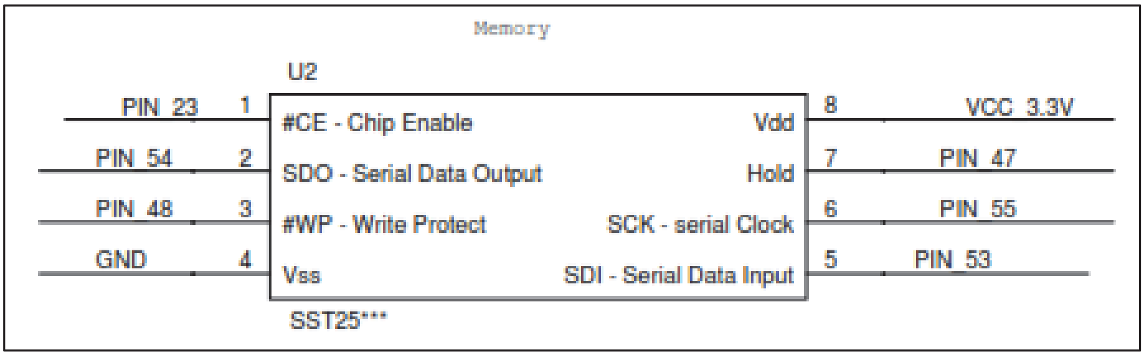


Fig.42. Sensor board print screen

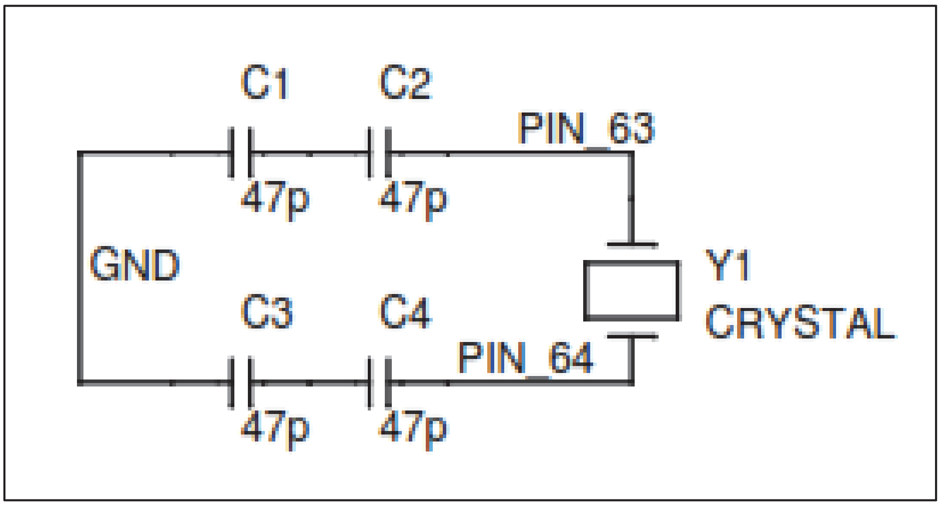


Fig.43. Sensor board print screen

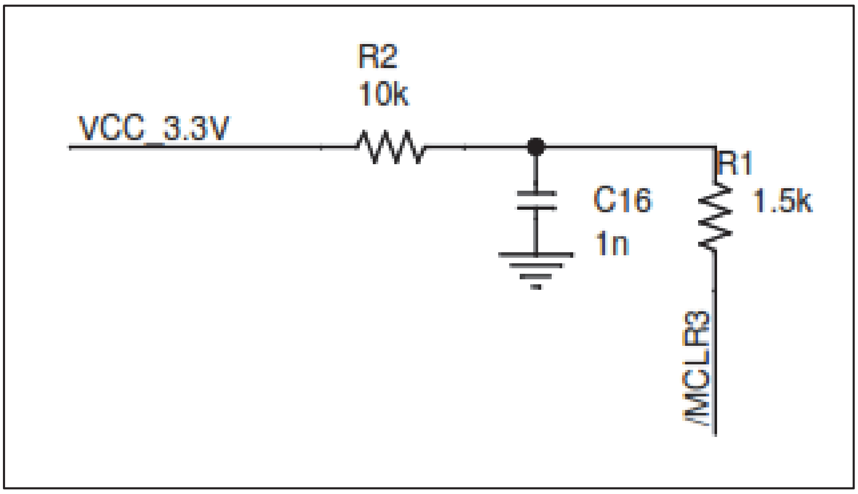


Fig.44. Sensor board print screen

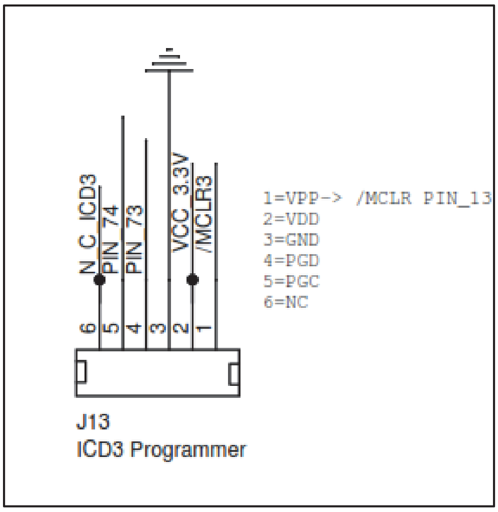


Fig.45. Sensor board print screen

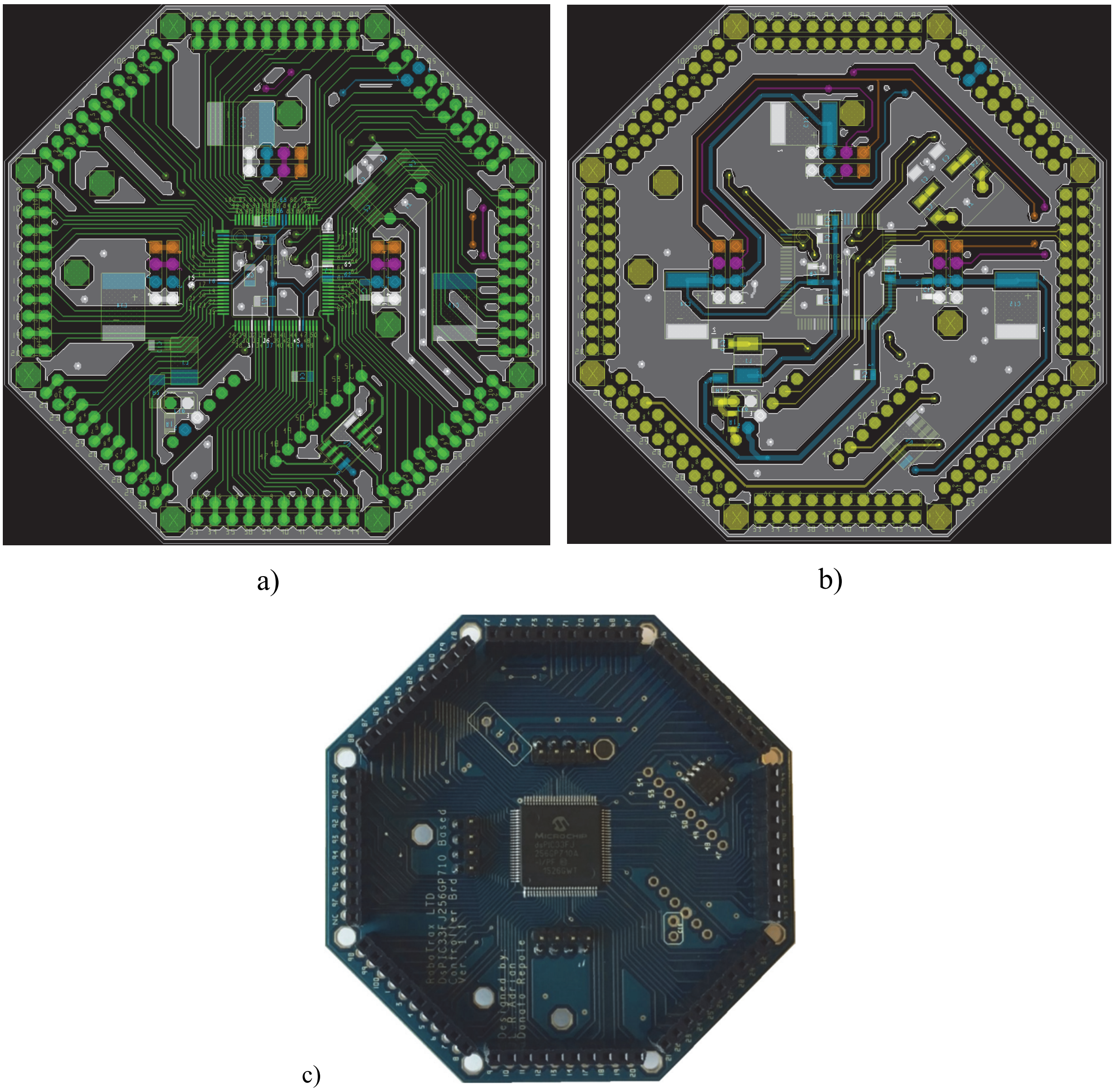


Fig.46. MCU Wafer PCB, a) board front b) board back and c) completed board

F. PRINTED CIRCUIT DEVELOPMENT WAFER.3.POWER

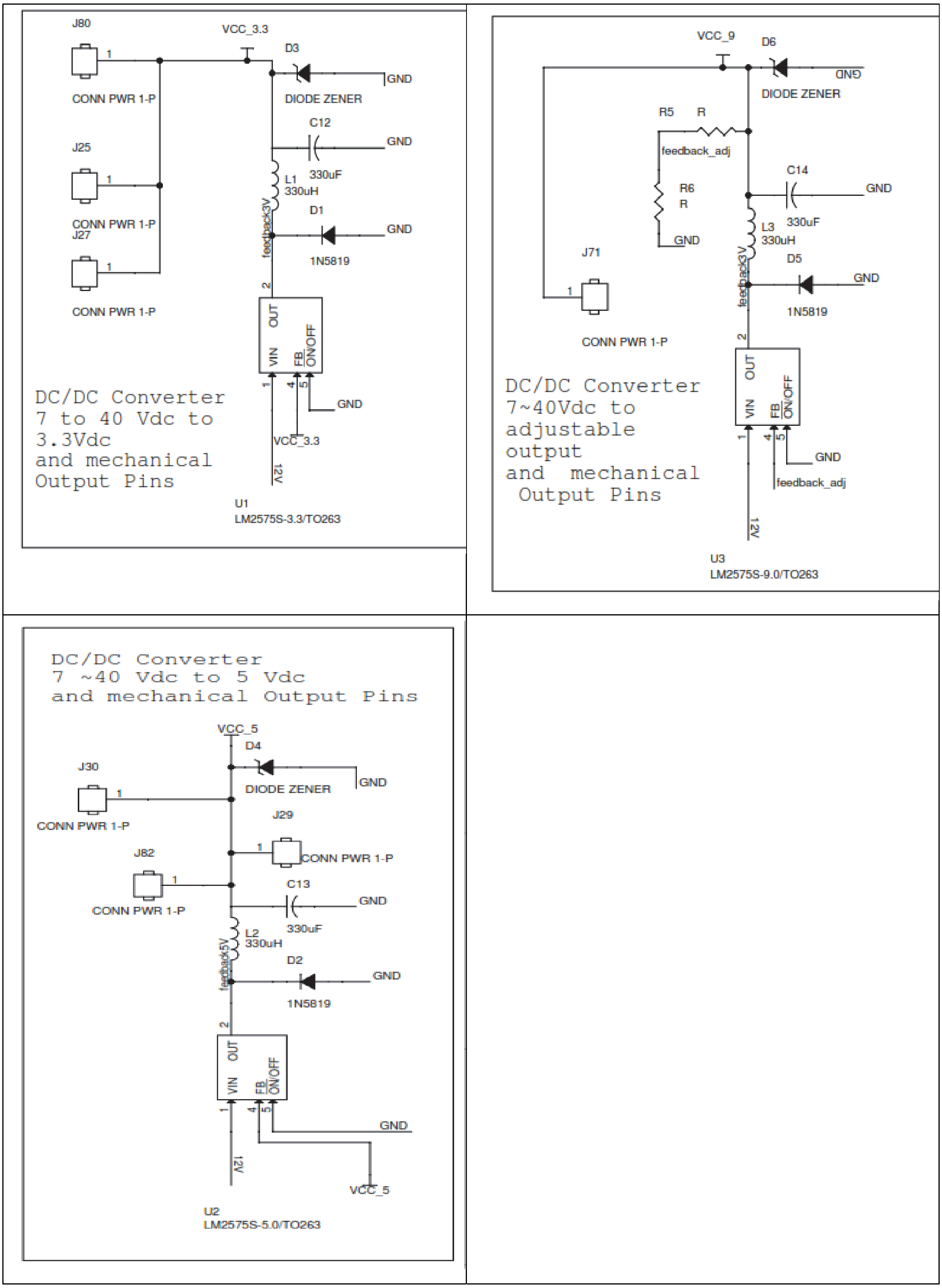
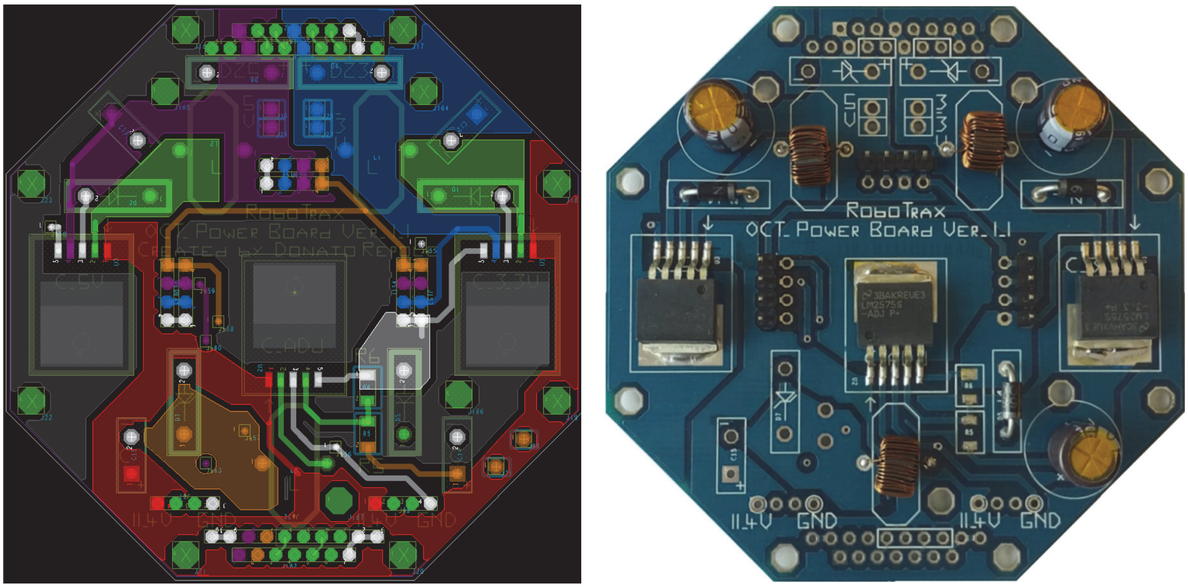


