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Intelligent low cost telecontrol system for agricultural vehicles in harmful environments

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ABSTRACT

The use of vehicles to control pests and crop diseases is needed to maintain agricultural production. This paper describes how to design and implement a low cost intelligent telecontrol system applied for agricultural machinery that are designed for use in places where human presence is not adequate, such as pesticide spraying tasks in farming environments as greenhouses. The intelligent system designed basically consists of these parts: States Encoding, Console Automaton, Vehicle Automaton, Communication System and Security of Communications. This system has been developed with a special-purpose UHF narrow band modem that interchanges digital operative commands/states from the console to the vehicle. The intelligent telecontrol system acts as a security system to protect against outsiders, and loss of communications due to fading or others interference. The originality of this system is based on the fact that it is 10 times cheaper than autonomous systems; those systems need electronic systems, GPS, a complex sensorial system, and a beforehand mapping performed on the new work environment. Related to classic remote control, our system protects from potential oversights of the operator. In addition, in the proposed system, the vehicle state is shown in the console, due the bidirectional communications. The system was successfully applied in prototype vehicle used for spraying tasks, and the result shows that the system operated stably and has confirmed the effectiveness of this intelligent telecontrol system. The proposed technology will help providing solutions for humans and robots working together in agricultural environments considered to be harmful to humans.

1. Introduction

Increasing yields on existing farmland is essential for 'saving land for nature' and for agricultural production systems, including systems with two or three crops per year. These crops may become progressively susceptible to disease and insect pests because of the insufficient diversity in crop rotation (Tilman et al., 2002; Stoate et al., 2009). Agriculture production has evolved into a complex process requiring the accumulation and integration of knowledge and information from many diverse sources, including marketing, horticulture, insect management, disease management, weed management, accounting and tax laws (Shaalan et al., 2012). Often, agronomic practices alone are insufficient for obtaining economically successful production, especially in the high value per acre production of vegetables and fruit (Felsot and Rack, 2007; Hilton and Mills, 2012). The rapid expansion of global demands for agricultural products, together with climate change, has caused a greater development of agricultural techniques, appropriate machines and equipment (Miodragović et al., 2012; Bennett et al., 2012). The use of machinery to control pests and crop diseases is needed to maintain agricultural production. Consequently, pesticides are applied in the presence of the people, and most of the pesticides are toxic to human beings (Jepson et al., 2014). Advances in mechanical design capabilities, sensing technologies, electronics, and algorithms for planning and control have led to a possibility of realising field operations based on intelligent agricultural vehicles (Kester et al., 2013). Furthermore the reduction of labour costs (Van Henten et al., 2006), problems with the availability of skilled labour and the improvement of the production process both quantitatively as well as qualitatively were and still are main driving forces of agricultural systems (Mueller et al., 2012). The navigation of field

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robots in an agricultural environment is a difficult task due to the inherent uncertainty in the environment (Hiremath et al., 2014a, 2014b).

The harmful environments, derived from intensive agriculture are unfortunately frequent, e.g. in greenhouse farming the workers can suffer thermal stress (Callejón-Ferre et al., 2011; Pérez-Alonso et al., 2011), and this can affect more men than women (Manzano-Agugliaro et al., 2013). On the other hand, the use of low cost systems is extending for monitoring the environment (Cama et al., 2013) and in agricultural applications such as the stiffness analysis of wood with knots in bending (Guindos and Ortiz, 2013), for monitoring intensive agriculture (Montoya et al., 2013; Cama-Pinto et al., 2014), for fruit grading systems (Clement et al., 2012), and for agricultural land vehicles (Zhang et al., 2012).

Several control systems exist for vehicles for different uses. The deployment of autonomous robots is an opportunity for enhancing tasks such as weeding, spraying, harvesting and mowing (Emmi et al., 2014; Auat Cheein and Carelli, 2013; Suprem et al., 2013). These are characterised by their ability to navigate and perform certain tasks on their own (Montalvo et al., 2012). The main problem of Autonomous Vehicles is that they are very expensive (Pedersen et al., 2005). This means they can not be used on small farms, such as greenhouses farms, where the average farm size is about 2 ha (Manzano-Agugliaro and Cañero-Leon, 2010; Márquez et al., 2011).

So, semi-autonomous control could be used in small farms like greenhouses, and some low-level tasks could be performed by a robot, in order for the operator to focus his/her attention on more high-level control tasks including the supervision. The base contains recorded knowledge about the environment, possible obstacles and possible trajectories for the vehicle. Collision avoidance methods and navigational systems are used to estimate the position of the vehicle (Kruse et al., 2013).

