RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Industrial Electronics and Electrical Engineering

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Doctoral Candidate Computerized Control of Electrical Technologies program

RESEARCH AND DEVELOPMENT OF OBSTACLE AVOIDANCE SYSTEMS FOR MOBILE ROBOTICS

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis will be defended at a public session on June, 20, 2016 at the Faculty of Power and Electrical Engineering of Riga Technical University, 12/1 Āzenes Street, Room 212 at 4:00 PM.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Leslie Robert Adrian …………………………….

Date: ………………………

The PhD thesis is divided in seven chapters and includes 77 figures, 10 tables, 22 equations, 55 cross references in literature, annotation in English and Latvian, introduction, table of contents and is written on 125 pages.

Annotation

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.

Significant drawbacks exist 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 one 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 formulae and 10 tables.

Contents

Subject Introduction

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 ensure 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 the 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.

Usually referenced as the spacial envelope (SE) of a stationary factory type robot, the author’s 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).

The author’s motivation for this particular type of robotics application stems from the investigations and writings of Grey Walter, W. (1910–1977). His robots were unique because, unlike the robotic creations that preceded them, they did not display a fixed behavior. 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 behavior was an early form of what we now call Artificial Life [1].

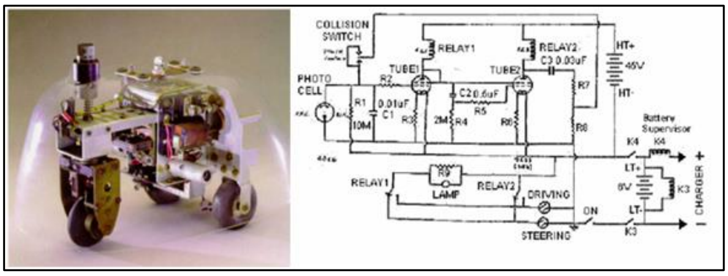

Fig.0. Walter Grey’s “Tortoise” and original circuitry

Tasks of the Thesis

The primary task of the thesis was to develop a *passive ambient light sensor array* and controller system to make full autonomous obstacle avoidance more practical.

The secondary task includes the initial investigations of an appropriate *guided neural learning* method enabling a pseudo-memory based reactive system for the sole purpose of obstacle avoidance predominantly within dynamic or unexplored environments.

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 developed for the adjustment, weighting and learning system of the sensor array.

Practical Application

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 range 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 have been thwarted by difficulties due to robotics limitations on mobility and these problems will only increase with distance in the future. 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.

Tools and Methodology of Research

Research has been first, foremost and of necessity, a hands on exercise which in the first instance involved the construction of AMBOA Ver.1 & Ver.2. Additionally, as very little similar circuitry exists for this method of sensor array construction it was necessary to design the sensor array which consists of 3 sensors each within 8 arrays, with each array performing the dual function of analogue and digital signal processing. All data has been assessed to verify measurements and preliminary modeling results. Verification of designed circuits, algorithms and hardware has been carried out using the following software:

- *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.

Testing and adjustment of completed PCBs involved numerous trial and error procedures having a prerequisite that the various sensors operated in unison and outputs of each sensor needed to be approximately equal under similar light input conditions.

Structure and Volume of the Thesis

The PHD thesis is devoted to the field of Robotics and in particular to the topic of obstacle avoidance which is arguably one of the more important aspects within the mobile robotics field. The thesis represents a beginning to end project in the development of a passive / read-only sensor array designed to operate using only available environment ambient light. The system is further enhanced through the utilization of both fuzzy logic and a guided learning neural network. The system as a whole has been designed as a research and development device capable of using many sensor types and algorithm functions which allows for a well rounded investigative mobile robotic platform. The author's vision was to create a robot capable of many and varied research projects or rather as an educational tool which may be adapted to many adaptronic systems.

A guided neural network algorithm was chosen that best suited the sensor array configuration however the on-board memory and high speed processor of the robot is designed to allow a multitude of choices in this regard.

The first chapter is devoted to an overview or introduction to obstacle avoidance, the topicality and associated problems. The author's assertions are discussed along with the methods of research and primary hypothesis. The scientific novelty, practical novelty and application are therein outlined.