Fig.47. Power wafer PCB.



a) b)

Fig.48. Power Wafer PCB, a) board top b) completed board

G. AMBIENT CONTROL OF COMPARATOR ARRAY UREF

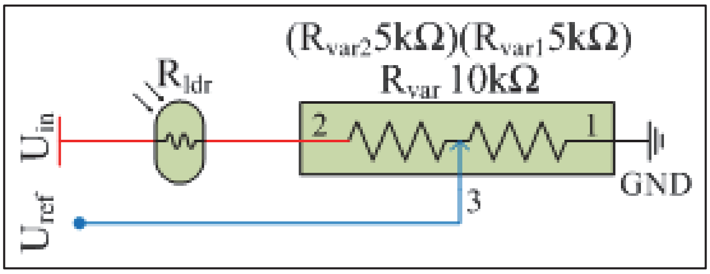


Fig.49. LDR /VAR Potential Divider Configuration

Intrinsically the variable resistor R_{var} consists of a single resistor layer {2..1} and a wiper {3} which adjusts the ratio between both halves. Within the circuit as can be seen in Fig 49, the addition of a Light Dependent Resistor dramatically alters the effect of the standard voltage divider allowing a dimming effect on U_{ref} which in turn increases sensitivity on sensors in that array. In this manner there is more accurate brightening or dimming is achieved when the mobile platform passes into brighter or lower light conditions. Calculation of U_{ref} parameters may be calculated using (11).

$$U_{ref} = \frac{R_{var1}}{R_{var1}+(R_{ldr}+R_{var2})} \times U_{in} \tag{11}$$

Ambient Lighting Level	R_{LDR}	R_{VAR1} @ 2.5kΩ	Ratio $R_{VAR1}/R_{VAR1}+(R_{LDR}+R_{VAR2})$	U_{REF} Volts
500 Lux	1kΩ	2.5kΩ	0.22	1.11
250 Lux	10kΩ	2.5kΩ	0.125	0.63
100 Lux	100kΩ	2.5kΩ	0.02	0.11

Table 5: Example Calculated Sensitivity of Reference Voltage.

Ambient Lighting Level	R_{LDR}	R_{VAR1} @ 5kΩ	Ratio $R_{VAR1}/R_{VAR1}+(R_{LDR}+R_{VAR2})$	U_{REF} Volts
500 Lux	1kΩ	5kΩ	0.45	2.25
250 Lux	10kΩ	5kΩ	0.25	1.25
100 Lux	100kΩ	5kΩ	0.04	0.02

Table 6

Ambient Lighting Level	R_{LDR}	R_{VAR1} @ 7.5kΩ	Ratio $R_{VAR1}/R_{VAR1}+(R_{LDR}+R_{VAR2})$	U_{REF} Volts
500 Lux	1kΩ	7.5kΩ	0.68	3.40
250 Lux	10kΩ	7.5kΩ	0.375	1.88
100 Lux	100kΩ	7.5kΩ	0.068	0.34

Table 7

Tables 5, 6 and 7 denote an average voltage swing on U_{ref} of 2.09 Volts between bright and darker environments. It is of note that the sensor array within darker environments becomes highly sensitive to peak spectral wavelength which allows sufficient resolution for assimilation to the ADC of the microprocessor.

H. RESPONSIVITY –V- GENERATED PHOTOCURRENT

(The following approximates general necessary information about the selected Photodiodes for AMBOA. The photodiodes are high end market sensors with associated precision and are available at [50])

Photodiode responsivity may be defined as the ratio of photocurrent generated (I_{PD}) to the electromagnetic spectral incident power (P) at its given wavelength:

$$R(\lambda) = \frac{I_{PD}}{P} \qquad (12)$$

Theoretical Photodiode Operation –v- Practical Result

A photosensitive diode is a very fast and highly linear device exhibiting high quantum efficiency based upon the application and may be used in a variety of different applications. A junction photodiode is fundamentally a device that behaves in the same manner as a commonplace signal diode, however it generates a photocurrent when electromagnetic radiation or light is absorbed in the depleted region of the junction semiconductor. Determining the level of output current to expect is referred to as the responsivity of the photodiode and is based upon the incident light received across its substrate and subsequent generated voltage. A junction photodiode model Fig.50, is used to assist in visualizing the primary characteristics of photosensitive diodes and is composed of basic discrete components.

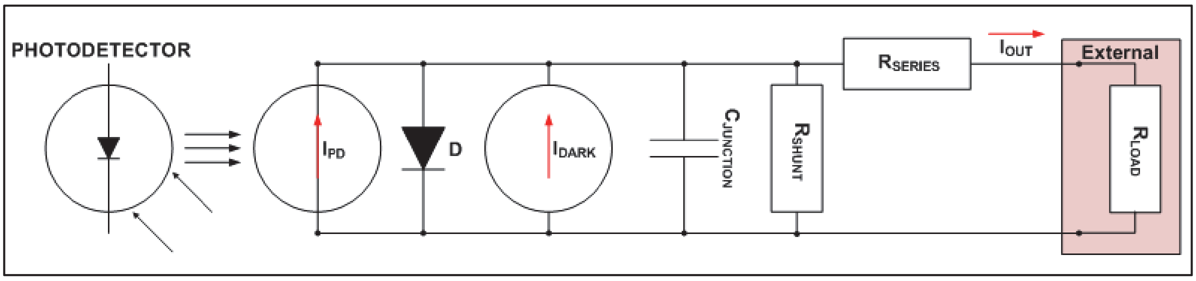


Fig.50. Junction diode model

$$I_{out} = I_{dark} + I_{PD} \qquad (13)$$

Modes of Operation (Photoconductive vs. Photovoltaic)

When operation is required to be in a photo-voltaic mode the PD is “zero-biased” however if a photo-conductive mode is required the PD is “reverse-biased”. These two modes of operation are completely dependent on the requirements of the appliance. A suitable mode selection must be made according to the tolerable amount of leakage current and or with consideration of speed requirements.

Photoconductive

In photoconductive mode, an external reverse bias is applied, which is the basis for our DET series detectors. The current measured through the circuit indicates illumination of the device; the measured output current is linearly proportional to the input optical power. Applying a reverse bias increases the width of the depletion junction producing an increased responsivity with a decrease in junction capacitance and produces a very linear response. Operating under these conditions does tend to produce a larger dark current, but this can be limited based upon the photodiode material.

Photovoltaic

Utilization of the photovoltaic effect, which is the remedial method of solar cell operation and a minimization of dark current allows operation in a photovoltaic mode and is the preferred method of action. A zero biased photosensitive diode is the basis for operation in photovoltaic mode where the voltage build up within the device is proportional to the restriction of current surge.

Dark Current

Dark current is leakage current that flows when a bias voltage is applied to a photodiode. When operating in a photoconductive mode, there tends to be a higher dark current that varies directly with temperature. Dark current approximately doubles for every 10 °C increase in temperature, and shunt resistance tends to double for every 6 °C rise. Of course, applying a higher bias will decrease the junction capacitance but will increase the amount of dark current present.

The dark current present is also affected by the photodiode material and the size of the active area. Silicon devices generally produce low dark current compared to germanium devices which have high dark currents. The table below lists several photodiode materials and their relative dark currents, speeds, sensitivity, and costs.

Junction Capacitance

Junction capacitance (C_j) is an important property of a photodiode as this can have a profound impact on the photodiode's bandwidth and response. It should be noted that larger diode areas encompass a greater junction volume with increased charge capacity. In a reverse bias application, the depletion width of the junction is increased, thus effectively reducing the junction capacitance and increasing the response speed.

Bandwidth and Response

A load resistor will react with the photo-detector junction capacitance to limit the bandwidth. For best frequency response, a 50 Ω terminator should be used in conjunction with a 50Ω coaxial cable. The bandwidth (f_{BW}) and the rise time response (t_r) can be approximated using the junction capacitance (C_j) and the load resistance (R_{LOAD}):

$$f_{BW} = \frac{1}{(2\pi R_{LOAD} C_j)} \quad (14)$$

$$t_r = \frac{0.35}{f_{BW}} \quad (15)$$

Terminating Resistance

A load resistance is used to convert the generated photocurrent into a voltage (U_{out}) for viewing on an oscilloscope:

$$U_{out} = I_{out} \times R_{load} \quad (16)$$

Depending on the type of the photodiode, load resistance can affect the response speed. For maximum bandwidth, we recommend using a 50 Ω coaxial cable with a 50 Ω terminating resistor at the opposite end of the cable. This will minimize ringing by matching the cable with its characteristic impedance. If bandwidth is not important, you may increase the amount of voltage for a given light level by increasing R_{LOAD}. In an unmatched termination, the length of the coaxial cable can have a profound impact on the response, so it is recommended to keep the cable as short as possible.

Shunt Resistance

Shunt resistance represents the resistance of the zero-biased photodiode junction. An ideal photodiode will have an infinite shunt resistance, but actual values may range from the order of ten Ω to thousands of MΩ and is dependent on the photodiode material. For example, and InGaAs detector has a shunt resistance on the order of 10 MΩ while a Ge detector is in the kΩ range. This can significantly impact the noise current on the photodiode. For most applications, however, the high resistance produces little effect and can be ignored.

Series Resistance

Series resistance is the resistance of the semiconductor material, and this low resistance can generally be ignored. The series resistance arises from the contacts and the wire bonds of the photodiode and is used to mainly determine the linearity of the photodiode under zero bias conditions.

Sensor Array Module

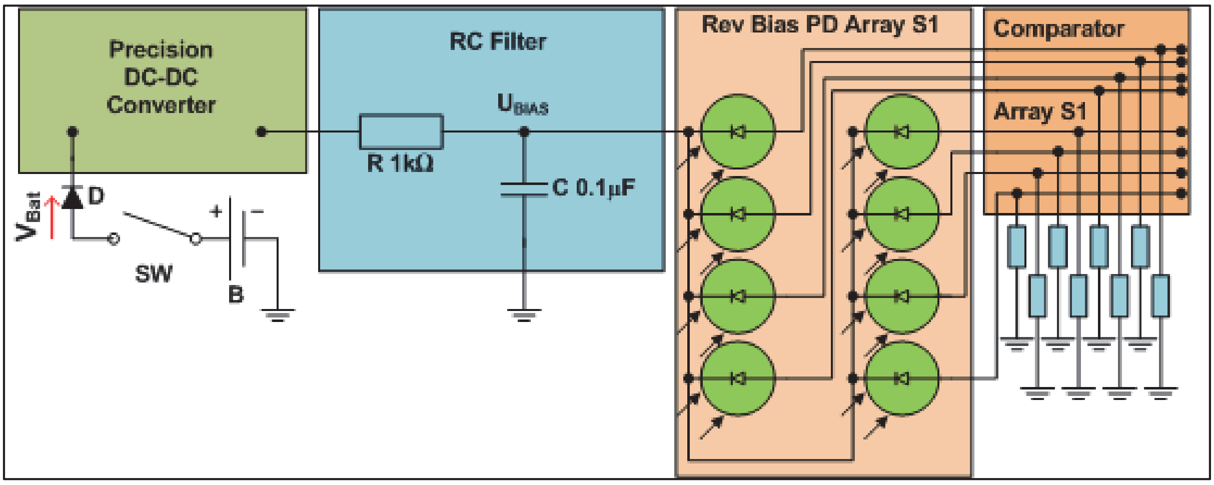


Fig.51 Model of the sensor array module

The photodiode array is reverse biased which serves to produce a very linear response to the incident spectral waveform.

During laboratory testing the results of oscilloscopic investigations led to the inclusion of a small yet significant RC filter Fig.51, the purpose of which serves to reduce high-frequency noise generated from both the power supply wafer board and from the robots motor array which contributed to a very noisy output across the array.

