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Motion Sensors and Transducers to Navigate an Intelligent Mechatronic Platform for Outdoor Applications

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Abstract: The initial goal of this project is to investigate if different sensor types and their attached transducers can support everyday human needs. Nowadays, there is a constant need to automate many time consuming applications not only in industrial environments but also in smaller scale applications, therefore robotics is a field that continuously tracks research interest. The area of human assistance by machines in everyday needs, continues to grow and to keep users interest very high. "Mechatronics" differ from Robotics in terms of integrated electronics, the advantage of being easily re-programmable and more over the versatility of hosting all kind of sensor types, sensor networks, transducers and actuators. In this research project, such an integrated autonomous device will be presented, focusing around the use of sensors and their feedback signals for proximity, position, motion, distance, placement and finally navigation. The ultimate sensor type choice for the task as well as all transducers signals management will also be highlighted. An up-to-date technology microcontroller will host all the above information and moreover move the mechatronic platform via motor actuators. The control algorithm which will be designed for the application is responsible for receiving all feedback signals, processing them and safely navigate the system in order to undertake its mission. The project scenario, the necessary electronic equipment and the controller design method will be highlighted in the following paragraphs of this document. Conclusions and results of sensor usage, platform's performance and problems solutions, forms the rest of this paper body. *Copyright © 2016 IFSA Publishing, S. L.*

Keywords: Motion sensors, Mechatronic platform, Microcontroller algorithm, Automated facilities, Human assistance.

1. Introduction

Designing a mechatronic autonomous system can be a simple and clear process but can also be very complicated and hazardous, depending on many aspects, as in [1-3]. The most important factor is if the robot has some short of interaction with the user or the environment. For example, devices using timer or an electronic agenda are reprogrammable but do not have anything to do with reaction or behavior change based on some external feedbacks. Their “output” will always be the same until the time that they are re-programmed or lose their power source, as in [4-5]. The objective of this project is particularly defined as the mechatronic vehicle that will cut the grass on a garden surface with the ultimate area coverage without human supervision. Although such systems already exist under huge company trademarks, an alternative of those in terms of safety and low cost has its own existence area and therefore worth the effort of this study. Up to date, the so-called "lawn mowers" and similar robots like robotic vacuum cleaners or swimming pool cleaners, are not interacting with humans, they do not adopt any kind of accident prediction, as in [6]. These machines operate automatically in a restricted area but there is no human or animal avoidance function in their control design. Given the fact that in such environments like, house yards or gardens, there is frequent presence of people and pets, the injury factor is high. This is the innovation of the mechatronic platform of this research, it can avoid obstacles, humans, pets and more, while operating at the same time with extreme performance results. The technical assistance that sensors and transducers can provide to successfully undertake the job, introduces the need of careful sensor and afterwards actuators selection to gear up the platform. At this stage, a brief overview of the relative sensors type for the task was considered necessary and will be summarized below.

2. State of the Art

There are hundreds of sensors made today to sense virtually anything anyone can think of, all physical parameters, that it is almost impossible to list them all. The more complex a mechatronic vehicle gets, the more number of sensors the engineer tend to use. A single task may require a combination of different sensors, or different tasks can be achieved using a single sensor. Sometimes, a task can be performed from any of the many available sensors. For the purpose of this project, the sensor selection was based on availability, cost and ease of use. The categorization is as follows.

2.1. Light Sensors

A Light sensor is used to detect light and create a voltage difference. The two main light sensors generally used in robots are Photoresistors and Photovoltaic cells that can be seen in Fig. 1. Other kinds of light sensors like Phototubes, Phototransistors, CCD's etc. are rarely used as in [7]. The Photoresistor is a type of resistor whose resistance varies with change in light intensity; more light leads to less resistance and less light leads to more resistance. These inexpensive sensors can be easily implemented in most light dependant robots.

Photovoltaic cells convert solar radiation into electrical energy. This is especially helpful in case of a solar robot implementation. Although the photovoltaic cell is considered as an energy source, an intelligent implementation combined with transistors and capacitors can convert this into a sensor. Photoresistors can also be used as a proximity sensor. When an object comes in close proximity to the sensor, the amount of light changes which in turn changes the resistance of the photoresistor. This change can then be detected and processed.