Additionally, well-known classical telecontrolled vehicles in which the operator remotely handles servomechanisms with a radio system can be considered an extension of the controls. These systems require intensive training by the operator, and information regarding what the vehicle is doing. The state of the vehicle is obtained by direct vision. Events such as a loss of communication may cause serious consequences in these systems or in the environment.

Collision avoidance methods can be divided into global and local approaches. Global methods assume that a complete model of the environment surrounds the vehicle, including routes, obstacles, alternative routes, allowed movements, etc. (Gasparetto et al., 2012). The main problem with these methods is that they are not appropriate for obstacles requiring fast avoidance. Local approaches consider only a small subset of obstacles surrounding the vehicle (Ogren and Leonard, 2005), which introduces limitations in the autonomous functioning of the vehicle. An interesting example of an autonomous vehicle that uses a combination of both techniques is given by Hentschel et al. (2007).

The position of the vehicle may be estimated using the Global Positioning System (GPS) (Gomez-Gil et al., 2011; Corpe et al., 2013) or Dead Reckoning (DR) (Ryan and Bevly, 2014). However, the use of these two methods or even a combination of these two methods does not provide a perfect solution to the problem of autonomous navigation.

Road scene analysis is a challenging problem that has applications in autonomous navigation of vehicles. Intelligent vehicles exist that navigate in complex, off-road terrain using embedded learning algorithms (Gopalan et al., 2012). Therefore, the main problem with autonomous systems is the necessity of a priori information regarding the workspace and possible changes in the environment for making decisions in unexpected situations. These vehicles have a complex sensorial system, including a local computer with a high capacity for calculus and information storing. In addition to a complete knowledge of the workspace, these vehicles require careful maintenance.

Intermediate solutions between autonomous and classical telecontrolled systems have already been considered by different authors. Schmidt and Boutalis (2012) proposed the substitution of a human controller with fuzzy automaton, which carried out decisions for the control of the vehicle in real time. This solution is quite similar to autonomous vehicles. Courbon et al. (2013) proposed a mixture of the two concepts. For the first stage of learning, the vehicle recorded marks, paths, etc., provided by a human controller. Later, in the second stage, the vehicle functioned as an autonomous vehicle. Rajamani and Zhu (2002) using simulation, they offered a similar solution to the one proposed in this paper. However, it is designated for road vehicles, where the semi-autonomous systems would be immediately deployable on today's highways.

However the semi-autonomous vehicle presents lower materials costs with same efficiency giving it better advantages over other systems. The developed system is mainly aimed for agriculture in greenhouses since horticultural areas necessitating use of pesticides are dangerous for human interaction at close distances. Some other authors determined that feedback information is used to control the vehicle automatically. Sharbafi et al. (2010) introduced a system in which the operator provides a final position instruction, the robot reaches that position in an autonomous way and the robot learn from the events that take place along the trajectory.

The system that is introduced in this work is a hybrid between autonomous and classical telecontrolled vehicles. It gives these vehicles some microprogrammed intelligence against unforeseen and requires the operator moderate supervision over the robot. An operation console interprets commands, and the vehicle performs the corresponding actions. A dialogue of operative commands and state responses is established, and the vehicle automatically solves serious problems, such as a loss of communication. Bandwidth use in the communication channel is reduced. Moreover, preprogrammed decisions can be selected for unexpected events, such as an automatic stop due to a loss of communication or the proximity of an obstacle in the vehicle's trajectory. The system is adequate for controlling vehicles that can be directly observed by the operator or monitored by video cameras in the vehicle in a control room in the area providing direct assistance through live video camera. The security of communications may also be an important issue depending on the purpose of the vehicle. Therefore, a novel encryption key selection method is used, which fits real time communications and is based on a Linear Feedback Shift Register (LFSR) that allows key selection from a list in a pseudorandom order (Novas et al., 2008). This remote control system has been tested for motor vehicle spraying and is manufactured at the University of Almeria.

Table 1 presents the three telecontrol types described here, and where advantages and disadvantages are highlighted. Intelligent telecontrol can be described as an intermediate approach that selects the best features of classical telecontrol and autonomous vehicles.

The gap which the proposed system tries to solve is to find a cheaper solution than autonomous systems to protect the vehicle and work space from the mistakes generated by the operator using classic remote controls. The final solution must neither be a complex system nor a too much expensive one. This aims to solve the problem of the operator who cannot pays permanent attention for driving a vehicle in a harmful environment for himself.

Table 1
Types of telecontrols and their main features.

