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Developing an outdoor Fuzzy Logic Controlled Agricultural Vehicle For Crop Following and Harvesting

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Abstract

This paper describes the design of a fuzzy controlled autonomous robot for use in an outdoor agricultural environment for crop following processes which involves spraying insecticide, distributing fertilisers, ploughing, harvesting, etc. The robot has to navigate under different ground and weather conditions. This results in complex problems of identification, monitoring and control. In this paper a fuzzy controller is identified which when used in conjunction with a novel outdoor sensor design deals with both crop tracking and cutting. The controller was tested on an in-door mobile robot using two ultrasound sensors. The controller showed a good response in-spite of the irregularity of the medium as well as the imprecision in the ultrasound sensors. The same controller was then transferred to both an electrical and diesel powered vehicles which operate in an out-door farm environment. These outdoor robots have used our novel sensor (mechanical wands) as well as outdoor ultra sound sensors. The robot had been tested in outdoor environments on fences and real crop edges in real fields. The robot displayed a good response following irregular crop edges full of gaps under different weather and ground conditions within a tolerance of roughly 2 inches.

1 Introduction

The problem of a decreasing agricultural workforce is universal. Therefore, there is a need for automated farm machinery, ultimately including unmanned agricultural vehicles. One of the most important tasks in a field are those based on crops planted in rows or other geometric patterns that involve making a vehicle drive in straight lines, turn at row ends and activate machinery at the start and finish of each run. Examples of this are in spraying, ploughing and harvesting.

In an agricultural setting the inconsistency of the terrain, the irregularity of the product and the open nature of the working environment result in complex problems of identification, dealing with sensing errors and control. Problems include dealing with the consequences of the robotic tractor being deeply embedded into a dynamic and partly non-deterministic physical world (e.g. wheel-slip, imprecise sensing and other effects of varying weather and ground conditions on sensors and actuators). Fuzzy logic excels in dealing with such imprecise sensors and varying conditions which characterises these applications.

AI techniques including expert systems and machine vision have been successfully applied in agriculture. Recently, artificial neural network and fuzzy theory have been utilised for intelligent automation of farm machinery and facilities along with improvement of various sensors. Ziteraya and Yamahaso [10] showed the pattern recognition of farm products by linguistic description with fuzzy theory was possible. Zhang et al [11] developed a fuzzy control system that could control corn drying. Ollis [6] has used machine vision to follow and cut an edge of a hay crop but however he did not address the problem of turning around corners and detection of the end of a crop row. Cho [2] have used a simulation of a fuzzy unmanned combine harvester operation but he used only on-off touch sensors for his fuzzy systems and hence lost the advantage of fuzzy systems in dealing with continuos data which had led him not to have smooth response and gave him problems when turning around corners. Also all of his work was in simulation which is different from the real world farm environment. Yamasita [8] tested the practical use of an unmanned vehicle for green house with fuzzy control. Mandow[5] had developed the greenhouse robot Aurora, but the application and environment variation in the greenhouse is restricted with respect to the outdoor situations.

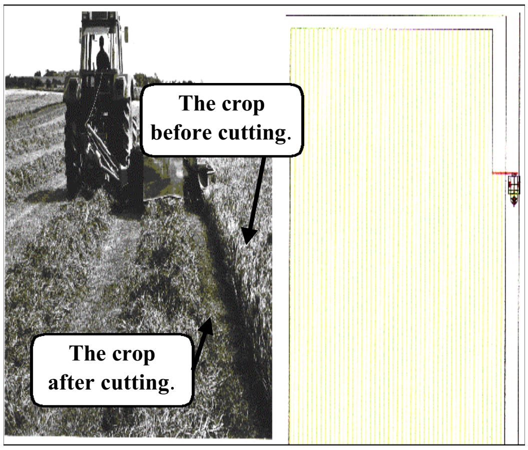
Little work has been done in implementing a real robot vehicle using fuzzy logic which can operate in open out door agricultural situations. The aim of this paper is to develop a fuzzy vehicle controller for real farm crop following and harvesting. An emulation of "crop-following" (which is also an example of fence following) is presented and its response and control surfaces are analysed. Then the same control architecture was moved to our outdoor robots. These robots are equipped with special outdoor sensors (a mechanical wand and an outdoor ultra sound sensor) which are designed to deal with the crop characteristics. The fuzzy controller has succeeded in following various outdoor crop and fence edges ranging from metal structures, lines of trees, to crops of hay (including irregular edges which include small gaps) within a tolerance of two inches, turning different kinds of corners smoothly in various weather conditions.