Fig. 1. Photovoltaic Cells and Photoresistors.

2.2. Contact Sensors

Mechanical sensors are indeed reliable solution but they have the disadvantage of limited use. Mostly known are the side guidance systems, as in [8]. These systems are based on detection of obstacles by actually touching them, in other words they require physical contact against other objects to trigger them. The most common type is provided in Fig. 2. Therefore they are not useful for non-contact applications. A push button switch, limit switch or tactile bumper switch are all examples of contact sensors. These sensors are mostly used for obstacle avoidance robots, like in this case, so when these switches hit an obstacle, it triggers the platform to do a task, which can be reversing, turning, switching on a LED, stopping etc. There are also capacitive contact sensors which react to human and animal touch. Touch screen smart phones available these days use capacitive touch sensors. Contact sensors can be easily implemented, but the drawback is that they require physical contact. In other words, the platform will not turn until it hits an object.

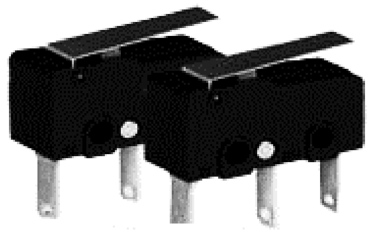

Fig. 2. Mechanical Contact Sensors.

2.3. Proximity Sensors

This kind of sensors detect the presence of a nearby object or obstacle within a given distance, without any physical contact. The working principle of a proximity sensor is simple. A transmitter transmits an electromagnetic radiation or creates an electrostatic field and a receiver receives and analyzes the return signal for interruptions. Although there are many different kinds of proximity sensors, only a few of them are generally preferred for robotic applications. For example, Capacitive Proximity sensors are available which detects change in capacitance around it. Inductive Proximity sensor detects objects and distance through the use of induced magnetic field. The most commonly subcategories, used in the robotics area, are the Infrared (IR) transceiver, the Ultrasonic sensor and the Laser Range sensor. The first type, the Infrared (IR) transceiver, adopts an IR LED that transmits a beam of IR light and if it finds an obstacle, the light is simply reflected back which is captured by an IR receiver, as seen in Fig. 3. IR circuits are designed on triangulation principle for distance measurement. A transmitter sends a pulse of IR signals which is detected by the receiver if there is an obstacle and based on the angle the signal is received, distance is calculated. A simple transmit and receive using a couple of transmitters and receivers will still do the job of distance measurement, but if precision is required, then triangulation method is preferred, like [9]. Some IR transceivers can also be used for distance measurements.

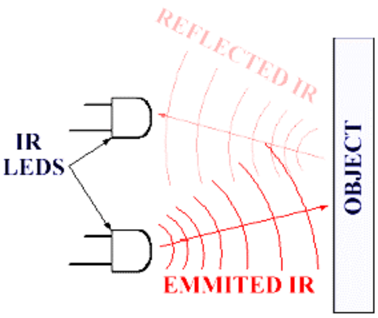

Fig. 3. The IR sensor operation schematic.

The most frequently applied sensor, the Ultrasonic one, generate high frequency sound waves; the received echo suggests an object interruption. Ultrasonic Sensors can also be used for distance measurement. The sensor actually emits an ultrasonic pulse, which is captured by a receiver, as illustrated in Fig. 4. Since the speed of sound is almost constant in air, which is 344 m/s, the time between send and receive is calculated to give the distance between the robotic platform and the obstacle. Ultrasonic distance sensors are especially useful for underwater robots.

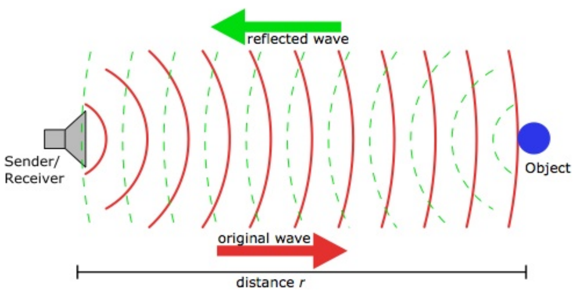

Fig. 4. The Ultrasonic sensor function.