Telecontrols	Advantages	Disadvantages	Application example
Classical	• Simple systems. • Inexpensive system.	• Needs operator. • Difficult to handle. • Need continuous operator attention.	• Radio-controlled models.
Intelligent	• Easy to operate. • Safety systems: automatic stop obstacle. • Embedded system microcontroller automatic functions: straight on, angle of turning ctr. Speed. • vehicle status in console	• Needs operator. • Moderate operator attention.	• Ideal for workplaces with multiple barriers and limited space: e.g. Greenhouse farms.
Autonomous Vehicles	• No operator. • Safety systems: automatic stop obstacle • Embedded system microcontroller automatic functions: straight on, angle of turning ctr. Speed.	• Very complex systems and sensors. • Need maps and position systems. • System powerful computer • Expensive system.	• Robot Aurora (Mandow et al., 1996). • Robotic weeding in high value, crop scouting in cereals and cutting grass on golf courses (Pedersen et al., 2005).

This paper is structured as follows: Section 2 offers a brief overview of associated technology, Section 3 describes the Intelligent System Design, Section 4 presents the evaluation of the system and discusses the results obtained and Section 5 summarizes the conclusions.

2. A brief overview of associated technology

The proposed system can be implemented using a low-cost microcontroller, which has a two-way communication system that exchanges commands and states with ultra-short packets for low-speed communications and for a narrowband radio with high reliability. Automatic features such as stopping near obstacles or a loss of communication can be implemented easily. The telecontrol system is divided into two parts: the operation console and the local control of the vehicle.

The console, displaying the state of the vehicle using indicators, is easy to manage and has new functionalities that can be easily added or modified by a firmware update without changing the hardware. The local control of the vehicle is performed by a microcontroller from the MCS-51 family, and the program is embedded in flash memory. The system has digital outputs from drivers of solid state, relay outputs and analogical power outputs with Pulse Width Modulation (PWM) technology, which act on the elements that control the vehicle:

- A hydrostatic actuation system with two variable flow pumps controlled by two proportional valves for the spraying task and two motors which drive the movement of the chain from the vehicle.
- An internal combustion engine of 614 cm^3 and 14.7 kW of power, which can achieve a maximum speed of 2.9 m/s.
- The Incremental encoders that measure the position, direction and speed of rotation of the shafts of the chains of the vehicle.
- An electronic compass to correct errors of incremental encoders.
- The Ultrasonic sensors for obstacle detection midway (40–300 cm) at the front and back of the vehicle and a short distance (15–100 cm) on both sides of the vehicle in order to guide the vehicle in a straight line between rows of crops.

The operation console has a joystick for entering input regarding motions, stops or directions from the operator. Lightning indicators exist in the console, which informs the operator about the state of the vehicle and the actions performed by the vehicle in real time. The console system has been implemented with an embedded microcontroller featuring Complementary Metal-Oxide-Semiconductor (CMOS) technology, which provides low power consumption with batteries.

The technology used for communications between the console and the local control of the vehicle is based on a narrow-band radio modem. This system allows reliable communication for long distances and low power. Radio modems are based on integrated modems and are controlled by a microcontroller, which also governs the operation of a radio transceiver. Fig. 1 presents a block diagram of the radio modem system.

The microcontroller receives the transmitted information through a serial port. Once this information is formatted and encrypted block by block, it is written into the buffer of the modem device (e.g., RAM). Next, the order is written to pass the block, and 12 bytes are modulated and output from TxA (ouput serial data). Premodulation is applied to the audio input that is transmitted via radio. An Interrupt Request (IRQ) interrupt informs the microcontroller that the task is complete, and new tasks can be accepted. The Push to Talk (PTT) signal is used for switching Tx/Rx (transmission/reception).

When the radio receives the command of reception that is sent to the modem, it detects a transmission that reports to the microcontroller through a Squelch (SQT) signal. If a properly formatted header is received, then reading orders are sequentially sent in packets of 12 bytes until the end of the message. The IRQ interrupt signals to the microcontroller that 12 bytes have been demodulated and are available to be read from the buffer.

Table 2 shows the main characteristics of the radio modem used. The device is the FX919B model from Consumption Microcircuits Limited (CML) Microcircuits. The modulation used is a direct type 4 Level- Direct Frequency Shift Keying (4L-DFSK) and has a very efficient narrow band. Direct correction of errors has a ¾ Forward Error Correction (FEC) that is a micro-programmed device and provides communication at 9600 b/s and 19,200 b/s half-duplex mode over long distances (tens of Km in direct visibility) and small all-directional antenna feeded with approximately 20 dBm power.