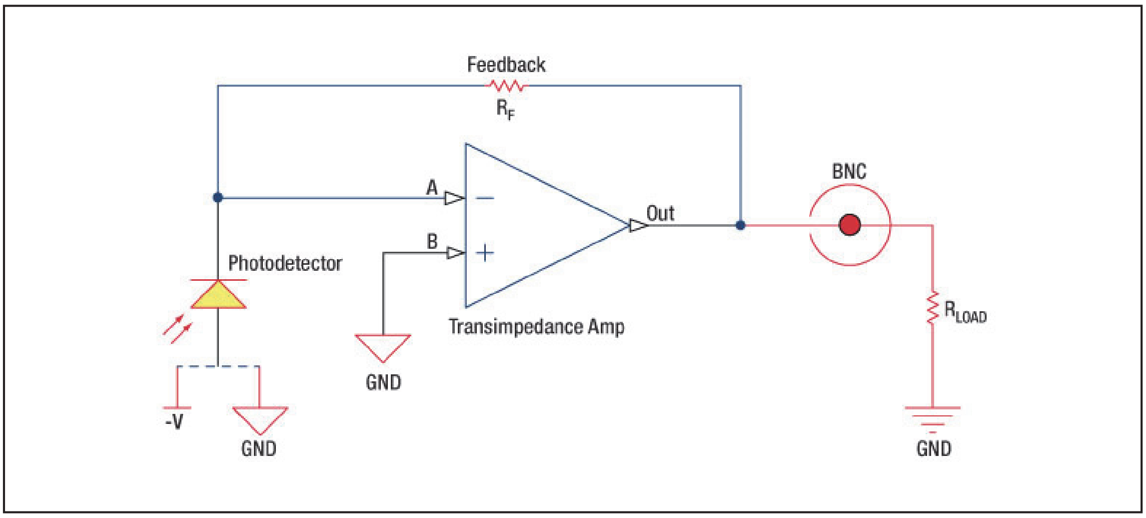


Fig.52. Generic image of transimpedence amplifier for photodiode signal detection

During the construction and testing of circuitry for AMBOA Ver.1 and Ver.2 it became evident that transimpedence amplification Fig.52, was not an ideal solution for many reasons. Primarily, the slight variation in gain across 24 amplifiers was difficult to control without an overburden of components. Also, control of ambient light readings could not be accomplished without the addition of as many as 24 separate LDR assisted potential divider due to the varying requirements of individual photodiode responsivities. It was found that higher gain was not necessary if the non-inverting and inverting input of the comparators was held at close to trigger point for the photodiode response. Thereafter the transimpedence array was redesigned to accommodate a comparator only array. The output from the comparator array has proven ideal for recognition through both the digital and ADC inputs of the microprocessor, rendering the TA unnecessary. The simplicity of only three adjustable LDR assisted potential dividers allows for a very easily adjusted sensory system with the only consideration being that of ensuring that each set of 8 comparators in the system operate at approximately the same level or are selected to produce close to identical output.

Testing of the photocurrent generated was performed and is based on the wavelength and incident spectral response and was seen using the oscilloscope and attaching a small load resistance to the output, allowing for selection of suitable photodiodes with similar reaction.

High gain can also be achieved using a photo sensor by using an amplifier giving the user the opportunity to operate in either photoconductive mode or photovoltaic mode. As has been previously covered, the original AMBAO robots utilized transimpedence amplification however that method was abandoned with preference toward a wholly comparator based circuit. However there are benefits of choosing this active circuit:

- In a photovoltaic mode: The circuit is held at zero volts across the photodiode, since point A is held at the same potential as point B by the operational amplifier. This eliminates the possibility of dark current and:
- In photoconductive mode: The photodiode is reversed biased, thus improving the bandwidth while lowering the junction capacitance. The gain of the detector is dependent on the feedback element (R_f). The bandwidth of the detector can be calculated using the following:

$$f(-3dB) = \sqrt{\frac{GBP}{4\pi \cdot R_f \cdot C_D}} \qquad (17)$$

Where GBP is the amplifier gain bandwidth product and C_D is the sum of the junction capacitance and amplifier capacitance.

Effects of Chopping Frequency

The photoconductor signal will remain constant up to the time constant response limit. Many detectors, including PbS, PbSe, HgCdTe (MCT), and InAsSb, have a typical 1/f noise spectrum (i.e., the noise decreases as chopping frequency increases), which has a profound impact on the time constant at lower frequencies.

The detector will exhibit lower responsivity at lower chopping frequencies. Frequency response and detectivity are maximized for:

$$f_C = \frac{1}{2\pi\tau_r} \quad (18)$$

Table 8: ***Test-Bench results of analysis of selected sensors***.

Wavelength (nm)	Responsivity UV(A/W)	Wavelength (nm)	Responsivity Mid(A/W)	Wavelength (nm)	Responsivity NIR(A/W)
130	0	410	0	675	0.001
140	0.008	420	0.014	680	0.003
150	0.00883	430	0.017	690	0.006
160	0.01058	440	0.022	700	0.01
170	0.01058	450	0.027	710	0.012
180	0.0103	460	0.036	720	0.014
190	0.0102	470	0.047	730	0.015
200	0.012	480	0.052	740	0.017
210	0.013	490	0.066	750	0.021
220	0.016	500	0.073	760	0.024
230	0.019	510	0.085	770	0.039
240	0.022	520	0.096	780	0.047
250	0.028	530	0.112	790	0.048
260	0.036	540	0.118	800	0.059
270	0.042	550	0.128	810	0.063
280	0.049	560	0.132	820	0.068
290	0.055	570	0.14	830	0.075
300	0.06	580	0.138	840	0.088
310	0.066	590	0.126	850	0.094
320	0.072	600	0.108	860	0.098

330	0.078	610	0.096	870	0.102
340	0.084	620	0.084	880	0.11
350	0.089	630	0.066	890	0.124
360	0.094	640	0.054	900	0.134
370	0.098	650	0.037	910	0.138
380	0.102	660	0.027	920	0.14
390	0.106	670	0.018	930	0.145
400	0.11	675	0.002	940	0.147
410	0.114	680	0.002	950	0.152
420	0.117	690	0.002	960	0.15
430	0.118	700	0.001	970	0.148
440	0.115	710	0	980	0.145
450	0.11	------	------	990	0.142
460	0.1	------	------	1000	0.132
470	0.09	------	------	1010	0.127
480	0.075	------	------	1020	0.124
490	0.06	------	------	1030	0.1
500	0.045	------	------	1040	0.09
510	0.034	------	------	1050	0.075
520	0.027	------	------	1060	0.06
530	0.019	------	------	1070	0.045
540	0.014	------	------	1080	0.034
550	0.008	------	------	1090	0.027
560	0.004	------	------	1100	0.019
570	0.002	------	------	1110	0.014
580	0.001	------	------	1120	0.008
590	0.001	------	------	1130	0.004
600	0	------	------	1140	0.002
------	------	------	------	1150	0
------	------	------	------	1160	0

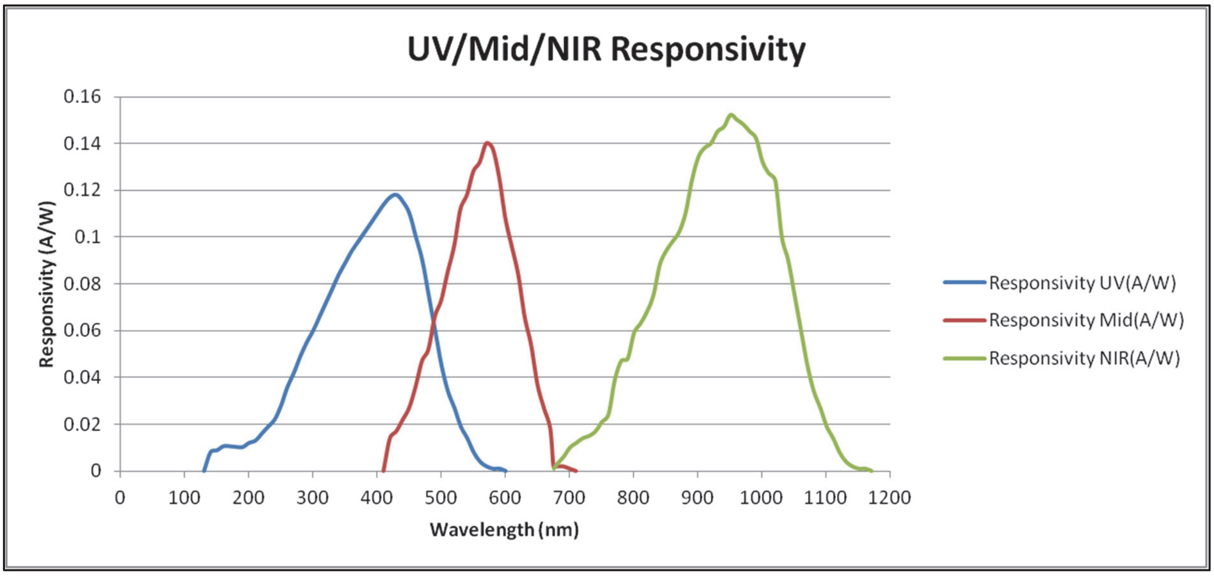


Fig.53. Result of responsivity relationship between selected sensors

I. FUZZIFYING AND DEFUZZIFYING

Creating Memberships

The Membership system inputs are most commonly associated with physical and sometimes non-physical variables and therefore are not strictly "fuzzified values" but almost certainly numerical values can be referred to as "crisp parameters". It is necessary to convert each numeric value to the corresponding input fuzzy sets, or in other words convert to an input fuzzification.

By an Input with a generic value (x_0) and a Fuzzy set (A), there is an establishment of a degree of truth of (A) not exceeding ($M_A(x_0)$) and with a sub-set (A') of (A) having as a maximum ordinate ($M_A(x_0)$) as in [15].

$$M_{A'(x)} = MAX\big(M_A(x_0), M_A(x)\big) \qquad (19)$$

What this means is that if the membership function input is a triangle ($M_A(x)$), then $M_{A'}(x)$ will be a trapezoid and this trapezoid will have a maximum value "MA(x0)" which is only true if: $0 < MAX(M_A(x_0)) < 1$.

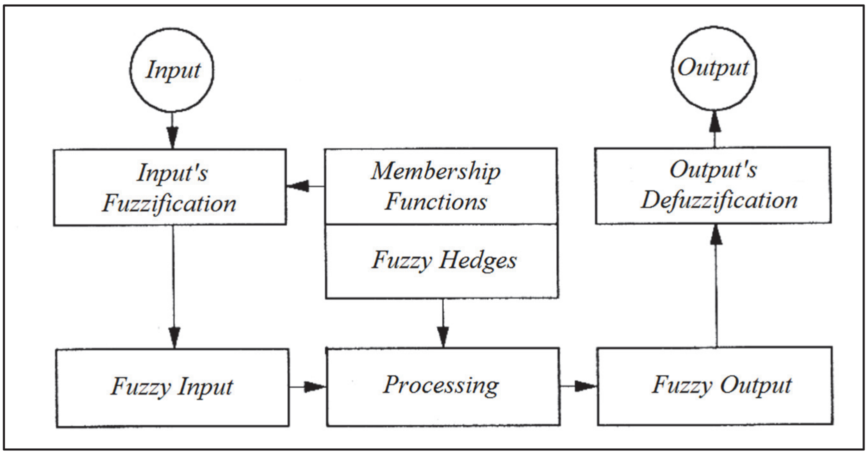


Fig.54. General purpose fuzzy controller flow chart [15]

Basically, a process is created that receives crisp values which will be the generic values ($x0$) and the input membership functions (A) in input and returns fuzzy sets triggered by those values (A'). In practice, rather than activated sets (A') it is preferable to use their maximum degree of truth (MA'(x0)), which incidentally coincides with (MA(x0)), with the last result being defined as the fuzzy input [15].

Fuzzy Hedges

Once the fuzzy inputs are obtained those values are processed within a block of Assessment Rules with each combination of fuzzy input activated by a particular rule, to which is associated a particular degree of activation. This value could be equal to the minimum degree of truth of the fuzzy input sets that define the combination. Thus, what is designed is a truth table, in which there are all the possible combinations of the fuzzy sets where each combination is associated with a particular fuzzy set, which in turn activates a fuzzy set for each type of output with a certain degree of truth. What is described is called Fuzzy Inference, precisely defined as the process that receives the Fuzzy Input and Fuzzy Rules and returns the output fuzzy sets inferred [15].

Output Defuzzification

The union of all output sets is defined as the Membership Output Function (MOF). In the Fuzzy Output Block (FOB) can define the results obtained in the Assessment Rules Block (ARB), according to a specific method. Whatever the method used, in the case of a set which is associated to more degrees of truth are by definition used to maximize the values. Generally there are two methods used being, Composition, where the output fuzzy sets obtained are the subject of a logical OR operation, and Sum Composition method where the output fuzzy sets obtained are simply added together.

Once obtained the Output Membership Function (OMF) may be ascertained however there is a final step required to get a usable output function and this is called Defuzzification. In this step a determination is made in establishing the numerical value most representative of the whole final output through the use of any of the following specific methods.

The Centroid Method (COG) where the defuzzification takes as output value the centroid abscissa of the solid figure bounded by all fuzzy output, the MAX method where the defuzzified output value corresponds with the maximum of the output and the Medium of Maxima (MOM), method, where the defuzzified output value is the average of the values corresponding to the maximum of the output [15].

J. LYAPUNOV THEOREM

Consider an autonomous nonlinear dynamic system:

$\dot{x} = f(x(t)), \quad x(0) = x_0$,

Where, $x(t) \in \mathcal{D} \subseteq \mathbb{R}^n$ denotes the system state vector, $\mathcal{D}$ an open set containing the origin and, $f : \mathcal{D} \to \mathbb{R}^n$ continuous on $\mathcal{D}$. Suppose f has an equilibrium at x_e so that $f(x_e) = 0$ then this equilibrium is said to be Lyapunov stable, if, for every $\epsilon > 0$, there exists a, $\delta = \delta(\epsilon) > 0$, such that, if $\|x(0) - x_e\| < \delta$, then for every, $t \geq 0$ we have, $\|x(t) - x_e\| < \epsilon$.

The equilibrium of the above system is said to be asymptotically stable if it is Lyapunov stable and if there exists, $\delta > 0$ such that if, $\|x(0) - x_e\| < \delta$, then $\lim_{t \to \infty} \|x(t) - x_e\| = 0$.

The equilibrium of the above system is said to be exponentially stable if it is asymptotically stable and if there exists, $\alpha, \beta, \delta > 0$ such that if, $\|x(0) - x_e\| < \delta$, then, $\|x(t) - x_e\| \leq \alpha \|x(0) - x_e\| e^{-\beta t}$, for $t \geq 0$.

Conceptually, the meanings of the above terms are the following:

Lyapunov stability of an equilibrium means that solutions starting "close enough" to the equilibrium (within a distance δ from it) remain "close enough" forever (within a distance ϵ from it). Note that this must be true for any ϵ that one may want to choose. Asymptotic stability means that solutions that start close enough not only remain close enough but also eventually converge to the equilibrium. Exponential stability means that solutions not only converge, but in fact converge faster than or at least as fast as a particular known rate $\alpha\|x(0)-x_e\|e^{-\beta t}$. The trajectory x is (locally) attractive if $\|y(t)-x(t)\|\rightarrow 0$ (where y(t) denotes the system output) for $t\rightarrow\infty$ for all trajectories that start close enough, and globally attractive if this property holds for all trajectories.