The second chapter gives a brief outline of conventional sensors and their use in modern robotics. Some pros and cons are examined and those utilized or not able to be utilized in the AMBOA system noted. Details are also given regarding the practical methods used for obstacle avoidance and the author's conclusions are drawn based on practical experience and researched materials.

The third chapter analyzes obstacle avoidance in robotics, its most common applications and subtle differences between obstacle avoidance and the not to be confused obstacle recognition technologies. The benefit of reverse biasing of sensors is introduced and evaluated showing the preferred method adopted in the AMBOA system.

The forth chapter provides a brief look at the stages of development of AMBOA from Ver.1 to Ver.3.

The fifth chapter introduces fuzzy and neural architecture into the control functions of the AMBOA system. This chapter includes an introduction to fuzzy logic and applications currently utilizing the method. Neural-Fuzzy architecture is discussed along with the software used in the project and covers autonomous vehicle motor control and how it necessarily relates to the AMBOA project.

The sixth chapter is the final chapter in the thesis which gives an outline of the neural network Delta Rule referred to as "Guided Learning" and together with Appendix B covers the approach utilized.

Approbation of the Results - Relevant International Conferences

1. Compatibility and Power Electronics (CPE), Tallinn, Estonia, 2011.
2. (International Journal Arts & Sciences) International Conference for Academic Disciplines in Gottenheim, Germany, 2012.
3. The 16th International Conference of ELECTRONICS, Palanga, Lithuania , 2012.
4. International Journal Arts & Sciences, International Conference for Academic Disciplines in Rome, Italy, 2013.
5. EUROCON, IEEE, European Conference, Zagreb, Croatia, 2013.
6. RTUCON, 54th International Scientific Conference of Riga Technical University, Riga, Latvia, 2013.
7. EPE'14-ECCE Europe, Lappeenranta, Finland, 2014.
8. RTUCON, 55th International Scientific Conference of Riga Technical University, Riga, Latvia, 2014.
9. RTUCON, 56th International Scientific Conference of Riga Technical University, Riga, Latvia, 2015.

List of the Scientific Publications on the Topic of the Thesis

1. **L. Adria**n, 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 analog 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. **Adrian, L.R**.; Repole, D.; 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.

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.

The authors premise is that a mobile robot should also have the benefit of a (WE), albeit mobile, which 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 Fig.1.1. 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.

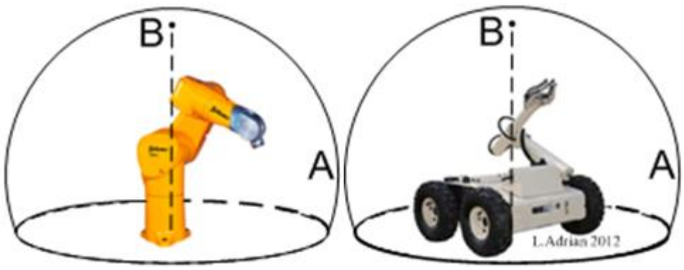

Fig.1.1 Stationary and mobile robots both require workspace envelopes.
(Author's assertion)

There are many articles and tutorials written explaining many ways to accomplish the task of OA within the home environment and outside or far away exploration of foreign and dynamic environments.

The image, Fig.1., represents the network of one, three sensor bank, in its most reduced form. Each bank is designed to send both analogue and digital data to the microprocessor with analogue signals mediated through a fuzzy logic filtering process and digital signals processed directly through the chip.

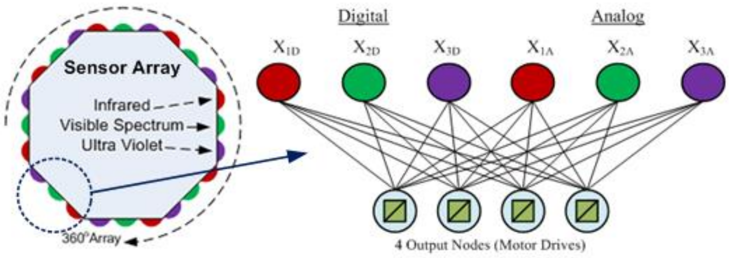

Fig.1.2 Consists of 3 sensors each within 8 banks forming 1 array of 24 sensors, each performing the dual function of analogue and digital ambient light receivers

2. Sensor Technologies

Light sensors form the primary functional envelope of the AMBOA system, and include the family of sensors which are designed with responsivity to many wavelengths (λ) of the electromagnetic spectrum from low nanometer through visible spectrum to much higher wavelength dependent on the type of band-pass filters used. Many types of detectors exist, such as photo resistors, photo-transistors, photo-diodes and sensors able to detect color and some with close to human eye receptivity. Incident light sensing based devices can read the quantity of light falling upon the sensor surface or substrate.