2 The Problem Definition.

In this section we introduce the architecture of the robot and describe our novel sensor design which is suitable for sensing crop boundaries.

The robot is designed to harvest a crop by following its edge while maintaining a safe distance, in this case 45 cm from the vehicle, while at the same time allowing the cutter, which is fixed to the side of the vehicle, to cut the crop. Figure (1a) shows a hay harvester with the associated cutting technique being depicted in Figure (1b). The robot can also follow the crop edge for other purposes like spraying insecticide, distributing fertilisers, ploughing, harvesting, etc.

Initially we have tested our design with an indoor mobile robot, introducing to it all the hard conditions that it might encounter in a real field. Although there are clearly big differences between the indoor environment and that of a farm we have done what we could to make the experiments more realistic such as using noisy and imprecise sensors, irregular geometrical shapes and fences constructed from hay (in baled form). However, it is self evident that ultimate test of a farm robot is on a real outdoors farm and we thus included as a subsequent stage an assessment stage based on the use of our outdoor electric and diesel vehicles. We feel that this approach is better than a computer simulation which suffers from well known modelling difficulties (especially when trying to model the physical environment comprising varying ground and weather conditions and objects such as trees and hay).



(a) (b)

Figure 1 : a) A real world manned harvester to cut hay
b) The harvesting technique.

2.1 The Robots Description

The diesel robot is as large as a small tractor. Its engine provides traction and generates electrical power for the computers (via a battery system). The electric vehicle is about the size of a wheelchair and indeed utilises many wheelchair parts. Both robots have mechanical wands (potentiometer arms connected to analogue to digital converter to sense the edge of a crop), ultra-sound sensor, GPS, and a camera. The camera forms part of a system developed by our group [7] to locate hay bales. The robot have two separate motors for traction and steering. The indoor robot shown in Figure(3) has a ring of 7 ultrasonic proximity detectors, an 8-axis vectored bump switch and an IR scanner sensor to aid navigation and it has two independent stepper motors for driving front wheels, the steering is done by driving at different motors speeds. We try to give all our robots a similar architecture (to simplify development work) so its hardware is also based on embedded Motorola processors (68040) running VxWorks RTOS.

Other papers reported problems using certain types of sensor in outdoor environments. One reported solution uses simple touch sensors [2] which have ON-OFF states only which is not efficient for fuzzy control. However, we have designed a mechanical wing which is simply an 80 cm. elastic rod connected to a variable potentiometer providing a varying voltage which can then be converted to digital value through an analogue to digital converter. In this way we can have a cheap sensor which gives a continuous signal monitoring distance from the crop edge (and other obstacles). The sensor configuration for crop harvesting implemented on the electrical vehicle is shown in Figure(2-a) and the computer controlled diesel vehicle is shown in Figure(2-b), the outdoor robots are also equipped with ultrasound sensors which are characterised by high noise immunity level.

3 The Fuzzy Logic (FLC) Controller Design

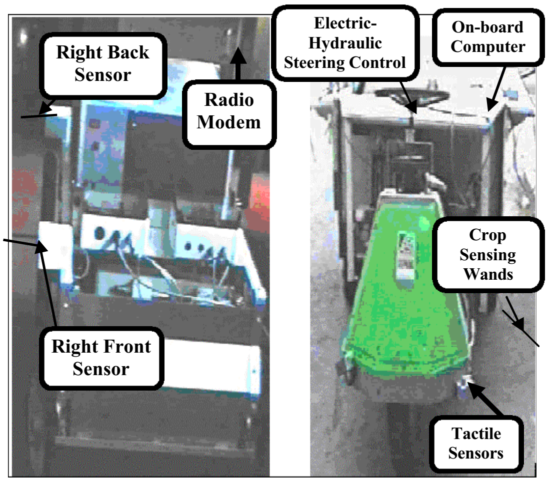
Lotfi A.Zadeh introduced the subject of fuzzy sets in 1965[9]. In that work Zadeh suggested that one of the reasons humans are better at control than conventional controllers is that they are able to make effective decisions on the basis of imprecise linguistic information. He proposed fuzzy-logic as a way of improving the performance of electromechanical controllers by using it to model the way in which humans reason with this type of control information. Figure(4) shows the basic configuration of an FLC, which consists of four principal components which are fuzzification interface, knowledge base (comprising knowledge of the application domain and the attendant control goals), decision making logic (which is the kernel of an FLC), defuzzification interface