That is, if *x* belongs to the interior of its stable manifold, it is asymptotically stable if it is both attractive and stable. (There are counterexamples showing that attractivity does not imply asymptotic stability. Such examples are easy to create using homoclinic connections.)
[23].

K. ARTIFICIAL NEURAL SYSTEMS

Artificial neural systems, or neural networks, are physical cellular systems which can acquire, store, and utilize experimental knowledge. The knowledge is in the form of stable states or mappings embedded in networks that can be recalled in response to the presentation of cues [24].

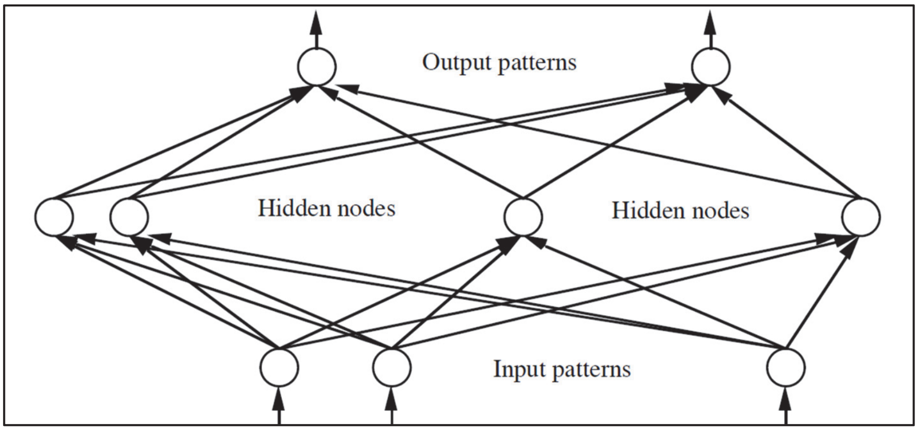


Fig.55. Multi-layer feed forward NN

The basic processing elements of neural networks are called artificial neurons, or simply neurons or nodes. Each processing unit is characterized by an activity level (representing the state of polarization of a neuron), an output value (representing the firing rate of the neuron), a set of input connections, (representing synapses on the cell and its dendrite), a bias value (representing an internal resting level of the neuron), and a set of output connections (representing a neuron's axonal projections). Each of these aspects of the unit are represented mathematically by real numbers. Thus, each connection has an associated weight (synaptic strength) which determines the effect of the incoming input on the activation level of the unit. The weights may be positive (excitatory) or negative (inhibitory).

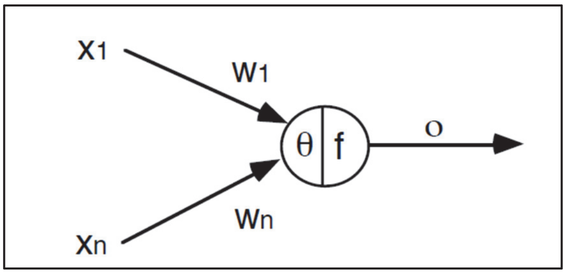


Fig.56. Processing element with single output connection [16]

The signal flow from of neuron inputs, *xj*, is considered to be unidirectional as indicated by arrows, as is a neuron's output signal flow. The neuron output signal is given by the following relationship:

$$o = f(< w, x >) = f(w^T x) = f(\sum_{j=1}^{n} w_j x_j) \qquad (20)$$

Where, w = $(w1,...,wn)^T \in IR^n$ is the weight vector. The function *f(wT x)* is often referred to as an activation (or transfer) function. Its domain is the set of activation values, net, of the neuron model, we thus often use this function as *f*(net). The variable net is defined as a scalar product of the weight and input vectors

$$net =< w, x >= w^T x = w_1 x_1 + \cdots + w_n x_n \qquad (21)$$

and in the simplest case the output value o is computed as:

$$o = f(net) = \begin{cases} 1 & \text{if } w^T x \geq \theta \\ 0 & \text{otherwise,} \end{cases} \qquad (22)$$

where θ is called threshold-level and this type of node is called a linear threshold unit.

[16]

L. TYPES OF NEURO-FUZZY SYSTEMS

Co-operative Neuro-Fuzzy Systems

In a co-operative system the neural networks are only used in an initial phase. In this case, the neural network determines sub-blocks of the fuzzy system using training data, after this, the neural networks are removed and only the fuzzy system is executed. In the cooperative neuro-fuzzy systems.

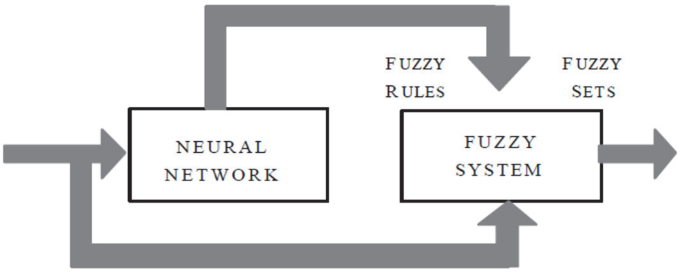


Fig.57 Co-operative system [19].

Concurrent Neuro-Fuzzy Systems

A concurrent system is not a neuro-fuzzy system in the strict sense, because the neural network works together with the fuzzy system. This means that the inputs enters in the fuzzy system, are pre-processed and then the neural network processes the outputs of the concurrent system or in the reverse way.

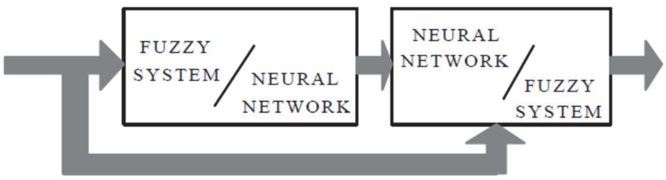


Fig.58 Concurrent system [19]

Hybrid Neuro-Fuzzy Systems

In Nauck [18] definition: “A hybrid neuro-fuzzy system is a fuzzy system that uses a learning algorithm based on gradients or inspired by the neural networks theory (heuristical learning strategies) to determine its parameters (fuzzy sets and fuzzy rules) through the patterns processing (input and output)”.

A neuro-fuzzy system can be interpreted as a set of fuzzy rules. This system can be total created from input output data or initialized with the à priori knowledge in the same way of fuzzy rules. The resultant system by fusing fuzzy systems and neural networks has as advantages of learning through patterns and the easy interpretation of its functionality.

There are several different ways to develop hybrid neuro-fuzzy systems, therefore, being a recent research subject, each researcher has defined its own particular models. These models are similar in its essence, but they present basic differences.

Many types of neuro-fuzzy systems are represented by neural networks that implement logical functions. This is not necessary for the application of a learning algorithm in a fuzzy system, however the representation through a neural network is more convenient because it allows us to visualize the flow of data through the system and the error signals that are used to update its parameters. The additional benefit is to allow the comparison of the different models and visualize its structural differences. There are several neuro-fuzzy architectures including:

- *Fuzzy Adaptive Learning Control Network*

  (FALCON) C. T. Lin and C. S. Lee [25];
- *Adaptive Network based Fuzzy Inference System*

  (ANFIS) R. R. Jang [26];
- *Generalized Approximate Reasoning based Intelligence Control*

  (GARIC) H. Berenji [27]:
- *Neuronal Fuzzy Controller*

  (NEFCON) D. Nauck & Kruse [28];
- *Fuzzy Inference and Neural Network in Fuzzy Inference Software*

  (FINEST) Tano, Oyama and Arnould [29];
- *Fuzzy Net*

  (FUN) S. Sulzberger, N. Tschichold and S. Vestli [30];
- *Self Constructing Neural Fuzzy Inference Network*

  (SONFIN) Juang and Lin[31].
- *Fuzzy Neural Network*

  (NFN) Figueiredo and Gomide [32];
- *Dynamic/Evolving Fuzzy Neural Network*

  (EFuNN and dmEFuNN) Kasabov and Song [33].

M. Algorithm Motor, Sensor & AUAV: DsPic33 PWM Generator Function

(The following is a test version algorithm for example purposes and was developed for propagation in AMBOA Ver. 3.)

```
#include <stdio.h>
#include <stdlib.h>
#include "p33FJ12MC201.h"
#include <float.h>
#include <i2c.h>
#include <I2CSlaveDrv.h>
#include <Generic.h>
#include <delay.h>
#include <reset.h>
#include <stdbool.h>
/* Configuration Bit Settings */
//_FOSCSEL(FNOSC_FRC)
//_FOSC(FCKSM_CSECMD & OSCIOFNC_ON)
//_FWDT(FWDTEN_OFF)
//_FPOR(FPWRT_PWR128)
//_FICD(ICS_PGD2 & JTAGEN_OFF)
// Confiuration Register Settings
// Internal FRC Oscillator
_FOSCSEL(FNOSC_FRC);            // FRC Oscillator
_FOSC(FCKSM_CSECMD & OSCIOFNC_OFF  & POSCMD_NONE);
        // Clock Switching is enabled and Fail Safe Clock Monitor is disabled
        // OSC2 Pin Function: OSC2 is Clock Output
        // Primary Oscillator Mode: Disabled

_FWDT(FWDTEN_OFF);          // Watchdog Timer Enabled/disabled by user software
void init_PWM(void);
unsigned char RAMBuffer[256];       //RAM area which will work as EEPROM for Master I2C
device
unsigned char *RAMPtr;                  //Pointer to RAM memory locations
```

```
struct FlagType Flag;
void __attribute__((interrupt,no_auto_psv)) _SI2C1Interrupt(void)
{
	unsigned char Temp;  //used for dummy read

	if((I2C1STATbits.R_W == 0)&&(I2C1STATbits.D_A == 0))	//Address matched
		{
			Temp = I2C1RCV;		//dummy read
			Flag.AddrFlag = 1;	//next byte will be address
		}
	else if((I2C1STATbits.R_W == 0)&&(I2C1STATbits.D_A == 1)) //check for data
		{
			if(Flag.AddrFlag)
			{
				Flag.AddrFlag = 0;
				Flag.DataFlag = 1;	//next byte is data
				RAMPtr = RAMPtr + I2C1RCV;
				#if defined(USE_I2C_Clock_Stretch)
					I2C1CONbits.SCLREL = 1;	//Release SCL1 line
				#endif
			}
			else if(Flag.DataFlag)
			{
				*RAMPtr = (unsigned char)I2C1RCV;// store data into RAM
				Flag.AddrFlag = 0;//end of tx
				Flag.DataFlag = 0;
				RAMPtr = &RAMBuffer[0];	//reset the RAM pointer
				#if defined(USE_I2C_Clock_Stretch)
					I2C1CONbits.SCLREL = 1;	//Release SCL1 line
				#endif
			}
		}
	else if((I2C1STATbits.R_W == 1)&&(I2C1STATbits.D_A == 0))
```

```
        {
                Temp = I2C1RCV;
                I2C1TRN = *RAMPtr;          //Read data from RAM & send data to I2C master
device
                I2C1CONbits.SCLREL = 1;  //Release SCL1 line
                while(I2C1STATbits.TBF);//Wait till all
                RAMPtr = &RAMBuffer[0];  //reset the RAM pointer
        }
        _SI2C1IF = 0; //clear I2C1 Slave interrupt flag
}
main()
{       Init I2C1 Bus*/
        #if !defined(USE_I2C_Clock_Stretch)
                I2C1CON = 0x8000;  //Enable I2C1 module
        #else
                I2C1CON = 0x9040;  //Enable I2C1 module, enable clock stretching
        #endif
        I2C1ADD = 0x50      // 7-bit I2C slave address must be initialised here.
        IFS1=0;
        RAMPtr = &RAMBuffer[0];
//set the RAM pointer and points to beginning of RAMBuffer
        Flag.AddrFlag = 0;    //Initlize AddFlag
        Flag.DataFlag = 0;    //Initlize DataFlag
        _SI2C1IE = 1;
      I2C1CONbits.IPMIEN =1 ;
      I2C1CONbits.SMEN =1;
      I2C1CONbits.GCEN =1;
      I2C1CONbits.STREN=1;
      I2C1CONbits.I2CEN =1;
   unsigned int Duty1a ; /* unsigned int is 16bit register, 0 t0 65535*/
   unsigned int Duty2a ; /* float 32 bit ; double 32 bit ; long double 64 bit */
   unsigned int Duty1b ;
   double  F1x ;
```

```
   double F2x ;
   double F3x;
   double  F4x;
/* Configuration register FPOR */
/* High and Low switches set to active-high state */
//_FPOR(RST_PWMPIN & PWMxH_ACT_HI & PWMxL_ACT_HI)
/* PWM time base operates in a Free Running mode */
P1TCONbits.PTMOD = 0b00;
/* PWM time base input clock period is TCY (1:1 prescale) */
/* PWM time base output post scale is 1:1 */
P1TCONbits.PTCKPS = 0b00;
P1TCONbits.PTOPS = 0b00;
/* choose PWM time period based on input clock selected - Refer to Equation 14-1 */
/* PWM switching frequency is 20 kHz (7.37Mhz),  FCY is 20 MHz */
P2TCONbits.PTMOD = 0b00;  /* PTMOD<1:0>: PWM Time Base Mode Select bits */
P2TCONbits.PTCKPS = 0b10; /* PTCKPS<1:0>: PWM Time Base Input Clock Prescale
Select bits */
P2TCONbits.PTOPS = 0b00;  /* PTOPS<3:0>: PWM Time Base Output Postscale Select bits
*/
/*for PTMOD 00 or 01 is used free running counter mode and the register values are : */
/*  PxTPER= ((FCY)/(Fpwm*PxTMR Prescaler))-1 */
/* Fpwm= ((FCY)/((PxTPER -1)*PxTMR Prescaler))*/
/*for PTMOD 10 or 11 is used UP/Down mode and the register values are :*/
/*  PxTPER= ((FCY)/(Fpwm*PxTMR Prescaler*2))-1 */
/* Fpwm= ((FCY)/((PxTPER -1)*PxTMR Prescaler*2)) */
/* la rel;azione giusta per il Dspic33FJ12MC201 e`:*/
/* Fpwm= ((FCY)/((PxTPER -1)*PxTMR Prescaler*2)) */
/*  PxTPER= ((FCY)/(Fpwm*PxTMR Prescaler*2))-1 */
/* dove FCY = 7.37 MHz*/
P1TPER = 77;  /* 77 should be approx 47MHz */
P2TPER = 4605 ;  /* Fpwm approx 50 Hz*/
/* PWM I/O pairs 1 to 3 are in complementary mode */
/* PWM pins are enabled for PWM output */
```

```
PWM1CON1bits.PMOD1 = 0; /*PWM channel 1*/
PWM1CON1bits.PMOD2 = 0;
PWM1CON1bits.PEN1H = 1;
PWM1CON1bits.PEN2H = 1;
PWM1CON1bits.PEN1L = 1;
PWM1CON1bits.PEN2L = 1;
/* Immediate update of PWM enabled */
PWM1CON2bits.IUE = 1;
/* Clock period for Dead Time Unit A is TcY  */
/* Clock period for Dead Time Unit B is TcY */
P1DTCON1bits.DTAPS = 0b00; /*00 means ty=0*/
P1DTCON1bits.DTBPS = 0b00;
P1DTCON1bits.DTA = 0;   /* Dead time value for Dead Time Unit A */
P1DTCON1bits.DTB = 0;  /* Dead time value for Dead Time Unit B */
/* Dead Time Unit selection for PWM signals */
/* Dead Time Unit A selected for PWM active transitions */
/* Dead Time Unit B selected for PWM inactive transitions */
P1DTCON2bits.DTS2A = 0;
P1DTCON2bits.DTS1A = 0;
P1DTCON2bits.DTS2I = 1;
P1DTCON2bits.DTS1I = 1;
/* PWM I/O pin controlled by PWM Generator */
P1OVDCONbits.POVD2H = 1;
P1OVDCONbits.POVD1H = 1;
P1OVDCONbits.POVD2L = 1;
P1OVDCONbits.POVD1L = 1;
//  PWM channel 2///
PWM2CON1bits.PMOD1 = 0;
PWM2CON1bits.PEN1H = 0;
PWM2CON1bits.PEN1L = 0;
PWM2CON2bits.IUE = 0;
P2DTCON1bits.DTAPS = 0b00;
P2DTCON1bits.DTBPS = 0b00;
```

```
P2DTCON1bits.DTA = 0;
P2DTCON1bits.DTB = 0;
P2DTCON2bits.DTS1A = 0;
P2DTCON2bits.DTS1I = 0;
P2OVDCONbits.POVD1H = 0;
P2OVDCONbits.POVD1L = 0;
        unsigned int i;
        // Configure Oscillator to operate the device at 40Mhz
        // Fosc= Fin*M/(N1*N2), Fcy=Fosc/2
        // Fosc= 7.37*43/(2*2)=80Mhz for 7.37 input clock
        PLLFBD=41;                              // M=43
        CLKDIVbits.PLLPOST=0;           // N1=2
        CLKDIVbits.PLLPRE=0;            // N2=2
        OSCTUN=0;                               // Tune FRC oscillator, if FRC is used
        RCONbits.SWDTEN=0; // Disable Watch Dog Timer
        // Clock switch to incorporate PLL
        __builtin_write_OSCCONH(0x01);          // Initiate Clock Switch to
                                                // FRC with PLL (NOSC=0b001)
        __builtin_write_OSCCONL(0x01);          // Start clock switching
        while (OSCCONbits.COSC != 0b001);       // Wait for Clock switch to occur
        // Wait for PLL to lock
        while(OSCCONbits.LOCK!=1);              // Now PLL is ready
        for(i = 0;i<256;i++)
        {
                RAMBuffer[i] = i;       //Initlize RAMBuffer with some value
                                                //in case MasterI2C device wants to read
                                                //before it writes to it.
        }
while(1){
// _SI2C1Interrupt();
//SCLREL
/* Initialize duty cycle values for PWM1, PWM2 and PWM3 signals */
/* The PxTMR resolution is TCY, and the PxDCy resolution is TCY/2 */
```

```
/* for 1:1 prescaler selection*/
/* PxCDy = (Ton*2)/ (T * PxTPER)*/
/* F2x=(0.0000133)*F1x+0.0015 is the control function for HS-125MG Servo Motor*/
/* where F1x is the servo angle that should be in the range [-45deg,+45deg] */
/* for robust aileron control I have to define F1x in [-40deg;+40deg] */
/* F2x=(0.00001)*F1x+0.0015 is the control function for HS-55 MG Servo Motor */
/* and for the HS-322HD servo motor */
/* for robust rudder control I have to define F1x in [-80deg;+80deg]*/
/* for robust elevator control I have to define F1x in [-80deg;+80deg]*/
F1x= 45;
F2x=(13.3333)*F1x;
F3x= (F2x+ 1500)/(20000);
F4x= (2*F3x)*4605;
Duty1a = 77;  /* duty = 50 % */
Duty2a = 88; /* duty = 57.143 % */
Duty1b = (unsigned int)F4x; /* convertion from Float value to unsigned int */
P1DC1 = Duty1a;
P1DC2 = Duty2a;
P2DC1 = Duty1b;
P1TCONbits.PTEN = 1; /* pwm enable pin for channel 1*/
P2TCONbits.PTEN = 0; /* pwm enable pin for channel 2*/
}}
```