Fig.2.1. AMBOA Ver.2, sensor array module

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 analog 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. The 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 analog hardware device. In addition, photo sensitive devices have a minimal energy impact on the robot systems, unlike the 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. Three high quality light dependent resistors, together with high end (military quality), multi-turn variable resistors, Fig. 2.2 and 2.3 make up a simple yet very effective technology to adjust the sensitivity of the sensor array [2], [3] and [4].

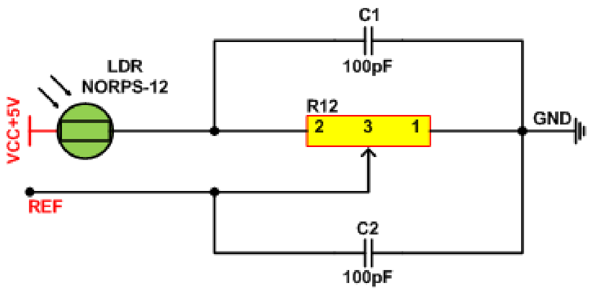

Fig.2.2. LDR /VAR Potential divider configuration

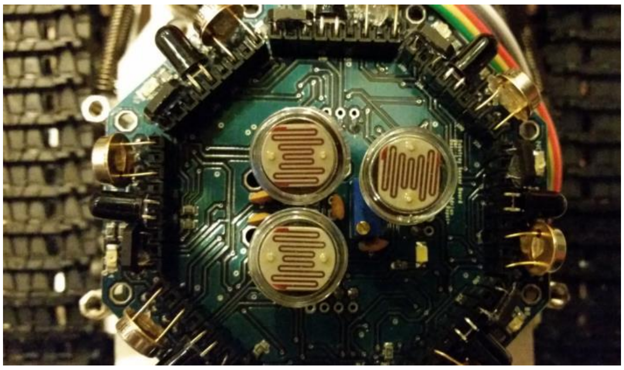

Fig.2.3. Three LDR /VAR potential dividers for adjustment of ambient lighting

3. Obstacle Avoidance

This chapter of the thesis is devoted to a short analysis of obstacle avoidance.

The first that comes into 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, [5] and [6].

The chapter includes;

- Common Applications of Obstacle Avoidance;
- Obstacle Avoidance or Recognition.

4. Three 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, Fig.4.1 a), 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 analog 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.

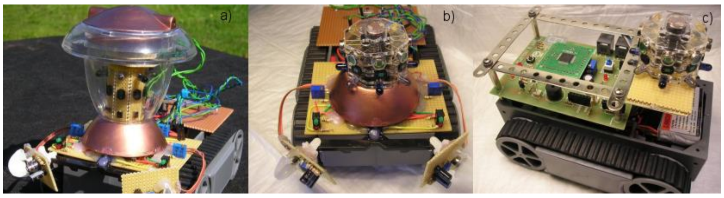

Fig.4.1. AMBOA original test robots

AMBOA, Fig.4.1 b), and, Fig.4.1 c), were dedicated to a redesign of the sensor array, utilizing more sensitive photodiodes in an attempt to alleviate problems occurring with transimpedence amplification across the 24 Photodiode array as mentioned within Appendix D of the thesis. 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 [7] and [11], as the author has previously concluded within earlier work and subsequently witnessed within the project.

Thereafter AMBOA Ver.2 was enabled with a digital only system to enable cross references of the adaptability of the system to a programmed system as is further detailed in Section 5 of the thesis. Irrespective, both systems were dropped in favor of a Hybrid Analogue & Digital AMBOA Ver.3, which effectively double the permutations of the sensory system as it is described in Section 8 and within “Appendices B to G” of the thesis.

5. Fuzzy Logic Introduced to AMBOA Ver.3.

The use of qualitative inferences in the design of artificial systems solves the problem whether it is 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, using empirical and qualitative rules that affect a world of unclear or fuzzy actions, instead of the logic of either black or white [8], [9] and [10].