The Laser Range sensor is considered to be the newest entry in the obstacle avoidance category of sensors. Laser light is transmitted and the reflected light is captured and analyzed. Distance is measured by calculating the speed of light and time taken for the light to reflect back to the receiver, as shown in Fig. 5. These sensors are very useful for longer distances than the previously mentioned types of sensors.

Fig. 5. A Laser sensor shield and its function representation.

2.4. Motion Sensors

There are many more parameters that need to be identified while investigating a mobile robot's navigation. Apart from position and distance signals, it is very useful sometimes to include in the controller algorithm feedback signals referring to vehicle acceleration, velocity and tilt. Therefore a significant number of sensing devices are today designed, in an attempt to provide as many as possible information about a vehicle's moving condition. An accelerometer for instance, (Fig. 6) is a device which measures acceleration and tilt. There are two kinds of forces which can affect an accelerometer: Static force and Dynamic Force.

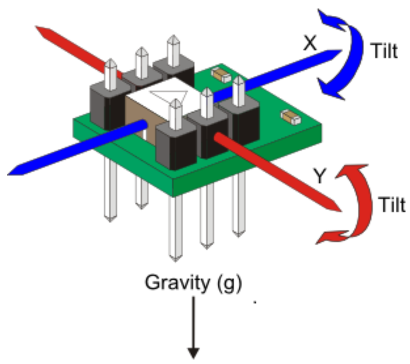

Fig. 6. A typical Accelerometer layout.

The Static force is the frictional force between any two objects. For example earth's gravitational force is static which pulls an object towards it. Measuring this gravitational force can provide details of how much the platform is tilting as seen in [10]. This measurement is exceptionally useful in a balancing robot, or furthermore to inform if the vehicle is driving uphill or on a flat surface. On the other hand, Dynamic force is the amount of acceleration required to move an object. Measuring this dynamic force using an accelerometer provides data about the velocity/speed at which the vehicle is traveling. In case it is needed, vibration can also be measured by an accelerometer.

A Gyroscope (or simply Gyro) is a device which measures and helps maintain orientation using the principle of angular momentum. In other words, a Gyro is used to measure the rate of rotation around a particular axis, as shown in Fig. 7. Gyroscope is especially useful when the engineer desires the robot not to depend on earth's gravity for maintaining Orientation, which is exactly the opposite operation of the Accelerometer.

The fusion phenomenon of the last two types of sensors is provided as a graph in Fig. 8. There are also integrated solutions, electronic shields, the Inertial Measurement Units (IMU) that combine properties of two or more sensors such as Accelerometer, Gyro, Magnetometer, etc, to measure orientation, velocity and gravitational forces. In simple words, IMUs are capable of providing feedback by detecting changes in an objects orientation (pitch, roll and yaw), velocity and gravitational forces. Few IMUs go a step further and combine a GPS device providing positional feedback.
It must be stated that all aerial mechatronic implementations depend on such sensors in order to balance in the air. The project under investigation in this research operates on the surface of earth and therefore does not host this kind of sensors.

An old but still widely used type of motion sensors are the Encoders. They have been used for many years now in mechanical systems and are still at the top of the task. This fact illustrates the reliability of their measurements and the ease of use by an engineer. These sensors (not actually sensors, but a combination of different components) convert angular position of a shaft or wheel into an analog or digital code. The most popular encoder is an optical or incremental encoder which includes a rotational disk, light source and a light detector, (generally an IR transmitter and IR receiver) as in Fig. 9. The rotational disk has transparent and opaque pattern (or just black and white pattern) painted or printed over it, as viewed in Fig. 9. When the disk rotates along with the wheel the emitted light is interrupted generating a signal output. The number of times the interruption happens and the diameter of the wheel can together give the distance travelled by the robot, as in [11]. Incremental encoders are sensors capable of generating signals in response to rotary movement. In conjunction with mechanical conversion devices, such as rack-and-pinions, measuring wheels or spindles, incremental shaft encoders can also be used to measure linear movement. The shaft encoder generates a signal for each incremental change in position. With the optical transformation, a line-coded disc made of metal, plastic or glass and positioned on a rotary bearing interrupts the infrared light ray emitted generally by gallium arsenid sender diode. The number of lines determines the resolution, i.e. the measuring points within a revolution. The interruptions of the light ray are sensed by the receptor element and electronically processed. The information is then made available as a rectangular signal at the encoder output.