Table 9

Swarm Robot Motor Control	AUAV Powertrain Control
/* fuzzyTECH 6.00 Professional Edition */ /* License Number: FT 10004 27 HS*/ /* Code Generator: C Source Code */ /* Code Generation Date: Thu Dec 04 16:30:20 2014 */ /*- Fuzzy Logic System: SWARM_AV */ /*Performance Optimization Capabilities (Memory): 0 Bytes */	/*fuzzyTECH 6.00 Professional Edition */ /* License Number: FT 10004 27 HS */ /* Code Generator: C Source Code /* Code Generation Date: Thu Dec 04 13:29:11 2014 */ /*Fuzzy Logic System: MOTOR_SI /*Performance Optimization Capabilities (Memory): 0 Bytes*/

/*Performance Optimization Capabilities (Runtime): 0 Points */
/* (c) 1991-2012 INFORM GmbH, Pascalstr. 23, 52076 Aachen, Germany */
#define PROFESSIONAL
#define FTLIBC16
#include "ftlibc.h"
#define FUZZYDEFINED
#define FLAGSDEFINED
#include "SWARM_AV.h"
static FUZZY crispio[2+2];
static FUZZY fuzvals[6+6+0];
static double dcvs[2+2];
double * const pcvswarm_av = dcvs;
static const FUZZY tpts[24] = {
0x0000, 0x0000, 0x051F, 0x10FA,
0x0798, 0x0CCE, 0x0CCE, 0x147B,
0x1146, 0x3333, 0xFFFF, 0xFFFF,
0x0000, 0x0000, 0x051F, 0x1102,
0x07B1, 0x0CDE, 0x0CDE, 0x147B,
0x1102, 0x3333, 0xFFFF, 0xFFFF};
static const FUZZY xcom[6] = {
0x0000, 0x4666, 0x7311,
0x0000, 0x4666, 0x7333};
static const FUZZY weights[3] = {
0xFFFF, 0xFFFF, 0xFFB3};
static const BYTE rt0[75] = {
0x01, 0x02, 0x03, 0x80, 0x06, 0x80, 0x09,
0x01, 0x02, 0x04, 0x20, 0x07, 0x60, 0x09,
0x01, 0x02, 0x05, 0x20, 0x07, 0x20, 0x09,
0x01, 0x02, 0x03, 0x60, 0x06, 0x20, 0x0A,
	/*Performance Optimization Capabilities (Runtime): 0 Points */
	/* (c) 1991-2012 INFORM GmbH, Pascalstr. 23, 52076 Aachen, Germany */
	#define PROFESSIONAL
	#define FTLIBC16
	#include "ftlibc.h"
	#define FUZZYDEFINED
	#define FLAGSDEFINED
	#include "MOTOR_SI.h"
	static FUZZY crispio[3+1];
	static FUZZY fuzvals[9+3+0];
	static double dcvs[3+1];
	double * const pcvmotor_si = dcvs;
	static const FUZZY tpts[40] = {
	0x0000, 0x0000, 0x3333, 0x8000,
	0x4000, 0x7333, 0x8CCC, 0xBFFF,
	0x8000, 0xCCCC, 0xFFFF, 0xFFFF,
	0x0000, 0x0000, 0x0026, 0x8000,
	0x4666, 0x9333, 0x9333, 0xB999,
	0x0000, 0x0000, 0x6CCC, 0x0000, 0xFF8C, 0xFF66, 0xFFFF, 0xFFFF, 0x0000, 0x0000, 0x3333, 0x6666, 0x3315, 0x6666, 0x9999, 0xCCCC, 0x9973, 0xCCCC, 0xFFFF, 0xFFFF};
	static const FUZZY xcom[3] = {
	0x0000, 0x4AA4, 0xFFFF};
	static const BYTE rt0[186] = {
	0x02, 0x01, 0x03, 0x06, 0x80, 0x0B, 0x02, 0x02, 0x03, 0x07, 0x0D, 0x0A, 0x80, 0x0B,
	0x02, 0x02, 0x03, 0x08, 0x20, 0x0A, 0x80, 0x0B, 0x02, 0x01, 0x04, 0x06, 0x80, 0x0B,

```
  0x01, 0x04, 0x04, 0x40, 0x06, 0x40, 0x07,
0x40, 0x09, 0x40, 0x0A,
  0x01, 0x04, 0x05, 0x20, 0x06, 0x60, 0x07,
0x60, 0x09, 0x20, 0x0A,
  0x01, 0x02, 0x03, 0x60, 0x06, 0x20,
0x0A,
  0x01, 0x04, 0x04, 0x60, 0x06, 0x20, 0x07,
0x20, 0x09, 0x60, 0x0A,
  0x01, 0x02, 0x05, 0x80, 0x08, 0x80,
0x0B};
static const FRAT frat0[6] = {
  0x0015, 0x0000, 0x001D, 0x0001,
0x0019, 0x0002};
static const FUZZY BVRCode[8] = {
  0x0000, 0xFFFF,
  0x0000, 0xFFFF,
  0x0000, 0xFFFF,
  0x0000, 0xFFFF};
static const double BVRShell[12] = {
  0, 5, 0.0001,
  0, 5, 0.0001,
  0, 100, 0.002,
  0, 100, 0.002};
FLAGS swarm_av(void) {
  for (fuzptr = &fuzvals[0];
      fuzptr <= &fuzvals[11];
      *fuzptr++ = 0);
  crispio[0] =
BVScaleShell2Code(&BVRCode[0*2],
&BVRShell[0*3], dcvs[0],
BVRCode[0*2+1]<MAXBVRANGE,
MAXBVRANGE);
```

```
  0x02, 0x02, 0x04, 0x07, 0x80, 0x0A,
0x13, 0x0B, 0x02, 0x02, 0x04, 0x08, 0x80,
0x09, 0x13, 0x0A, 0x02, 0x02, 0x05, 0x06,
0x80, 0x0A, 0x0D, 0x0B, 0x02, 0x02, 0x05,
0x07, 0x80, 0x09, 0x20, 0x0A, 0x02, 0x01,
0x05, 0x08, 0x80, 0x09, 0x02, 0x01, 0x03,
0x06, 0x80, 0x0B, 0x02, 0x02, 0x03, 0x07,
0x0D, 0x0A, 0x80, 0x0B, 0x02, 0x02, 0x03,
0x08, 0x0D, 0x0A, 0x80, 0x0B, 0x02, 0x02,
0x04, 0x06, 0x20, 0x09, 0x80, 0x0A, 0x02,
0x01, 0x04, 0x07, 0x80, 0x09, 0x02, 0x01,
0x04, 0x08, 0x80, 0x09, 0x02, 0x01, 0x05,
0x06, 0x80, 0x0A, 0x02, 0x01, 0x05, 0x07,
0x80, 0x09, 0x02, 0x01, 0x05, 0x08, 0x80,
0x09,
  0x02, 0x01, 0x03, 0x06, 0x80, 0x0B, 0x02,
0x02, 0x03, 0x07, 0x80, 0x0A, 0x20, 0x0B,
  0x02, 0x02, 0x03, 0x08, 0x80, 0x0A,
0x0D, 0x0B, 0x02, 0x01, 0x04, 0x06, 0x80,
0x0A,
  0x02, 0x01, 0x04, 0x07, 0x80, 0x09, 0x02,
0x01, 0x04, 0x08, 0x80, 0x09, 0x02, 0x02,
0x05, 0x06, 0x80, 0x09, 0x1A, 0x0A, 0x02,
0x01, 0x05, 0x07, 0x80, 0x09, 0x02, 0x01,
0x05, 0x08, 0x80, 0x09};
static const FRAT frat0[6] = {
  0x0042, 0x0000, 0x003C, 0x0001,
0x003C, 0x0002};
static const FUZZY BVRCode[8] = {
  0x0000, 0xFFFF,   0x0000, 0xFFFF,
  0x0000, 0xFFFF,   0x0000, 0xFFFF};
static const double BVRShell[12] = {
  -10, 10, 0.0005,
```

```
  crispio[1] = BVScaleShell2Code(&BVRCode[1*2], &BVRShell[1*3], dcvs[1], BVRCode[1*2+1]<MAXBVRANGE, MAXBVRANGE);
  fuzptr = (PFUZZY) fuzvals;
  tpptr  = (PFUZZY) tpts;
  crisp = crispio[0];
  bTNum = 3;
  flms();
  crisp = crispio[1];
  bTNum = 3;
  flms();
  fuzptr = (PFUZZY) fuzvals;
  usNumber = 3;
  fratptr  = (PFRAT)  frat0;
  rtptr   = (PFTBYTE) rt0;
  iMFMin(); /* Max-Min + FAM */
  invalidflags = 0;
  fuzptr      = &fuzvals[6];
  xcomptr      = (PFUZZY) xcom;
  wptr        = (PFUZZY) weights;

  crispio[2] = 0x148;
  bTNum  = 3;
  defuzz = &crispio[2];
  dwCoXX();
  crispio[3] = 0x148;
  bTNum  = 3;
  defuzz = &crispio[3];
  com();
```

```
  -10, 10, 0.0005,
  -25, 25, 0.001,
  0, 100, 0.002};
FLAGS motor_si(void) {
  for (fuzptr = &fuzvals[0];
       fuzptr <= &fuzvals[11];
       *fuzptr++ = 0);
  crispio[0] = BVScaleShell2Code(&BVRCode[0*2], &BVRShell[0*3], dcvs[0], BVRCode[0*2+1]<MAXBVRANGE, MAXBVRANGE);
  crispio[1] = BVScaleShell2Code(&BVRCode[1*2], &BVRShell[1*3], dcvs[1], BVRCode[1*2+1]<MAXBVRANGE, MAXBVRANGE);
  crispio[2] = BVScaleShell2Code(&BVRCode[2*2], &BVRShell[2*3], dcvs[2], BVRCode[2*2+1]<MAXBVRANGE, MAXBVRANGE);
    fuzptr = (PFUZZY) fuzvals;
  tpptr  = (PFUZZY) tpts;
  crisp = crispio[0];
  bTNum = 3;
  flms();
  crisp = crispio[1];
  bTNum = 1;
  flms();
  bTNum = 1;
  flms();
  fLinear();
```

```
  dcvs[2] = BVScaleCode2Shell(&BVRCode[2*2], &BVRShell[2*3], crispio[2]);
  dcvs[3] = BVScaleCode2Shell(&BVRCode[3*2], &BVRShell[3*3], crispio[3]);
  return invalidflags;
}
void initswarm_av(void) {
  /* check fuzzyTECH C Runtime Library version */
  ftcr200805();
}
/*
| Memory   |   RAM   |   ROM   |
| Fuzzy Logic System | 64 (0040H) | 269 (010DH)|
| Total   |   64 (0040H) |  269 (010DH) |
*/
```

```
  tpptr += 8;
  crisp = crispio[2];
  bTNum = 3;
  flms();
  fuzptr = (PFUZZY) fuzvals;
  usNumber = 3;
  fratptr  = (PFRAT)  frat0;
  rtptr   = (PFTBYTE) rt0;
  iMFMin(); /* Max-Min + FAM */
  invalidflags = 0;
  fuzptr      = &fuzvals[9];
  xcomptr     = (PFUZZY) xcom;
  crispio[3] = 0x148;
  bTNum  = 3;
  defuzz = &crispio[3];
  com();
  dcvs[3] = BVScaleCode2Shell(&BVRCode[3*2], &BVRShell[3*3], crispio[3]);
  return invalidflags;
}
void initmotor_si(void) {
  /* check fuzzyTECH C Runtime Library version */
  ftcr200805();
}
/*| Memory |  RAM   |  ROM    |
| Fuzzy Logic System |  64 (0040H) |  400 (0190H) |
| Total    |  64 (0040H) | 400 (0190H)| */
```