6. Autonomous Vehicle Motor Control

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 to allow the system to remain 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. 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 communicates through some specific protocols, with smaller microcontrollers (usually DSP) specifically designed to control peripherals.

It was a requirement that no matter what motor topology was chosen it would be necessary to change only a few parameters of the algorithm of the PIC32 or of the DsPIC33. In fact it 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 DsPic33outputs as in Fig. 6.1, 6.2 and Fig.6.3, is the final L293 driver version chosen for AMBOA.

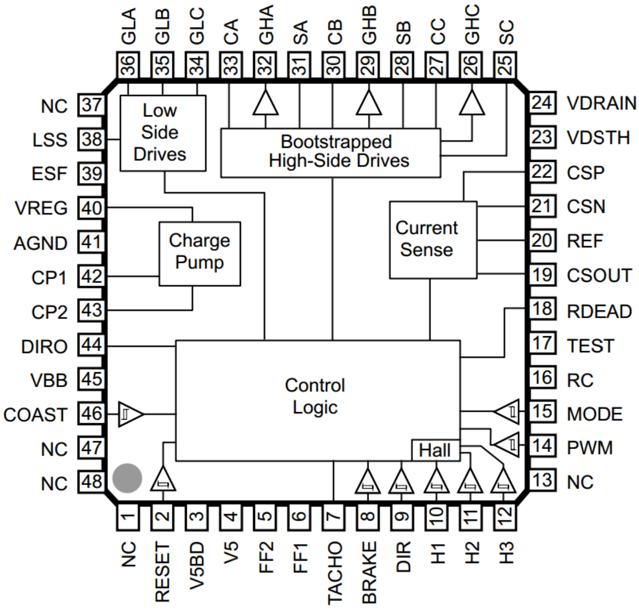

Fig. 6.1. A3930 Pin Out

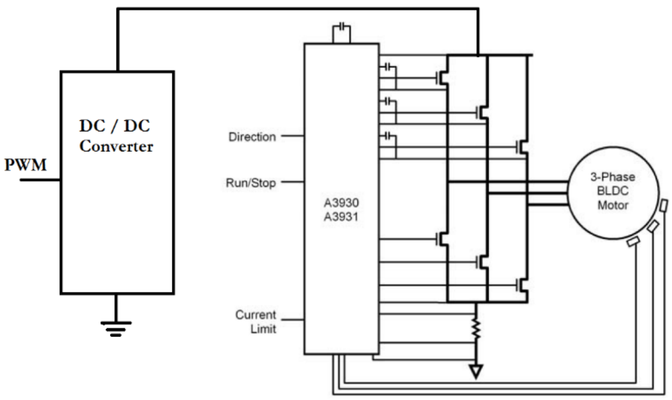

Fig. 6.2. Motor Driver with DC/DC converter unit

As previously stated as a research tool, the robot must be capable of many and varied system alteration to enable researcher design to be fully implemented and therefore Fig.6.2, is only one of the possible motor configurations for the AMBOA system [12] and [13].

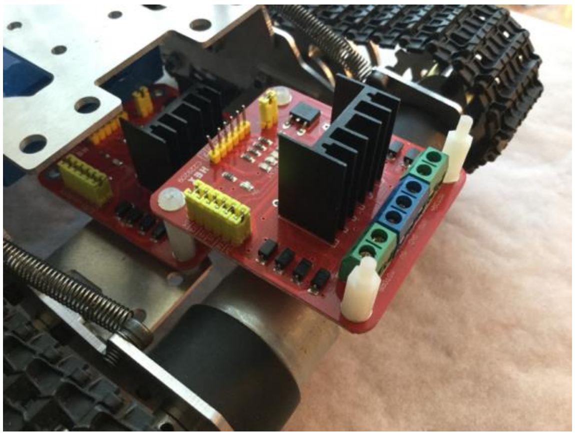

Fig.6.3. AMBOA dual L293 drivers selected

7. Analysis and Mathematical Basis

The PhD thesis includes and analyzes the mathematical basis that has been used in research, development of methods and measurement, modeling and resultant analysis including:

- LDR/VAR controlled potential divider utilized for the three individual ambient Light Dependant Resistors; *Refer Thesis Appendix G "Ambient Control of Comparator Array U_{REF}"*;
- Photodiode responsivity defined as the ratio of photocurrent generated to the electromagnetic spectral incident power at its given wavelength [14];
    - Theoretical Photodiode Operation –v- Practical Result
    - Junction Capacitance
    - Bandwidth & Response
    - Terminating resistance
    - Photoconductive Mode
    - Effects of Chopping Frequency
    - Test-Bench results of analysis of selected sensors, Fig.7.1. and Appendix A herein, Table.1.