In the following analysis we will use a singleton fuzzifier, triangular membership functions, product inference, max-product composition, height defuzzification. The selected techniques are selected due to their computational simplicity.
The equation that maps the system input to output is given by :

$$\frac{\sum_{p=1}^{M} y_p \prod_{i=1}^{G} \alpha_{Aip}}{\sum_{p=1}^{M} \prod_{i=1}^{G} \alpha_{Aip}} \qquad (1)$$

Where M is the total number of rules , y is the crisp output for each rule ,α_{Aip} is the product of the membership functions of each rule inputs, G is the total number of inputs. More information about fuzzy logic can be found in [4].

The Membership Functions (MF) of the inputs denoted by Left Front Sensor (LF) and the Left Back Sensor (LB) (Right Front Sensor (RF), Right Back Sensor (RB) in case of the outdoor robots) are shown in Figure (5). The output membership functions shown in Figure(6) are the left and right speeds for the indoor mobile robot, the robot steering is performed by moving at different wheel speeds. The outdoor memberships are the same for the inputs sensors (in spite of using different sensors from the indoor robots). Because the outdoor robots have a steering motor the output membership functions consist of speed in Figure (7) and the steering parameters Figure(8).



(a) (b)

Figure 2: a) The outdoor electrical robot,
b) The outdoor Diesel robot.

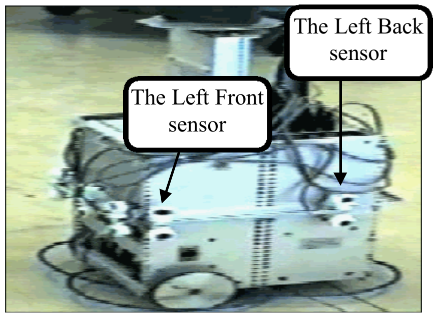


Figure 3 : The indoor robot and its sensor configuration.

The rule base of the indoor controller is the same for the outdoor robots except for speed and steering aspects. Also the indoor robot was left edge following while in the outdoor robots it will be right edge following (a peculiarity of the fact the vehicles were built by different people). These rule bases and the membership functions were designed using human experience but we are developing methods to learn them automatically using genetic algorithms.

Figure (9), Figure (10) represent the control surfaces of the indoor and the outdoor robots. Figure(9) represents the indoor robot control surface in which the LF and the LB were plotted against their outputs which are the left speed (left figure) and the right speed(right figure). Figure (10) represents the control surface of the outdoor robots in which RF and RB were plotted against their outputs which are the robot speed (left figure) and the robot steering (right figure).

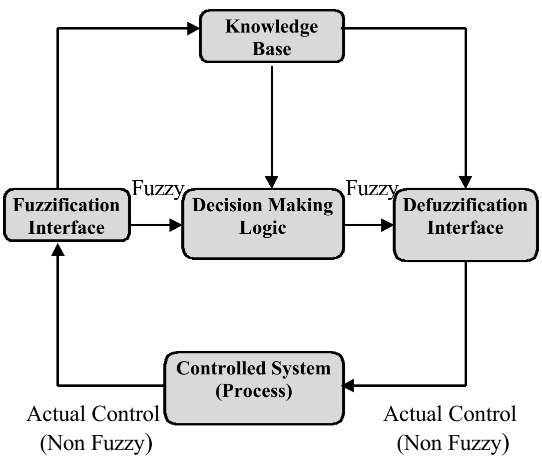


Figure 4 : The basic configuration of an FLC.

4 Experimental Results

The performance of the architecture has been assessed in two main ways. Firstly, we physically emulated (rather than simulating) the crop following process. In this emulation we have conducted practical experiments with the indoor robots to track the robots paths and reactions to the irregular geometrical shapes forming fences (which fake the crop edge) including real bales of hay (forming a fence) which are real challenge to the robot because of their irregularity and low sensitivity of sonar sensors toward them. In the next phase we have tried the same architecture in the outdoor environments to track fences and real crop edges in real farms. Each experiment was repeated 5 times and each time the path was recorded to test the system repeatability and stability against different weather and ground conditions (like rain, wind , holes in the ground, going up and down hill etc.).