N. ANCILLARY RESULTS FROM THE THESIS WORK

The following annexure, though not specifically relating to the construction of the AMBOA robot system, outlines two derivatives of the thesis research as examples of some aspects of the sensor array capabilities. The sensory system as developed has led to the evolution of other non-specific yet useable applications and these applications n turn have produced reliable data relative to the thesis.

Intelligent "street lighting", along with its immense energy saving potential, relies upon many factors, not least, the importance of maintaining useable levels of light for both vehicles and pedestrian traffic. One element in the establishment of such a regime is the development of sensory equipment capable of vehicle and human detection with a negligible degree of error. The paper proposes a hybrid long range passive sensory system based on both static (IR Photodiode) and non-static (PIR) sensors.

With the development of the street light came also the accompanying energy consumption, and being an indispensable infrastructure much research is devoted to smart lighting systems and control. Efficient management, energy saving and safety within the lighting system are factors to take into account. The advent of the WSN, (wireless sensory network) promise many variants for solutions to street lighting efficiencies, though this paper will deal specifically with the sensory aspects of the system.

Pyroelectric Infrared sensors (PIR) permit us to sense the motion of a hot body passing within and usually directionally across the range of the sensor. The range of the sensor is increased in normal circumstances with the introduction of a Fresnel lens which increases the range and detection angle, therefore amplifying the amount of IR received. The detection or viewing angle is generally from 90o through 180o with a standard range of 6 to 12 meters, rendering the PIR very useful in common motion detection applications such as security where used to detect whether a human has crossed into or out of the sensors range. Static infrared sensors however allow us to measure either by digital or photovoltaic methods the average radiation within an environment, or alternatively being emitted from a specific object.

Predominantly the PIR sensor has been utilized also in street lighting scenarios and street surveillance cameras to set off a series of functions according to predetermined rule blocks, however the sensors used provide insufficient prior knowledge (event trigger) to the device due to the short range limitations of the sensors.

In order to obtain sufficient prior knowledge of an event trigger the detection range must be far greater than is currently available. Long range sensors exist within the marketplace, combinations of PIR and Microwave technologies, however they are prohibitively expensive and bulky solutions having a form factor around 150mm square and due to internal mirror construction, require individual adjustment for each installation. At the same time it is envisaged that it will not be necessary for installation of the proposed system at each pole of the street lighting array, but one every 100 meters dependant on existing specific pole separation.

Public safety remains the prevalent issue when the automatic brightening and dimming of lights is involved with a critical factor being the temporary blinding of a driver if lights are activated to full brightness in a very short time frame, or in the alternative removal of light at inappropriate times.

Reduction in erroneous errors is also of prime concern as the PIR detector is prone to activation from many sources, to name a few, the non-static movement of trees in the wind, various animals moving into the range of the sensors and even a sudden warm breeze may activate the sensors.

Intelligent Power Management Device

Street Lighting Control Incorporating Long Range Static and Non-Static Hybrid Infrared Detection System

The system model consists of the following parts being the PIR sensor, one passive IR photodiode, zoom lens, amplification and comparator circuitry (PIR and Passive IR) and the author has opted to utilize fuzzy logic methods for vehicle and human identification and error reduction due to the variance in the nature of received signals. The sensor prototype circuit includes a PCB mounted Dual PIR with a vertical topography Fig.59, as opposed to the horizontal topography used in standard motion detector applications. Together with a fixed IR sensor with λ of 700nm to 1100nm and spectral peak of 900nm, the model is able to capture moving vehicles or pedestrian traffic. Due to the extension of the angle of detection and the method of sensor signal amplification the system become bi-directional, enabling real time assessment of approaching or departing movement.

Preliminary observations have been performed with the use of an 8X zoom lens with a 9º field of view, at 100 meter distance this represents 1.6 percent of a 1X area, giving the field of view as a cross section of road and pedestrian path only at approximately 100 meters. It is important to note that plastic lens give improved responsivity due to the IR dispersion qualities of glass.

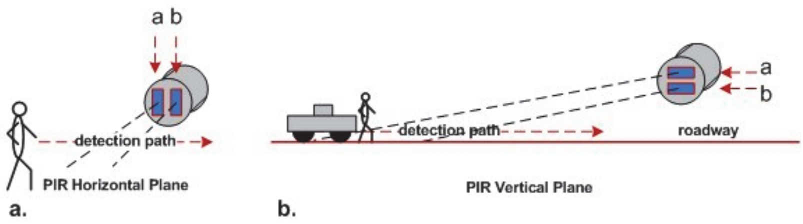


Fig. 59: Standard PIR motion detection and b. Vertical plane used within the model. Not to scale

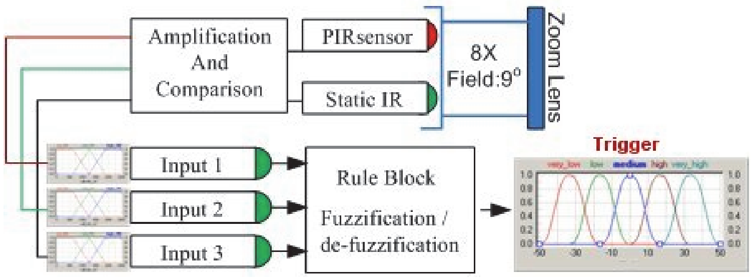


Fig. 60: System model

Considerations

When tuning the PIR sensor with the IR Photodiode it is necessary to apply an identical infrared source. This will ensure that both sensors produce a similar photovoltaic output from the amplifier, which is necessary from various aspects. Firstly, it will correctly identify because both sensors receive approximately the same view from the zoom, irrespective that the IR Photodiode will receive a static view and the PIR will transfer its view from the a) substrate to the b) substrate or vise verse. Fig.61, below shows the configuration of the prototype board for easier understanding.

Fig. 61 Hybrid sensor board and off the shelf zoom 8X Field 9°

Responsivity

Being in effect, two small flat plate capacitors the PIR have a typical capacitance of 30pF. Insulation resistance is 5x1012 Ohms. PIR's are constructed using either a JFET source follower, for voltage mode or a trans-impedance amplifier to obtain current mode. The simplified equation found in (23), allows estimation of the expected signal from a common PIR sensor. Where: I = from 0.5 to 1 micro-ampere per watt, R is the load or feedback resistor and C is the detector capacitance: Voltage mode = 30pF or Current Mode using stray feedback capacitance of around 0.03pF [34].

Further analysis of the Pyroelectric substrates, indicating the wavelength dependency of the voltage responsivity for different materials may be located at [35], though the following is adequate where amplification through transimpedence is utilized.

$$I * \left(\frac{R}{\sqrt{1+(2\pi fRC)^2}}\right) \tag{23}$$

Wavelength amplification and comparison

To convert the photodiode current to voltage the prototype incorporates high sensitivity transimpedance amplifiers with a gain of around 10000, sufficient to amplify the received signals to the millivolt range. Output voltage as a function of incident light is linear over 7-9 orders of magnitude, and electrical response is dependent on the response of the detectors due to incident radiation across their substrates [36][37]. The circuitry in Fig.62, enables both amplification and trigger definition, (a – b) or (b – a) of the two PIR substrates allowing bi-directional knowledge of a triggered event. The modified PIR sensor, necessary for correct operation of the device may be found in detail at [38].

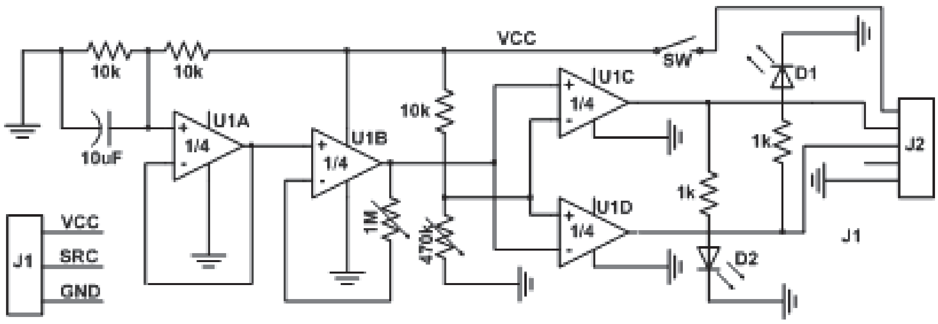


Fig.62 Amplification and comparator circuit

Indications of direction, where forward motion is indicated with a positive first half cycle response and reverse motion is indicated with a negative first half cycle response, determines the appropriate output from the microprocessor and peak to peak timing allows accurate calculation of velocity as in Fig.63.

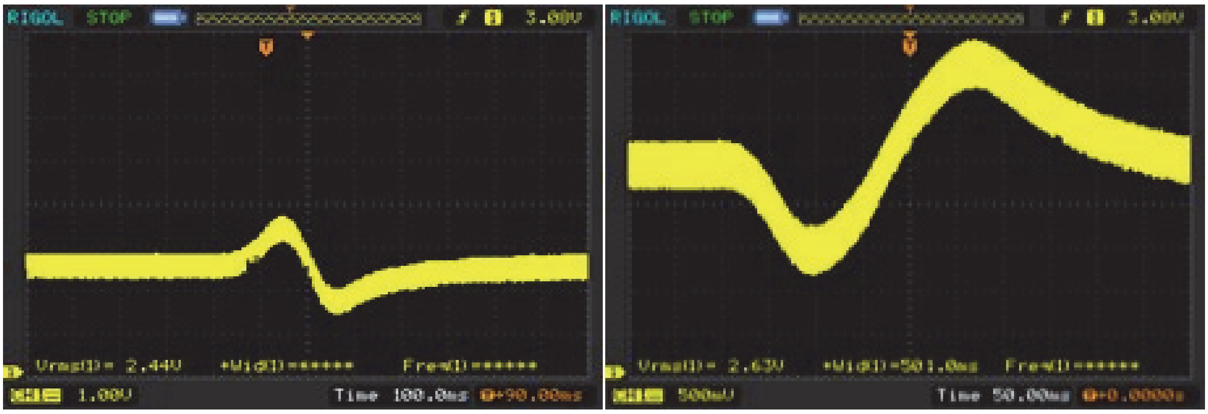


Fig. 63 Sensor activation a ~ b, (forward triggering), with positive first half cycle and b ~ a, (reverse triggering), with negative first half cycle.

The PIR sensor is essentially split into its two substrates and in this configuration allows bi-directional reading plus two readings of radiation sensed (a positive followed by a negative) and is mounted on the vertical axis as in Fig.59. The second IR sensor input is static and used as a comparison to make certain assumptions. For example:

1. A bird flies across the path of both sensors. The result could be that the PIR sensor triggers, producing a photovoltaic reading of 20mV, however the IR Sensors reading is negligible, therefore the system does not register a trigger response
2. A large tree is swaying in the breeze, The PIR registers a thermal change across its substrates triggering a lesser response than example 1, say 10mV, however, again the IR Sensor registers none, no trigger.
3. The PIR registers a vehicle across its substrates with an amplified signal of 50mV, however the registered signal has produced a (ba) result, the IR sensor also register a 50 mV signal, however the system will not trigger because a (ba) signal indicates a vehicle departing the area.
4. The PIR registers a vehicle across its substrates with an amplified signal of 50mV, the registered signal has produced a (ab) result, the IR sensor also registers a 50 mV signal, the system will trigger because an (ab) signal indicates a vehicle is approaching the area.