Refer Thesis Appendix H "Responsivity –V- Generated Photocurrent"; [15]

- Creation of Memberships, Fuzzy Hedges, Output Defuzzification and Centroid Method

Refer Thesis Appendix I "Fuzzifying and Defuzzifying"; [16]

- Autonomous nonlinear dynamic system:

Refer Thesis Appendix J "Lyapunov Theorem"; [17]

- Processing element with single output connection:

Refer Thesis Appendix K "Artificial Neural Systems"; [18] [19]

- Responsivity amplification through transimpedence:

Refer Thesis Appendix N "Modified Pyroelectric Sensor System Adaption's"; [20]

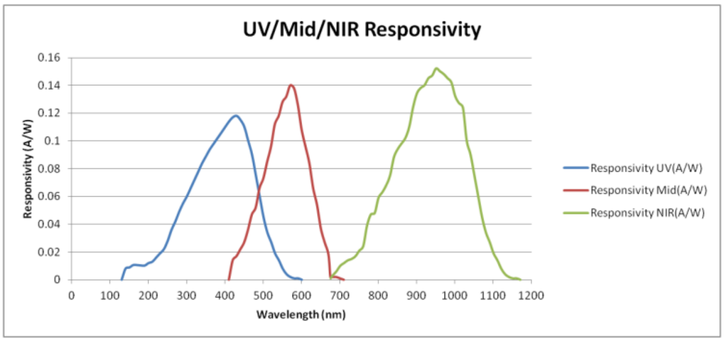

Fig. 7.1. Overlay result of responsivity relationship between selected sensors.

Conclusion Section 7

The selected sensors for testing purposes in the final AMBOA array comprised the following:

- FGAP71- Ultra Violet Photodiode with wavelength range of 150 nm to 500 nm.
- BPW21R - Mid Visible Spectrum with human eye equivalent responsivity, 420 nm to 675 nm with a peak spectral sensitivity of 565 nm and the
- BPW34F - Daylight Filtered IR photodiode, 780 nm to 100 nm with a peak spectral sensitivity of 950 nm.

As can be seen in Fig.7.1 the individual sensitivities of each sensor have little response overlap, necessary in order to accurately enable both the fuzzification and neural learning processes of the system.

The wavelength recordings in Table 1 in Appendix "A" denote a reliable base for the assessment of the system. The sensors revealed some overlap at the wavelength of 500 nm giving us close to the desired sensory input needs required, without need to produce additional band pass filters for each sensor.

The system has been designed to accommodate many sensor types. These may be varying combinations of photo sensor, tuned sound sensors, ultrasonic sensors or combinations of different sensors with the only restriction being that the sensors utilized have an analogue and or digital output, preferably both.

The system in the testing phase has been allocated to the sensors covering the spectrum from UV to NIR. To make this more understandable the overlap when processed through the fuzzy logic system can be a benefit when distinguishing the true output from any two sensors.