Figure (11-a) shows the robot emulating the crop cutting operation. Here it continues going inwards to complete the harvesting operations. The cutting action was simulated by reducing the size of the fence. Note that the response is smooth especially when the robot turns. This is due to the smooth transition between rules and the smooth interpolation between different actions which are characteristics of fuzzy logic. The same experiment was repeated but with real bales of hay and gave a very smooth and a repeatable response as in Figure (11-b)

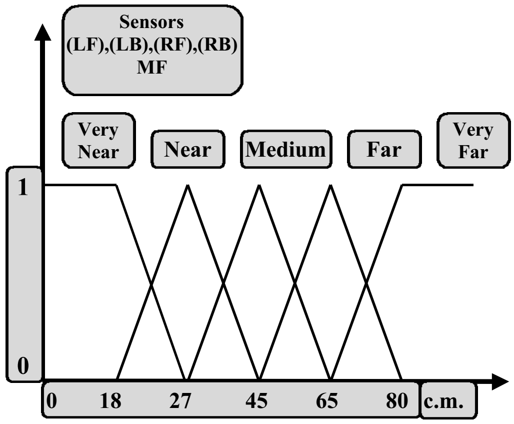


Figure 5: The MF of the input sensors.

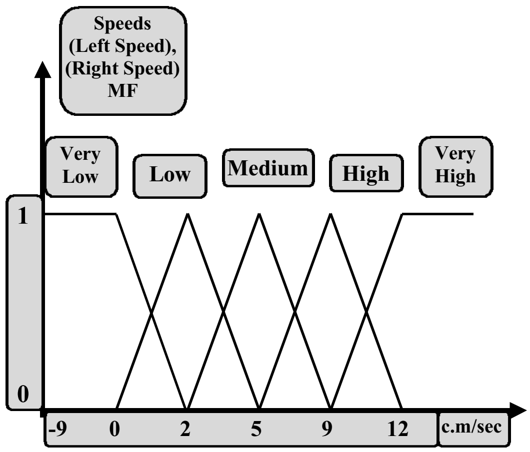


Figure 6: The MF of the indoor robot output speeds.

We then have tried the robot in out-door environments following many crop edges such as weeds, hay and tree hedges.. The system was also tried under different weather conditions like wind , rain, etc. and under different ground conditions like holes in the ground, going uphill and down hill.

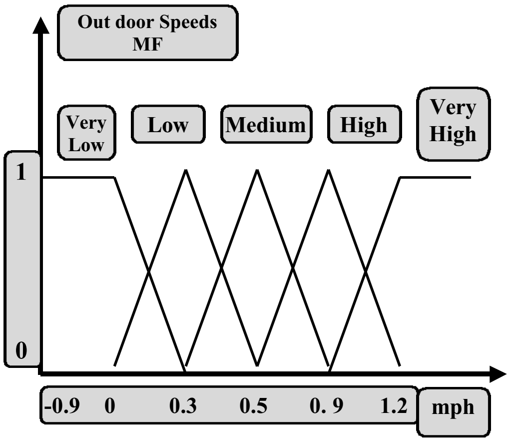


Figure 7: The output membership functions of the outdoor robot speed.

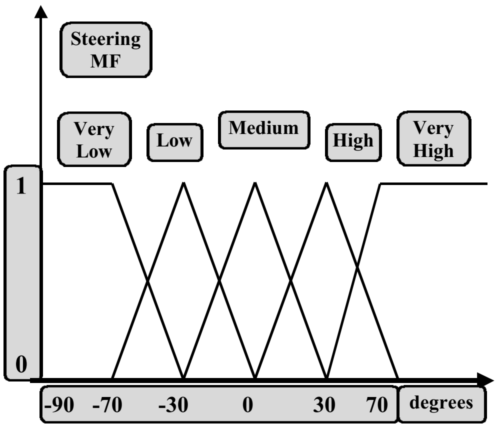


Figure 8: The output MF of the outdoor robot steering.

The same control architecture was used in all robots only varying the output (MF) of the robots and slightly varying the rule base to cater for the differing steering and speed characteristics of the robots. We have experimented with mechanical wands and ultra sound sensors. In spite of the varying weather conditions the systems had displayed a very good response showing the fuzzy controller can deal with imprecision and noise.