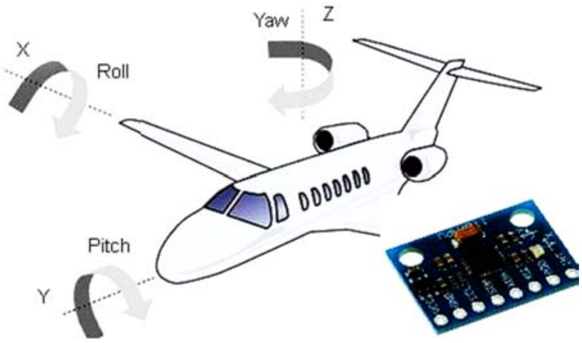

Fig. 7. A common Gyroscope to measure 3 axis rotation.

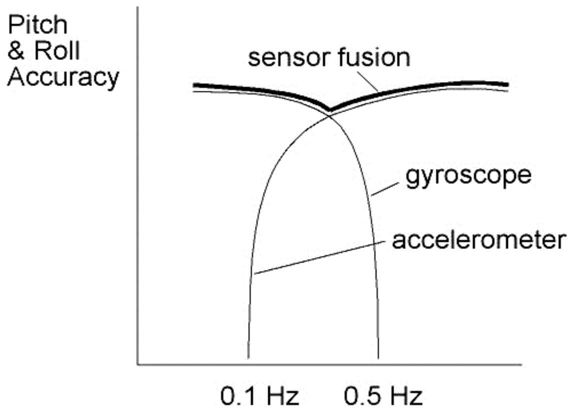

Fig. 8. Gyroscope and Accelerometer fusion.

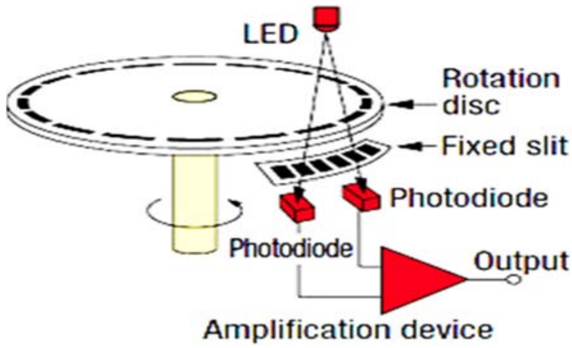

Fig. 9. Optical Encoders principles.

Another category of encoders is the Absolute shaft encoders, also known as shaft-angle encoders, which are by no means used only to detect angular positions. They are also suitable for linear movements that can be converted into rotary movements by a toothed belt, drive pinion, or wire winch. The special feature of absolute shaft encoders is that they assign a unique, digitally encoded signal to each individual measured increment. The method of transducing prevents erroneous readings, whether by a power failure, or by a transient malfunction. After the encoder is switched on again, or power is restored, the position can be read out. It is not necessary to move to a reference position, as it is for shaft encoders of the incremental type.

Last but not least, the Navigation / Positioning Sensors, a category that its name says it all. They are positioning sensors used to approximate the position of a vehicle, mostly for outdoor positioning applications. The most commonly used positioning sensor is a GPS (Global Positioning System). Satellites orbiting earth transmit signals and a receiver on the mechatronic vehicle acquires these signals and processes it. The processed information can be used to determine the approximate position and velocity of it. These GPS systems are extremely helpful for outdoor robots and especially for covering huge areas but fail indoors since the satellite signal fails inside building constructions. They are also more expensive than any other sensor, a fact that is not allowed for the scope of this project.

3. Mechatronic Vehicle Implementation

It is necessary at this stage to make clear the operation scenario of the mechatronic vehicle, the lawn mower. It should operate and actually cut grass on a restricted surface, autonomously and without the existence of the user. The safety factor, like explained before is the most important aspect of its design and therefore the obstacle (humans, pets, random rocks etc) avoidance ability is the great novelty here. After a large number of experimentations with many of the above listed sensors for position control of the device and obstacle avoidance, the Ultrasonic sensor was the best solution of reliability to cost ratio. The installation of the sensor at the top right edge of the vehicle as in Fig. 10, was chosen after many experiments. Keeping in mind that in the current work the obstacle avoidance is performed without physical contact, this front top placement provided the ultimate performance. This sensor has analog output which gives the ability to adjust the distance that the vehicle reacts to obstacles, which was set to 100mm. For better area coverage, the sensor was attached to an adjustable mechanical joint.