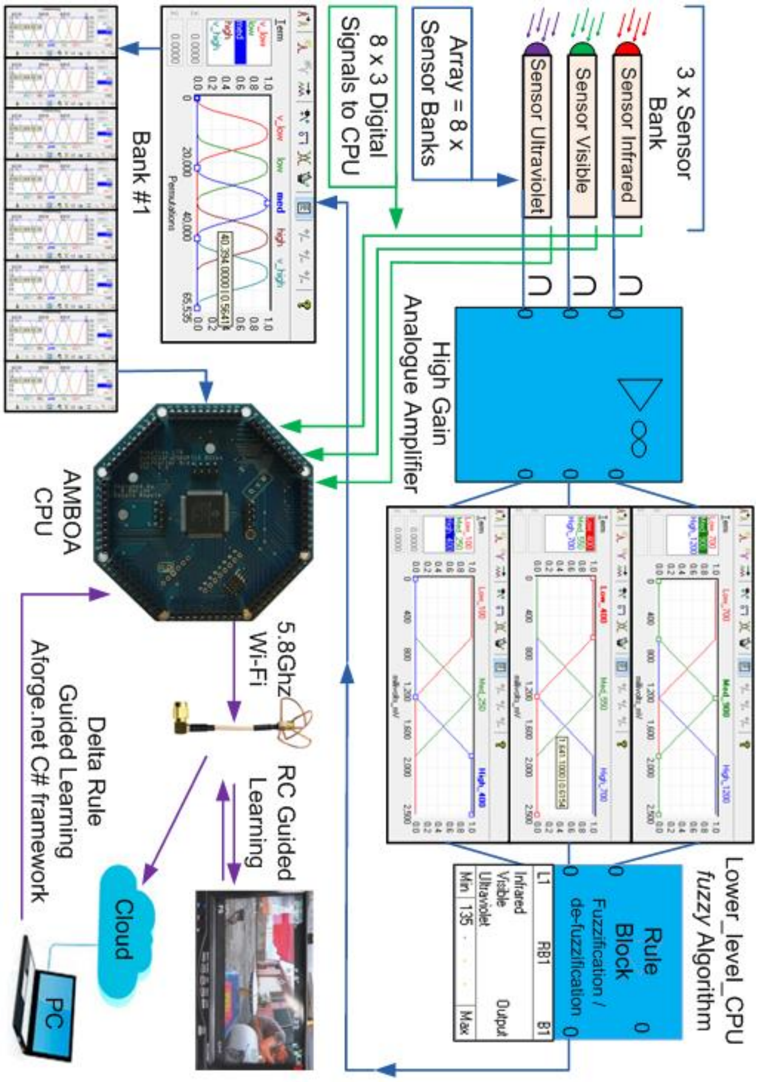

Fig.7.2 AMBOA system model

8. AMBOA Guided Learning Batch Processing

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 [21], 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.

Data collection is achieved as the robot is guided via remote control, 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 remote control 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. Thereafter data of both an analogue and digital nature is captured during the allocated learning period T_{learn}.

Permutations within the sensor array become exponentially greater when account is taken to the duplication or repetition of the received signals. In other words, we can raise 24 sensors to the 24th power to calculate the number of combinations obtainable with repetition of any received signal, though it is less likely for repetition to occur so often in the analogue method due to the large variance of photovoltaic readings. When accounting however for the digital aspect of the array, repetition is obviously commonplace. Refer Fig.7.2.

The raw sensor data is thereafter processed through the selected neural algorithm that in our case is the Aforge.net C# framework, purpose designed for developers and researchers in the fields of Artificial Intelligence. The process is referred to as batch learning because after the data has been collected it is analysed using the Delta Rule method. A single layer propagation network is used as a feed forward perceptron, a 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. The Delta Rule in its simplest form is described by [22].

Stages of the system:

- Data collection – Photovoltaic, Analogue and digital
- Direct feed of digital signals to Central Processing Unit
- Fuzzy analysis of analogue data – permutation reduction
- De-fuzzified photovoltaic data to Central Processing Unit
- Wireless transmission of batch data to cloud or PC
- Analysis through Guided Learning Framework
- Wireless transmission of neural process, represented as a correlation matrix with associated values back to AMBOA system

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 an error free result is possible with the required condition that all solutions must be a linear function of the inputs.

Section 6 and Appendix B of the thesis.

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 [23] the operator is able to upload a tab delimited file and achieve a visual approximation of what the robot sees Fig.8.1.

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

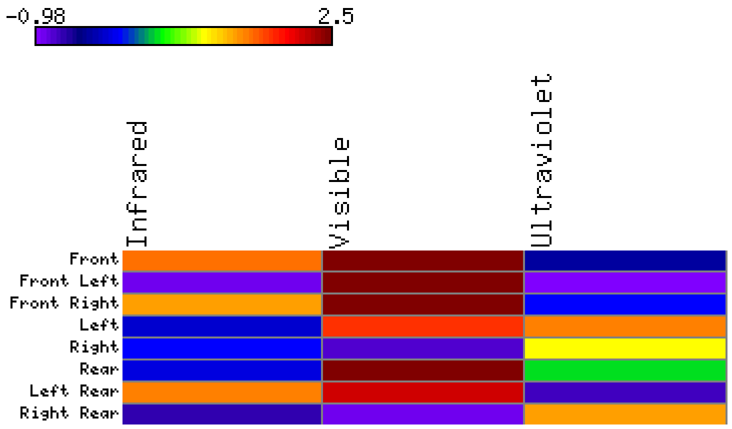

Fig.8.1. Human visual representation of what the robot sees

Therefore from a visual aspect and as an example, the front 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 produces an extremely more complex matrix however fig.8.1 gives the general idea.