Figure (12-a), Figure (12-b) show the robot path of the electrical outdoor robot following an outdoors fence. In Figure (12-a) the robot had succeeded in following an irregular rectangular metallic fence under different weather condition (i.e. wind and rain) using only two ultra sound (US) sensors. The robot had given repeatable and smooth path following the whole fence as well as turning around corners. In Figure (12-b) the robot had succeeded in following the same fence but using the mechanical wands, the robot again had succeeded in following the fence and with high repeatability and stability and responding rapidly but smoothly to any changes in the fence.

Figure (13-a) shows the electrical robot in a real farm following a plant edge characterised by high irregularity (gaps in edge, plants falling from the edge). The robot was also required to navigate up hill and down hill in a ground full of holes. It had used two ultra sound sensors to sense the crop edge. Again the robot gave a smooth response and followed the crop keeping always safe distance from the plant edge and responding rapidly but smoothly to any changes in the crop edge Figure (13-b). Although we currently have no quantitative means for evaluating the precision of the crop following, however we estimate that the crop edge was tracked successfully within a tolerance of 2 inches.

In Figure (14-a) we tried the diesel robot with the mechanical wands sensors in a hay field that has a very discontinuous edge and ill defined corners. The robot gave stable, repeatable and robust response as shown in Figure (14-b), and tracked the edge of the crop successfully within a tolerance of 2 inches. The robot have also turned smoothly around the ill defined hay crop corners as shown in Figure (15-a), Figure (15-b) shows the robot after turning smoothly around this corner.

5 Conclusions

In this paper we have developed a fuzzy controller for a robot aimed at automating crop following processes which includes spraying, ploughing and harvesting. We have developed a novel sensor design (outdoor mechanical wands) to be used in real farms under different conditions. We tested the fuzzy control architecture on an in-door mobile robot with only two ultrasound sensors. It had succeeded in maintaining itself at a constant distance from the emulated crop in-spite of boundary irregularities and the imprecision in the ultrasound sensors. After testing the architecture successfully indoors, the control architecture was moved to the outdoor robots and environment in which the robot displayed a smooth and fast response and was able to track various edges under different environmental and ground conditions.

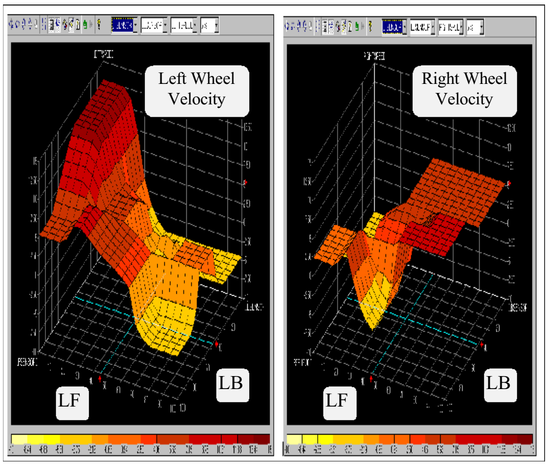


Figure 9: The control surface of the indoor robots.

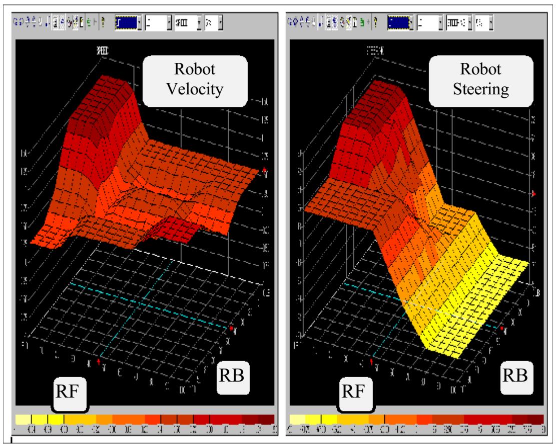


Figure 10: The control surface of the outdoor robots.

The outdoor robots tracked irregular crop edges successfully within a tolerance of 2 inches. The robot had turned also around real crop corners smoothly and had given high repeatable and stable response. To the authors' knowledge, the work described in this paper is the only system which has successfully guided a diesel tractor in outdoor environments following real crop edges (including irregular edges which include gaps) and turning around corners with a high degree of repeatability and following the crop edge with a tolerance of two inches. The system is totally autonomous with no pre specified plans reacting reactively to the changing field conditions.