In the above figure the platform is shown. It consists of a plastic chassis, 4 DC motors responsible for moving and turning the vehicle and all peripheral electronics. It is divided in 3 different layers which can open and close due to two hinges, as illustrated in Fig. 11. This type of construction provides a compact size device of 400 mm length while at the same time all electronic boards and circuitry for the task can be easily attached and approached by the user. The bottom layer hosts not only the DC motors for the 4 wheels but also the grass cutting tool, which is a DC rotary blade placed on the front bottom side of the vehicle. In the same Fig. 11 one can note the presence of optical encoders that are attached on 2 DC motor of the same axis wheels. Like indicated earlier in this paper, the optical encoders are the most appropriate speed and position type sensors for this task and therefore their feedback signals are sent to the microcontroller for analysis. On the second layer of the vehicle, the power sources (Li-Po batteries) are placed. Since on the bottom layer of the chassis there is no room left for that, it was decided to attach them on the second-middle level in order to ensure as much as possible for improved balanced and traveling behavior the vehicle.

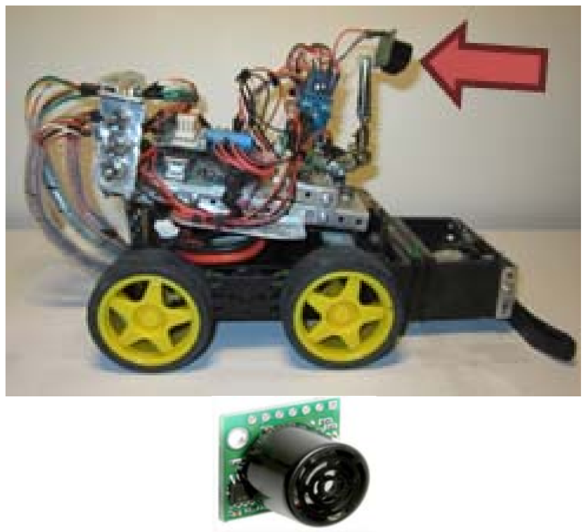

Fig. 10. The lawn mower device with the Ultrasonic sensor placed at the top right side.

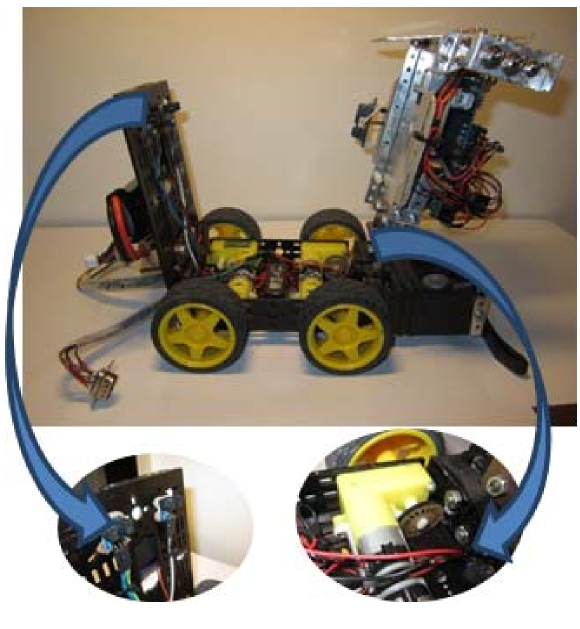

Fig. 11. The vehicle construction on three levels.

During experimentation, a more than 2 hours continuous operation of the device was recorded. This big autonomy is a result of the modern batteries technology as well as the overall low consumption design philosophy of the system electronics. The third layer at the top hosts the microcontroller and all its peripherals for signal amplification and transducing, button arrays, an I/O test board and multiple wiring connectors. Referring to the microcontroller of the mechatronic platform, it was chosen the AVR ATMega1280 for the task. Its abilities of low cost and low power consumption, multiple analog and digital inputs/outputs and moreover the C language programming, creates an overall robust profile for these kind of projects.