9. Conclusions

The thesis has been devoted to the development, assessment and feasibility of a 360^{o} passive read only system for obstacle avoidance in mobile robotics named AMBOA (***Amb***ient ***O***bstacle ***A***voidance robot). The project involved the design and production of numerous printed circuit boards with the primary focus upon the sensor array board and subsequently the 32 bit microcontroller which incorporated memory onboard and wireless transmission technologies as a forerunner to planned future research.

Efficiencies and Results

The measure of efficiency is a complicated task in its own right. The ability of an autonomous mobile robotic platform to be collision free is quite rare and most available data is assessed on systems using non-passive sensor technologies such as IR Proximity (radiating infrared wavelengths) or Ultra Sound (emitting specific frequency sound-waves) with little work having been presented on passive or read only systems which utilize only the emitted electromagnetic radiations of the environment.

Within a truly *static* environment, void of projectiles (other moving objects), the designed system is slightly superior to other obstacle avoidance systems. This is in that the learning period (section 7.2 of the thesis) is short and therefore after all static objects have been "recorded" the system becomes almost collision free with many other methods of obstacle avoidance systems having an efficiency level of around 80 % to 95 % [24] [25][26]. It should be considered also that, as $FOV_{max} \rightarrow 0$, efficiency decreases. In other words a system with three IR Proximity sensors mounted at the front of the vehicle has a much lower field of view than 360 ^{o} and must be by default less efficient than a system with full field of view and therefore a system boasting 95% efficiency with less than 360 ^{o} FOV cannot be justified.

An 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 neither 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.

The efficiency increase in the AMBOA system may not be immediately apparent due to the dynamic nature of the learning algorithm itself.

Within a *non-static* or *dynamic* environment the efficiency of the system must be assessed over increased periods of learning, the T_{learn} period. The system may be operated under the modes of “Guided Learning” or “Unsupervised Learning” and both rely on the T_{learn} period and the “Memory Onboard (MOB)” aspect of the robot. In more simplistic terms, efficiency has been proven to increase with an increased “learning period” which is restricted only by the memory storage capabilities of the robot.

10. Planned Future Research

The presented thesis covers three stages, necessary parts of the research required to develop and validate the chosen method able to produce a suitable obstacle avoidance system capable of semi or fully autonomous mobility. The stages include the development of the original AMBOA system through to the third system where neural fuzzy algorithms were employed to facilitate a pseudo-memory system for the mobile platform. In order to obtain a preliminary base for future research it has been necessary to construct three individual mobile robots, with each displaying improvements over the previous. The outcome, leaning toward definitive conclusions that the selected method of obstacle avoidance is both practical and efficient and may offer a more definitive system for the purpose of obstacle avoidance in mobile robotics. In future it is intended to continue research covering the following aspects:

- Data collection for pseudo-memory applications.
- Practical applications for swarm robotics manipulation through memory harvesting.
- Long range exploration technologies for fully autonomous vehicles.
- Safety modeling for closed environment robotics.
- Investigation into appropriate control methods for data access including MOB to Wi-Fi, Cloud or other access methods for single robots, swarm robots or remote exploration robots.

11.Bibliography

[1] Grey Walter, W. (1910–1977), ”The Living Brain”, Reprint, Publisher: The Norton Library, 2008.

[2] S.R. Munasinghe, C. L. J. J. Oh and O. Khatib, “Obstacle avoidance using velocity dipole field method,” in 2005, International Conference on Control, Automation, and Systems, ICCAS, Korea.

[3] J.J. Craig, Introduction to robotics: mechanics and control, Upper Saddle River: Pearson Prentice Hall, 2005.

[4] R. Balogh, “Educational Robotic Platform based on Arduino,” in Proceedings of the 1st international conference on Robotics in Education, RiE2010. FEI STU, Slovakia, 2010.