Fuzzy membership model

The scheme required three variable in each of the four input arrays, with an output array, (Trigger_Event) having five variables for more accurate result. The use of linear and triangular functions were utilized in line with a requirement for simplicity in modification and high speed computation. The resultant Rule Block (Table 10) consists of 405 individual rules enabling a suitably “smart” system. Three of the rules have been reproduced in (Table I) as an example of method used.

Table 10: Selection from rule block

if	and	and	and	operand	then
PIR_Seq_AB.high	PIR_Seq_BA.low	mV_Pos.med	IR_Static.high	=>	Trigger_Event.high
PIR_Seq_AB.low	PIR_Seq_BA.low	mV_Pos.low	IR_Static.high	=>	Trigger_Event.low
PIR_Seq_AB.low	PIR_Seq_BA.high	mV_Pos.high	IR_Static.med	=>	Trigger_Event.low

Four sets of functions, Fig.64, were created to express degrees of membership for the two sensors, having a membership from 0 to 1. The crisp values of the input functions are represented in millivolts in a range of 0mV to 100mV with an expected mean of 50mV. Currently with the completion of the latest prototype Fig.65, these original finding are proving to have less range with values from 0mV to 50mV indicating the system with its newer design is more evenly balanced across its substrates.

Reference Material: [34] to [38]

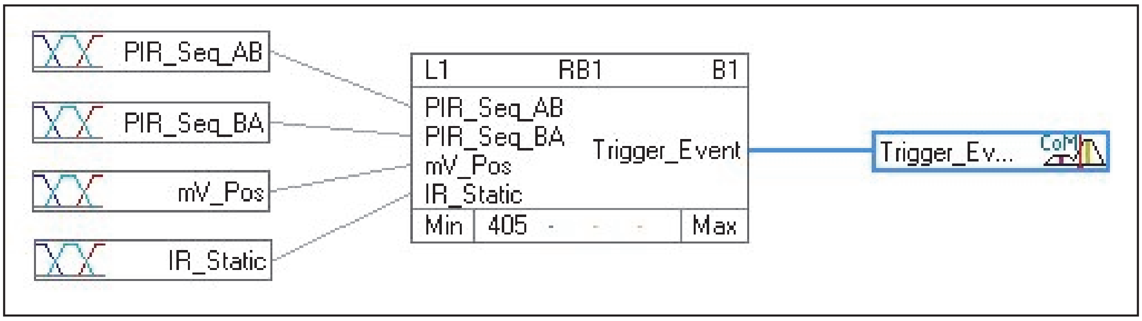


Fig.64. Fuzzification, de-fuzzification at the output block.

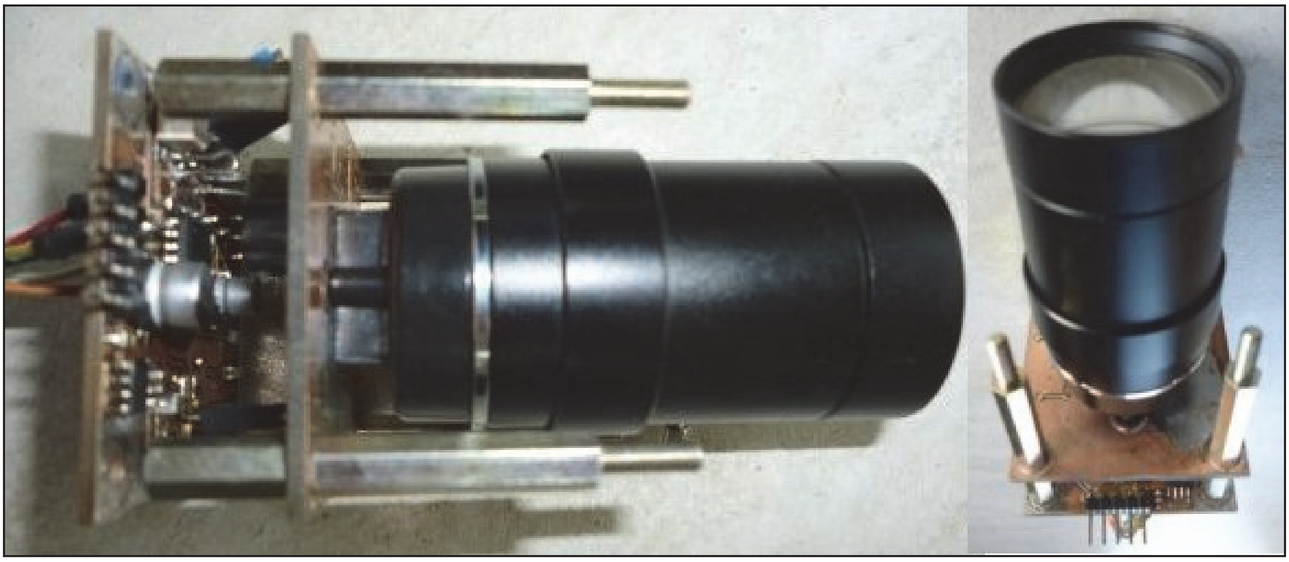


Fig.65 The most recent prototype displaying smaller form factor, advanced optics and an appreciatively increased sensitivity

Passive Human Tracking

A second and important derivative of the thesis research gleaned during the investigations of the thesis and the associated sensory capabilities.

A major goal in the field of robotics is the development of autonomous mobile robot agents capable of the passive following or tracking of humans within dynamic environments, simultaneously addressing problems of subject-selective following and also obstacle avoidance. To date the majority of human tracking methods assume a single mobile agent, a single human subject with little consideration to physical obstacles. In a dynamic environment we must assume and design with multiple agents, subjects and obstacles in mind. This paper therefore proposes a passive system consisting of a single pyroelectric sensor four spectral sensors and an appropriate obstacle avoidance method. Through measurement of the human emissions of near-infrared radiation in combination with other spectral wavelengths it is hypothesized that successful tracking may be achieved. At this stage sufficient testing for proof of concept has been achieved. A modified pyroelectric sensor achieves the tracking or following part of the system and a four band multispectral sensor determines constant on the fly identity of the selected subject. Converting those snapshot signals into voltage measurements we look to achieve adequate results without the need for non-passive tagging of the subject

The identification, tracking or following of human subjects is of great importance when humans and robots interact in any dynamic environment. Being task dependant they interact in many ways. Mapping robots when plotting an environment [39] are usually required to identify that part which is environment (static) and that dynamic part such as free moving objects, humans or animals or even plants swaying in the breeze and ensuring those do not become part of the map. The use of various wireless modules or tags [40] to enable precise tracking does not appear a feasible option unless the dynamic environment is closed such as in the case with patients or the elderly when the need to track location is vital and where the tagged subjects do not depart from a defined space.

Computer vision methods for human tracking [39,41,42] are many and promising in the detection of the human form, the facial recognition and mapping of the environment, however these attributes come at the high cost of camera equipment, the high computational load of mass image storage and the underlying requirement for robust algorithm filtering and recognition [43,44]. There are equally as many reasons for the requirement of human tracking robots as there are projects attempting to master the objective. It is clear that in the foreseeable future robots will engage with humans more and more and not every possibility can be immediately investigated or understood. We may have fully functional guide robots in museums for example where the humans are following the robot, yet the robot must have accurate positioning data of its followers in order to maintain a group formation, or surveillance robots whose sole objective is to identify and track the human subject. Other factory type robots may be allocated to a human worker with a requirement to follow and assist that worker in various tasks. These three examples simply serve to illustrate the differing technologies required to achieve the goal.

This paper separates these problems into three individual parts. The first being the following of the subject utilizing a one modified dual pyroelectric sensor, then the obstacle avoidance accounting for non-static objects and finally the subject identification technique. It is hypothesized that combining all three parts may achieve acceptable results. The remainder of this paper has been organized as follows. Section II describes the modified pyroelectric sensor architecture. Section III outlines the obstacle avoidance sensors chosen and section IV provides an overview of the multispectral snap-shot and initial results which forms the basis and conclusion for the paper.

Modified Pyrelectric Sensor

The single "dual pyroelectric sensor" has been converted from a simple motion detector, able to distinguish only temperature change across its band pass filter and substrates, to a bi-directional detector producing a primary and secondary signal across its band pass filter due to a partitioning of the sensor substrates and appropriate amplification and circuitry as in Fig.66, Due to these modifications first one and then the second pyroelectric substrate will produce voltage change allowing left and right directional detection of an infrared emitting body and in the case of a human being, those emissions in the spectral frequency of around 9 to 10μm. In a standard type motion detector a Fresnel lens is used to concentrate temperature emissions, providing a larger detection range of around 10 meters. The modified sensor in Fig.2, indicating the basic conversion, is devoid of a Fresnel lens reducing the effective range to approximately 1 to 2 meters. This distance is more appropriate for human following or tracking requirements.

For a more detailed paper concerning the operation of the modified pyroelectric sensor refer to "submitted for publication" [45].

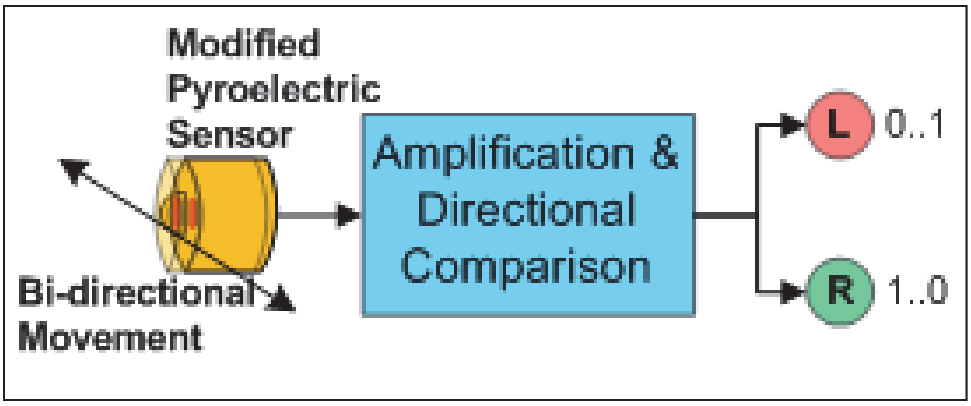


Fig.66 Bi-directional pyroelectric amplifier and comprator

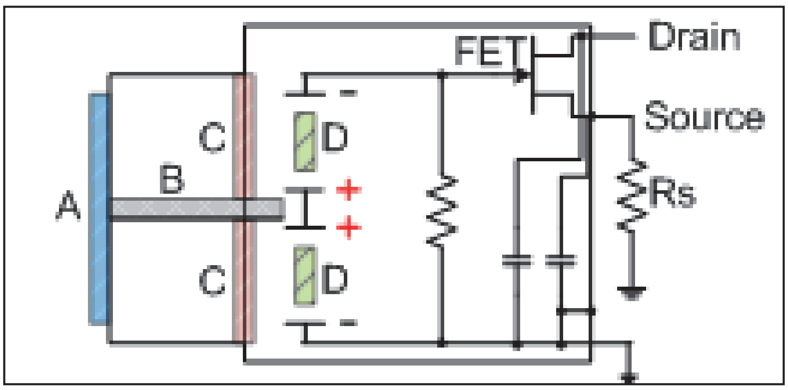


Fig.67 Modified pyroelectric sensor: a) glass window; b) mirrored partition; c) band-pass filters; d) pyroelectric substrates

When our robot is stationary, it responds much the same as a motion detector because the two substrates are configured such that one subtracts from the other. In the stationary position the sensor substrates are cancelled out by ambient light and our unit is effectively converted to a motion detector until such time as a subject's emission of infrared passes within two meters of its sensor. At this event the robot becomes mobile, reversing its role in that hereto before stationary it is now mobile and moving objects become virtually stationary. In this way we can follow the subject in much the same manner as a photo-trope robot will seek a light source.

Obstacle avoidance

This component of the system deals with obstacle avoidance and is a purely responsive element. In a dynamic environment where the goal is to pursue a predetermined subject, any number of non-static objects may hinder the path of the mobile robot and therefore neither the direction changes of the subject nor the occurrence of obstacles can be foreseen or evaluated. Therefore a Diffuse Reflectance Infrared Sensor Modules as in Fig.68, have been adopted for the purpose. There is no particular reason for selection of this sensor over another however the main criteria is that it be frequency tunable, making it less prone to noise disturbance or ambient infrared radiation which is a common problem for infrared detectors. For the uninitiated, this sensor uses the 74HC00 Quad 2-input NAND gate and its peripheral elements to compose a tunable frequency square-wave generator. The infrared emitter diode emits modulated infrared light at a certain frequency. Both the transmit frequency and the emission brightness are adjustable therefore it is possible to change the transmit power. The integrated infrared receiver module receives about 38Khz frequency of infrared light signal and other frequency bands of infrared light are filtered out.