4. Operation and Control Algorithm

The mechatronic vehicle of the project is supposed to move on a predefined range like a yard or garden and cover all area of it while at the same time cut grass and avoid any random or not obstacle interfering with its route. In robotics, there are a few methods for the general process of coverage path planning (CPP), while its definition is “the task of determine a path that passes over all points of an area or volume of interest”, as in [12-13]. These experimentally designed methods for better area coverage are summarized as Global Navigation Satellite System (GNSS), the Grid method, the Zig-Zag and Shrinking path methods and the Wire Guidance. The GNSS is a multifunctional system which provides all necessary data to a vehicle in order to follow a predefined route. The vehicle sends/transmits its actual position to a group of satellites and receives a correction signal in order to follow the ideal path. This method is used in large agricultural vehicles that operate in huge plantations. The Grid based method is utilized on the decomposition of the covering area to uniform grid cells, as in [14-15]. All cells are numbered and the control algorithm is used to pass through all cells from start point “S” until goal point “G” as in Fig. 12. Blue areas are considered to be steady obstacles.

The Zig-Zag and Contour Shrinking path methods are based on similar principles but they are different in terms of vehicle movement inside the target area as illustrated in Fig. 13.

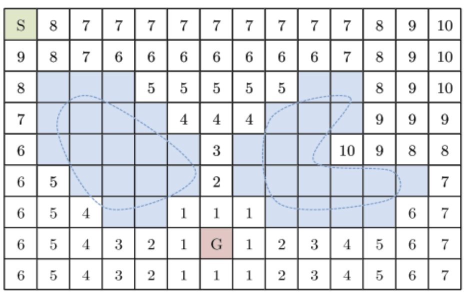

Fig. 12. Grid method schematics.

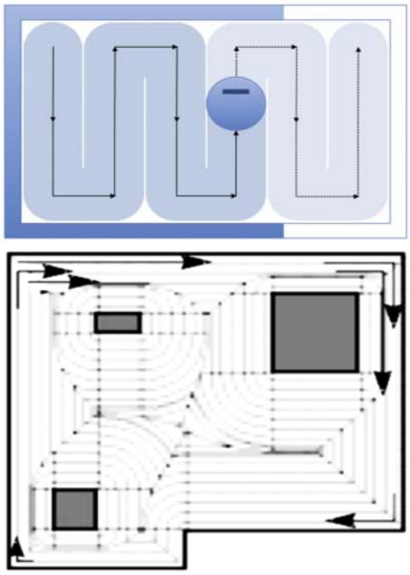

Fig. 13. Zig-Zag and Contour shrinking path method.

In case the Wire Guidance method is applied, the vehicle should detect a wire that sets the area boundaries. Depending on the controller’s algorithm the vehicle avoids the wire, which is placed as a closed loop and so it always stay within these limitations. The great advantage of this coverage method against the others, is that it can be adopted for any random shape area and requires simpler programming of the device movement and therefore, it was selected to get the job done in this project.

The methodology followed for the area limits as well as the sensors on board the vehicle that ‘recognize’ these limits include a buried wire inside the ground which defines the area that the lawn mower is supposed to be moving into. This wire sets the limits of the garden in which the vehicle will perform and is connected to an electrical circuit, which is easy to fabricate and powered up by a battery. This wire generates a magnetic field which is detected by 2 coils located on left and right side of the vehicle. The detection of this wire takes place by the time that the respective coil is almost above the wire and inside its magnetic field. The signal from the coil is sent to the microcontroller in order to turn the vehicle respectively and keep operating within the restricted (by the wire) area. An illustration of this method is provided in Fig. 14.

The mail principle is that the user of the Lawn Mower buries a wire under the area to be covered, which is connected to an electrical circuit creating a magnetic field around the wire. The vehicle is equipped with 2 coils on the front corners of the chassis (one on each side of the rotation blade), which can detect this magnetic field and generate a voltage on coils edges. This voltage is the signal that the processor is receiving and according to the algorithm is giving the appropriate moving or turning signal. The circuit is powered up from a 9 V battery and it consists of an AC current generator with the appropriate characteristics.