[5] American Honda Motor Co. Inc., “ASMIO – The World's Most Advanced Humanoid Robot,” American Honda Motor Co. Inc., 2015. [Internet research]. Available: http://asimo.honda.com/. [Accessed January 2015].

[6] J. Pramuk, “BMW unveils self-parking car system,” CNBC News, 16 December 2014. [Internet research]. Available: http://www.cnbc.com/id/102274053. [Accessed January, 2015].

[7] Xinshun Zhang, Jiyu Jin, Huimin Meng, Zhisen Wang, “A Sensor Optimal Proposal Based on Intelligent Street Lighting System”, R&D Institute of Integrated Measurement and Control, Dalian Polytechnic University, Dalian 116034, China, Proceedings of ICCTA2011.

[8] L.A. Zadeh, A theory of approximate reasoning, in: J. Hayes, D. Michie, L.I. Mikulich (Eds.), Machine Intelligence 9, Halstead Press, New York, 1979, pp. 149–194.

[9] Robert Fullér, Neural Fuzzy Systems, Donner Visiting professor Abo Akademi University, ISBN 951-650-624-0 ISSN 0358-5654, 1995, pages. 157–160.

[10] D. Nauck, F. Klawon; R. Kruse, “Foundations of Neuro-Fuzzy Systems”, J.Wiley & Sons, 1997.

[11] W. Ross Ashby, “An Introduction to Cybernetics" First Published (1956).

[12] American Honda Motor Co. Inc., “ASMIO - The World's Most Advanced Humanoid Robot,” American Honda Motor Co. Inc., 2015. [Internet Research]. Available: http://asimo.honda.com/. [Accessed January 2015].

[13] ST Microelectronics, “Designing with the L296 Monolithic Power Switching Regulator”, (Internet Research), http://www.st.com/web/en/resource/technical/document/applic-tion_note/CD00003945.pdf.

[14] Thorlabs, Inc. Website: http://www.thorlabs.de/ Available PDF, White-Papers, Internet Research and manufacturer of photo sensors utilized within the thesis.

[15] National Instruments,“Photo-Diodes”White-Paper,14839, Publish Date: Sep 18, 2013.

[16] R. Jang, “Neuro-Fuzzy Modelling": Architectures, Analysis and Applications”, PhD Thesis, University of California, Berkley, July 1992.

[18] Robert Fullér, Neural Fuzzy Systems, Donner Visiting professor Abo Akademi University, ISBN 951-650-624-0 ISSN 0358-5654, 1995, pages. 157-160.

[19] J.M.Zurada, Introduction to Artificial Neural Systems (West Publishing Company, New York, 1992).

[20] L. R. Adrian and L. Ribickis, “Design of Human Tracking Robot Utilizing Pyroelectric Sensor and Analogue Circuitry”, IEEE Eurocon, 2013.

[21] 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), Jan 2013 Vol 19, No 1 (2013).

[22] McClelland, J. L. & Rumelhart, D. E. (1988). A simulation-based tutorial system for exploring parallel distributed processing. Behaviour Research Methods, Instruments & Computers, 2, 263-275.

[23] Pavlidis, P. and Noble W.S. (2003) Matrix2png: A Utility for Visualizing Matrix Data. Bioinformatics 19: 295–296.

[24] Guoxiang Ping; Bing Wei; Xianglong Li; Xiang Luo, "Real time obstacle avoidance for redundant robot," in Mechatronics and Automation, 2009. ICMA 2009. International Conference on , vol., no., pp.223–228, 9–12 Aug. 2009.

[25] Bourdon, G.; Ruaux, P.; Delaplace, S., "Instantaneous fuzzy modelling for obstacle avoidance," in Systems, Man and Cybernetics, 1995. Intelligent Systems for the 21st Century., IEEE International Conference on , vol.3, no., pp.2546–2551 vol.3, 22–25 Oct 1995.

[26] Gevher, M.; Erkmen, A.M.; Erkmen, I., "Sensor based online path planning for serpentine robots," in *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on* , vol.1, no., pp.674–679 vol.1, 2001.

APPENDICES

A. FINAL ANAYSIS OF SELECTED SENSORS

Table 2: Final Test-Bench results of analysis of selected sensors. (from section 7)

Wave length (nm)	Responsivity UV(A/W)	Wave length (nm)	Responsivity Mid(A/W)	Wave length (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

B. FINAL AMBOA IMAGE