We are currently investigating the performance of other farm tasks (like bales of hay or fruit boxes collection). In these we are going to use a fuzzy hierarchical controller to combine several behaviours for safe navigation toward our goals. In this work we will integrate a vision system for bales of hay detection [7] and will try to integrate it with the fuzzy system for reactive navigation. Also are currently investigating the use of GA based methods in respect to adding a learning capability to the controller so that it can adapt itself to the changing conditions of a field

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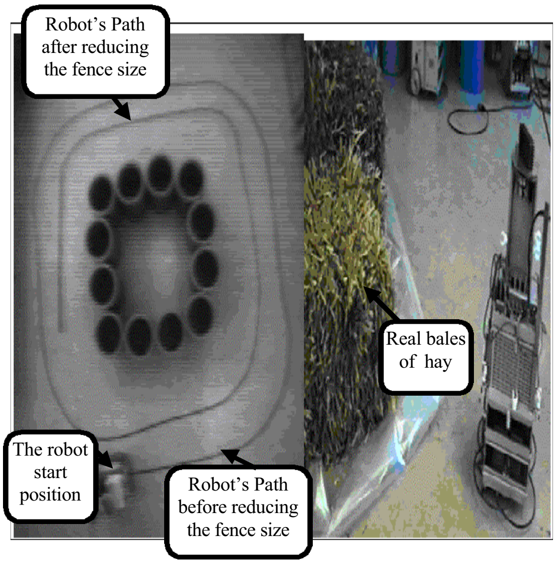
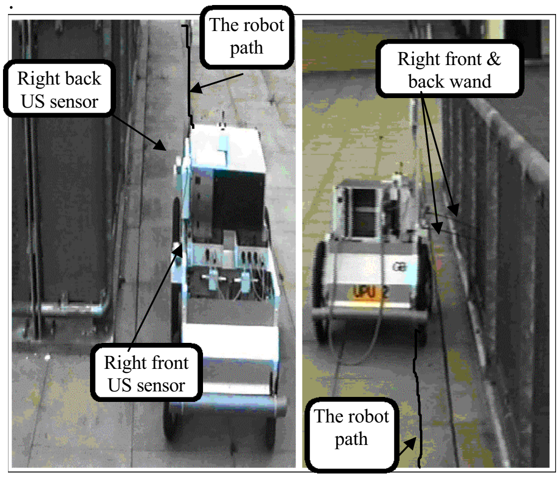


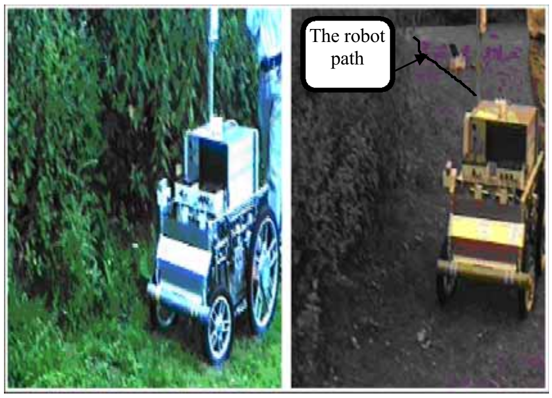
(a) (b)

Figure 11: a) The robot emulating the harvesting operation. b) The robot following fences formed by bales of hay.



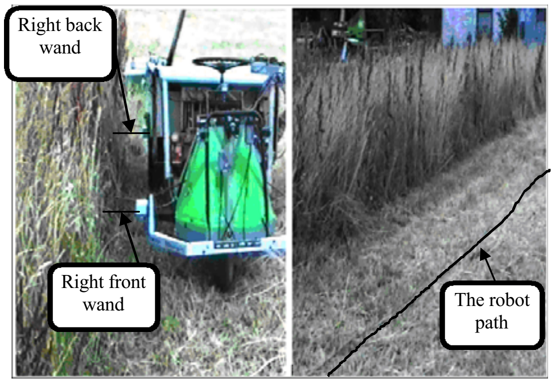
(a) (b)

Figure 12 :a) The outdoor electrical robot following an irregular fence using ultra sound sensors. b) The outdoor robot following an irregular fence using the mechanical wand sensors



(a) (b)

Figure 13: a) The electrical robot following out door irregular tree hedges. b) The robot path.



(a) (b)

Figure 14: a) The diesel robot following real irregular hay crop edge using the mechanical wands. b) The robot path

(a) (b)

Figure 15: a) The robot start turning around an irregular hay crop corner. B) The robot after turning smoothly around the corner.