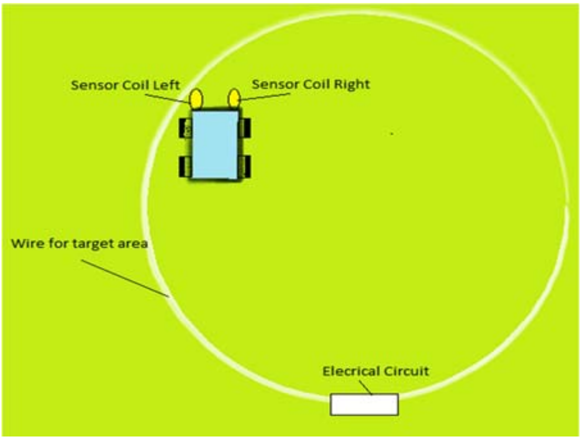

Fig. 14. Typical wiring limitations for area coverage.

The AC current which flows through the wire is having the appropriate frequency in order to be picked up by the coils that are placed on the vehicle. The basic idea is to create a radio transmitter and a receiver. In Fig. 15, the electrical schematic diagram of the ground circuit is shown.

The actual testing of the implemented circuit it showed that a frequency of approximately 80 kHz so ideal to be picked up by a coil of L=1 mH and resistor R=1.5 Ω. The on board circuit sensor of the vehicle was custom designed for the specific application. A coil is used to detect the magnetic field of the wire loop. At the time it is received, it is guided to a comparator LM-324N and sends back the voltage to the microcontroller. The electrical circuit schematic diagram is shown on Fig. 16.

With all the frequency tuning for better coil detection, voltage feedback is send to the relative microcontroller inputs, for left and right coil sensors respectively. More detailed, the output of the comparators are approximately 3.5 V at rest, before the coil detects any magnetic field. This is why in normal operation mode indication LEDs are "on". By the time that i.e. the left sensor will detect the magnetic field of the wire loop the comparator will give 0 V as output and the indication LED for the left turn will be "off". The voltage drop is very precise and sudden and it is the feedback that the processor receives in order to perform right turn.

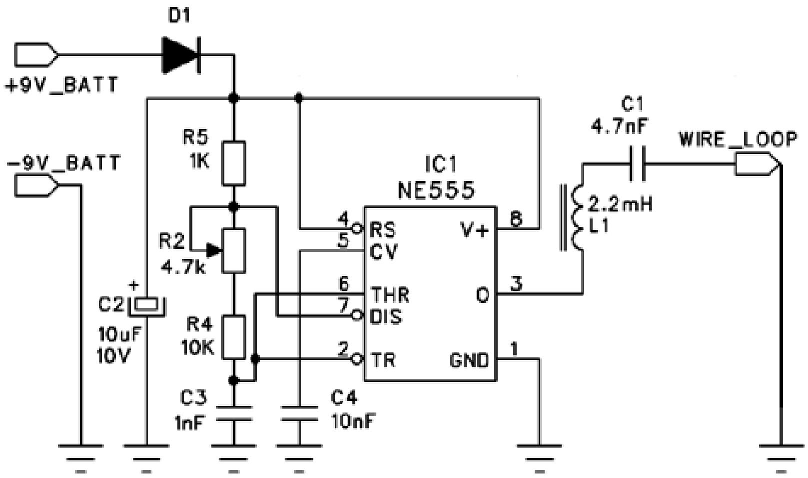

Fig. 15. Typical wiring limitations for area coverage.