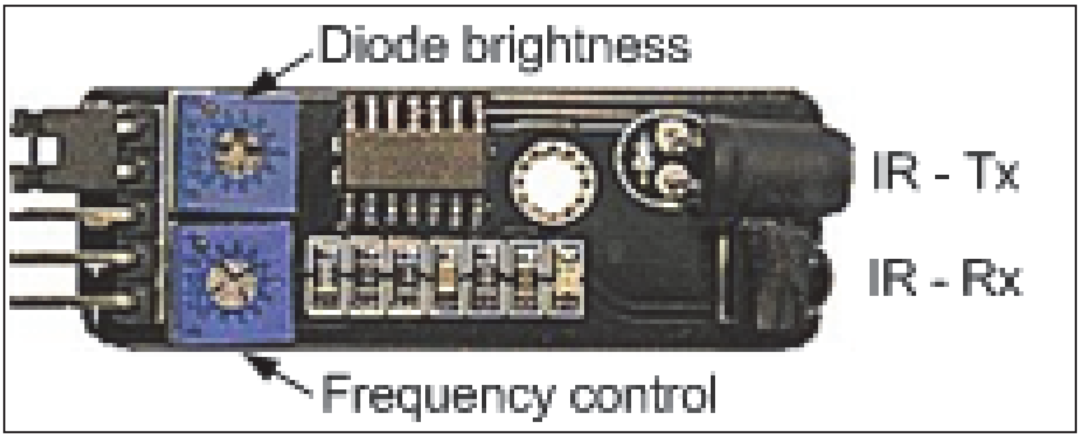


Fig.68 Diffuse reflectance infrared sensor module

So that the sensors may be useful to the system it is necessary to make appropriate observations. How many sensors are necessary for the mobile robot, to enable detection of an obstacle which may obstruct its path and what is the optimal “detection distance” to be attained on each sensor. A common and reliable configuration for a primarily forward moving robot, as in this system, uses two proximity sensors installed to the front and opposing sides of the robot. In this configuration it is possible to detect any obstacle that may obstruct the robot’s path, select and correct the new direction utilizing the four differing sensor output combinations by combining those output signals and creating a truth table where each of the four outputs can be associated with any combination of system action. In most instances a left or right movement, followed by a “continue forward” command will apply in line with the primary objective to maintain tracking of the subject. This can be demonstrated where the human subject traverses a corner in an arc like manner yet the mobile robot’s pyroelectric tracking will attempt to follow the subject via the shortest path as described in part II, tending to cut corners, and requiring constant adjustment by the proximity sensors as is depicted in Fig.69.

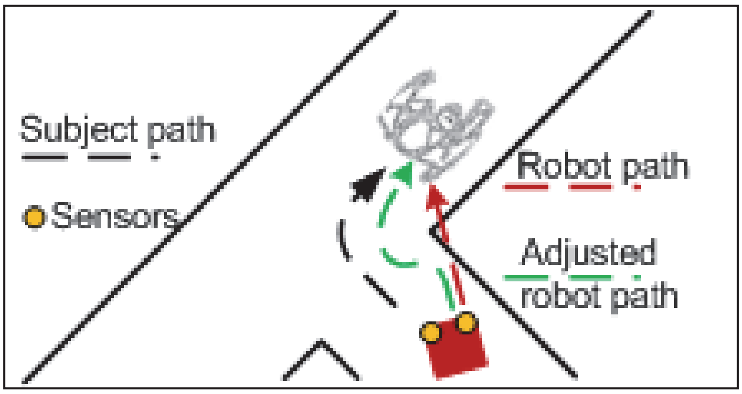


Fig.69 Example path following

To be able to avoid the collision between the robot and an obstacle, it is necessary to understand the distance the robot will need to stop, reverse or turn in its path. Pre-empting this system behavior is connected at least with three variables, the speed of the system control algorithm, the speed of the robot and the braking power or turning circle of the Robot. It is assumed initially that the tracking robot will maintain a constant speed behind the tracked subject which has been set at the average of a walking subject at 1 meter per second.
Final measurements for the realization of this part of the system have been attained in the laboratory however would exceed the allocated size of this paper. The final project shall utilize the following parameters. It is intended to use the Pic32 microcontroller at 80 MHz, controller unit status of the obstacle avoidance sensor every 50 milliseconds and to brake or turn the

system will require a maximum 50 milliseconds. Thus the allowance that the system with an allowance for error will require is 125 milliseconds between obstacle detection and reaction. Mobile robot speed set at 1 meter per second, the robot will move forward 12.5 cm before braking or turning. If we assume that the system will use 5cm to brake, it is therefore necessary to confirm an optimal solution is to fix the obstacle detection around 25 cm as in Fig.70 and 71.

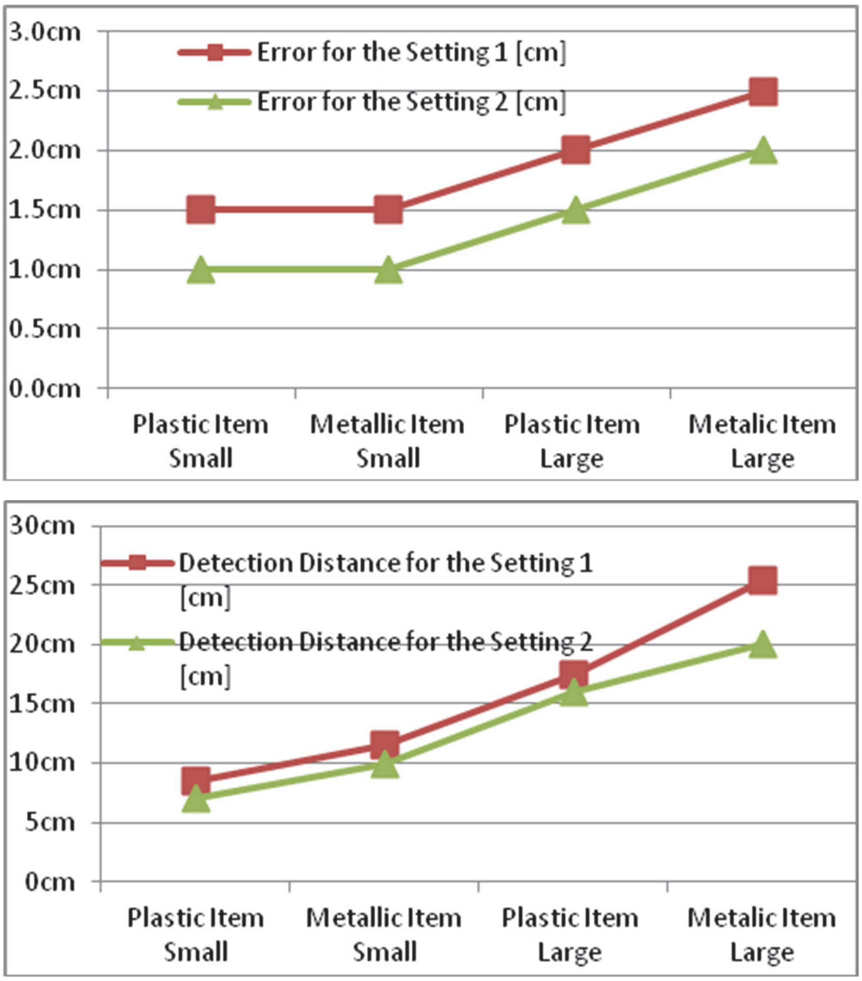


Fig.70 and 71. Laboratory results of obstacle avoidance sensors indicating optimal necessary avoidance settings

Four band multispectral snapshot

The Four Band Multispectral Snapshot should not be confused with Multispectral Imaging however the basic principle is similar and formed the basis for the author's speculation that sufficient information could be gleaned from the light spectrum emissions from humans to enable a tracking robot to successfully follow its subject, although photovoltaics and not imaging was to form the basis of experimentation.

References [46] and [47] explain how multi-spectral imaging allows us to capture scene information beyond the capabilities of RGB or grey-scale cameras. The wealth of data provided by multispectral sensors, especially with respect to the reflectance properties of objects can greatly facilitate further processing.

Similarly, multispectral snapshot as described here can allow us to some degree to distinguish between subjects without need for cumbersome algorithm filtering for recognition. Here we extract four bands of the spectrum from the ultraviolet to the near infrared using selected sensors, make an adjustment for ambient incident light, literally take a snapshot of the subject and greatly amplify the result.

Considerations for current mode operation

For our purposes it was necessary to obtain the largest possible amplification of the signal from the photo diode (PD). PD's of the type used consist of a very thin layer of pyroelectric substrate sensitive to light radiation and upon exposure to light frequencies from ultra violet through the whole spectrum exhibit temperature increases of fractions of degrees creating small electrical charges. When there is no light radiation the substrate cools and an opposite charge is created. Current mode amplification of the signal was selected where current to voltage conversion is obtained using trans-impedance amplification. In this case a suitable quad operational amplifier with adjustable feedback components as in Fig.72.

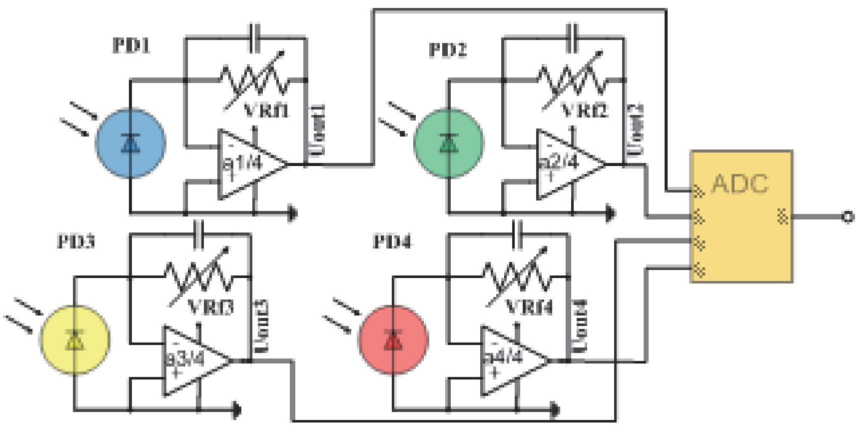


Fig.72 Adjustable quad-transimpedence amplifier

In this configuration we can expect signals of around 50mv to 150mV or more, dependent on the gain of the amplifier.

Current mode detectors operate between both the electrical and the thermal time constant with frequencies from 1 Hz up to more than 1 kHz. Current mode or voltage mode operation could be used however current mode offers a larger mV evaluation of the signal for our purposes as the electrical time constant in voltage mode can be changed only within a small range. The achievable gain of the signal in current mode is much higher and can be adjusted easily by changing the feedback resistor.

Photodiode selection

Initial selection of appropriate photodiodes (PD) was not critical with the exception that PD2 be in a range of 350nm to 700nm with a spectral peak of 550nm and that PD4 be in the range of 700nm to 1100nm with a peak sensitivity of 900nm or 9 to 10µm. PD1 to PD3 are equipped with infrared blocking filters and PD4 equipped with visible light blocking filter. PD1 and PD3 were selected at random in the lower and upper visible spectrum. Where necessary appropriate band filters were used to adjust peak spectral sensitivity of the photo detectors.

Considerations for the multispectral snapshot

The thermal response [48], of the detector due to incident radiation, the electrical time constant and the resulting signal is needed to ascertain an appropriate "snapshot" timeframe. The thermal time constant of the selected photodiodes is approximately 150ms.

In order to achieve the test results, a discarded SLR camera was used as it provided the necessary mechanisms without need for excessive modification. Following is the short list of the modifications. First the viewfinder prism was locked into an upright position and the aperture was locked fully open. The four sensor array was adhered to the negative plate so that it remained in a close to perfect focal length position. Finally the shutter speed of the camera was set to the setting higher than the thermal constant of the sensors which was 250ms.

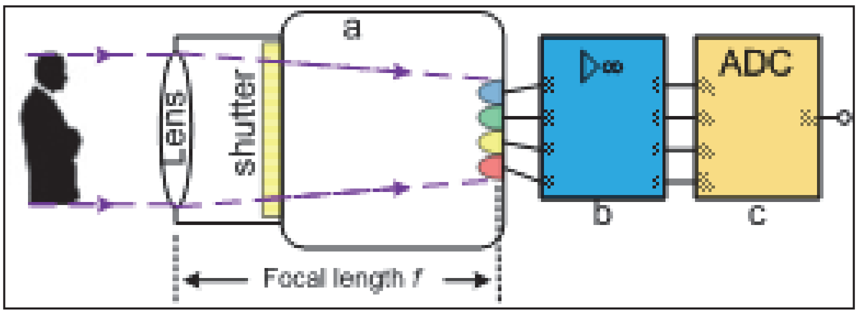
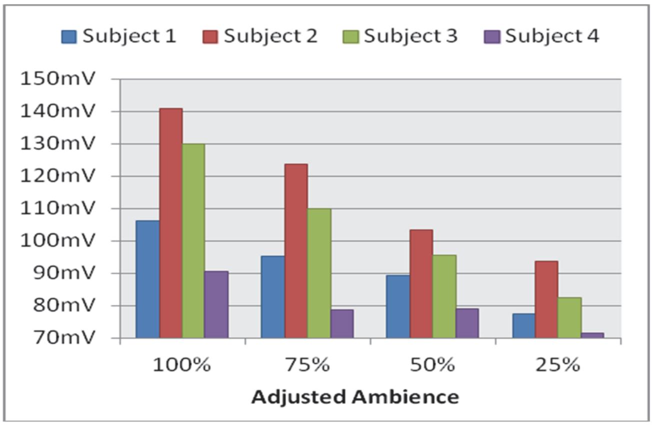


Fig.73 Testing apparatus: a) modified camera; b) high gain amplifier; c) analogue to digital converter

With the focal length adjustable on the camera lens it was a simple matter to set it at two meters distant in line with the operating parameters of the modified pyroelectric tracking sensor.

Four test subjects were selected of varying weight, gender and ethnicity. The tests were carried out with uniformly ambient lighting, reducing the ambient lighting source in three stages. The linearity of the results as shown in Fig.75, are encouraging as the primary goal is to be able to distinguish between subjects on the fly and through various lighting conditions.

Reference Material: [39] to [48]



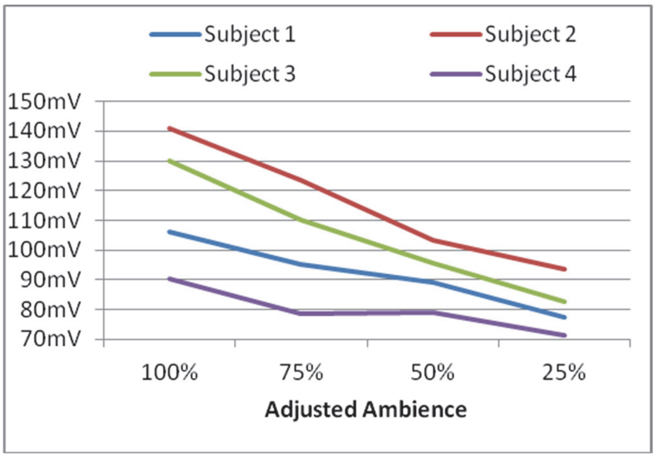


Fig.74 and 75. Test results using four subjects with a reduction of environmental ambience in three stages of 25%. All results were based on an averaged reading over the four sensors