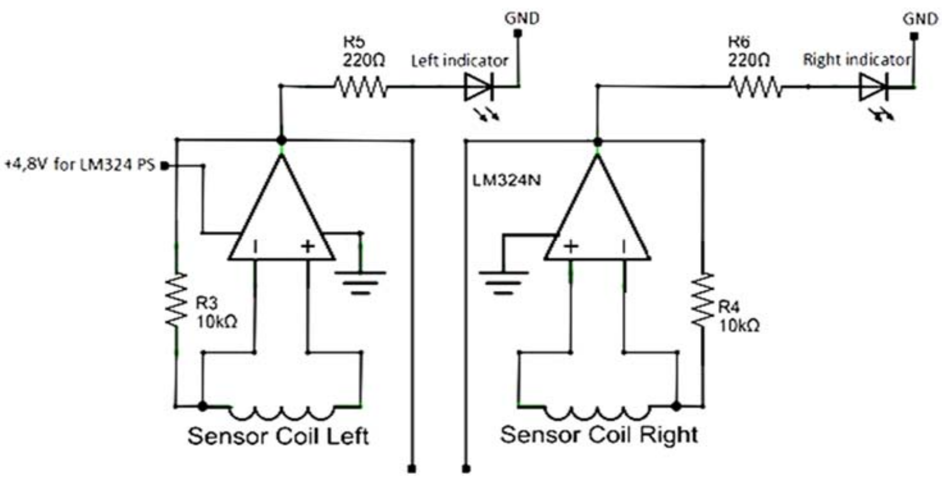

Fig. 16. On board coil sensors circuitry.

In general, a lawn mower, finds the correct path in an area without the presence of obstacles in order to cover every spot, like other similar robotic applications, [16-17]. Autonomous lawn mowers as well as other robotic devices like vacuum cleaners, are working in areas that not only humans and pets exist but also the environment itself is not steady. This is the reason that algorithms for robots are separated in two categories, the *Online* and *Offline* algorithms [10]. The first (Offline algorithms) are implemented in environments that are assumed to be known in advance and will remain in a steady state. This is proven to be unrealistic in many cases, see [18]. In the second category (Online algorithms) it is not taken as fact the condition of the environment or the area to be covered. Real time sensors are utilized to interact with the environment and for this reason they are called as "sensor-based algorithms".

As it was previously stated, the current work is an effort not only to study a robotic lawn mower function but also to construct the prototype. It was decided for the coverage path planning process to be based on the on-line algorithm method discussed earlier. Up to now and due to the nature of this application, engineers have not yet create an algorithm that would ensure a total area coverage, see [19]. Household robots that have been already released to the market and working with satisfactory results, are using randomize method. The current study also applied this method during experimentation. The obstacle avoidance procedure that ensures human safety, was an innovative design of not touching the obstacles like all other already built machines do but avoiding them from a distance without physical contact. The 'Coverage path planning' as well as 'obstacle avoidance' functions are having as requirement the route control of the vehicle. This means that when the vehicle turns, the angle of the turning must be calculated and adjusted if necessary. This is why the movement and turning process of the vehicle with encoders in both sides of vehicle. These sensors create pulses in real time following the rotation speed of the front wheels of the vehicle. Assuming that the grip of the vehicle is in an acceptable level (so the wheels are not spinning), these pulses can be related with the turning angle of the vehicle.

5. Conclusions and Future Applications

In this research project, an interesting device was implemented as a prototype after a lot of experimentation and performance testing. The basic idea of building a robust mechatronic vehicle that could operate as a lawn mower with additional functions that are not yet available in the market was successfully undertaken. The obstacle avoidance without physical contact is an innovation that ensures and increases safety in case the obstacle is a human or an animal. Throughout experimentation, the ability of this vehicle not to touch random placed objects (including people's feet) but locate and avoid them, while at the same time keep running its cutting function, was never interrupted or faulty executed. Based on ultrasonic sensing, and an up-to-date microcontroller, the movement procedure of the vehicle was always ultimate, taking also advantage of the real time data transmission from the optical encoders attached to front wheels.

The area coverage method which was adopted for the task, although based on simple electronic circuitry, proven to be a reliable and low cost solution that a possible user can place on any surface. Since the initial hypothesis of the project is satisfied and all safety requirements are met successfully, there is more space for further extensions and improvements of the device. For example, a camera placement can replace or co-operate with the ultrasonic sensor and predict a dynamic obstacle's presence on the area i.e. a walking person. At that time the vehicle should interrupt its operation and alert the person for an accident probability. In addition, the already installed microcontroller has the ability to host a camera sensor and at the same time with a GSM module, send text messages to the device owner with information like cutting time or battery discharge level. The establishment of such communication between the vehicle and the owner would allow the operation to start from a distance via a mobile phone device. Finally, the batteries autonomy could be further extended in order to limit up the operational time of the device. These future implementations can be hosted on the mechatronics vehicle as is right now, a fact that highlights the constructions versatility and expandability. In terms of usage in a "smart city' and adoption in any fully automated environment, this intelligent and versatile mechatronic platform could easily prove its assistance capabilities for human everyday needs.

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