An encryption system is used so that the system is protected from outsider interference. A crucial point that affects encryption is the fact that the vehicle and console communicate in real time. Therefore, a list of keys is used to encrypt the transmitted information.

A class of algorithms exists, called stream cipher algorithms, which handle information as bit-to-bit. This class of algorithms is very appropriate for real-time communications when buffering space is limited, as in the case for radio modems. These algorithms are based on Linear Feedback Shift Registers (LFSRs), which generate encryption sequences and are very suitable for hardware implementation (Deepthi and Sathidevi, 2009).

The beneficial properties of LFSRs have been used to design an efficient selection key method that outputs pseudo-random sequences of key identifiers. The source and destination share a list of keys and a simple algorithm so that the same sequence is generated at both sides. Therefore, sequences are not sent, and issues such as compromised keys are prevented. Identifier pairs and only some of

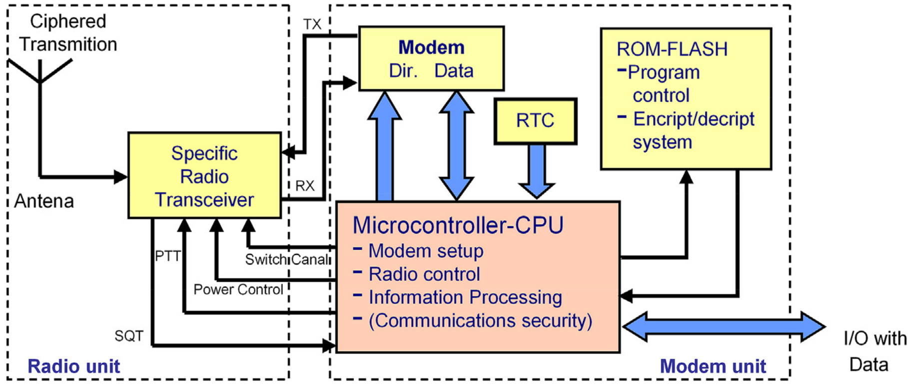

Fig. 1. Narrow band radio modem block diagram.

the additional information bits for the initial state of the system are required to encrypt/decrypt a large number of blocks of information.

3. Intelligent system design

The system is divided into two parts: the console and the control of the vehicle. A block diagram of the system can be observed in Fig. 2. The console has two control sticks to manage the direction of movement, start/stop switch, the speed selector and the remote drives (an example: the pump control spraying). As shown in Fig. 3, the console contains these main components: leds indicator, console automaton card, radiomodem card, direction levers, switch actuator, and speed selector. The operator is informed of the basic state of the vehicle (motion, turn, etc.) by five LEDs with different colours and behaviours (slow, fast or no blinking), which show the necessary information and allow the operator to view both the vehicle and the indicators at a glance. A display would require dedicated attention. Although more complex display may be interesting, the LED system that is controlled by the operator at the control room shows consistent efficiency for securing the developed semi-autonomous system.

Inputs and outputs are implemented on a port microcontroller directly to the stick entries or through a binary encoder as the speed selector. We have decided to use four speed levels and an inter-axis speed difference for turns. The difference depends on the turning radius as well. Nevertheless, the system uses 1 byte for speed codification so that other vehicles can distinguish between 256 different speed levels and precisely adjust the vehicle speed to function on the terrain. The communication port of the microcontroller unit is connected to the communication radio modem that interchanges operative commands with the vehicle in half-duplex mode. Automaton within the console processes the indications from the operator and produces the operative commands. These commands are sent to a different receiver automaton installed within the vehicle.

Table 2
Radio modem. Main features.

Parameter	Feature
Modulation	DFSK-4L
Bit rate	9600 b/s–19,200 b/s
Interface	Serial
Integrated modem	FX919B – Consumption Microcircuits Limited
FEC	Viterbi ¾
Radio band	UHF 400–470 MHz
Bandwidth	12.5 KHz @ 9600 b/s
Switching time Tx-Rx	6 ms
TX power	10 mW–500 mW
Rx sensibility	0.4 μV @ 10 dB S/N
VER	10^{-6} @ 0.4 μV and 9600 b/s

The vehicle controls obtain the information from the sensors for each axis. An angular R-speed and L-speed are coupled to the microcontroller through a port. In addition, the obstacle proximity sensor signal is introduced in another input bit port. Two PWM controllers are implemented with two MOS devices, which are connected to each bit port microcontroller with two 8-bit Digital to Analog Converter (DACs) each and are established at an angular speed on each axis with a variable step electric valve. Once the speed in each axis is set through an operative command, the control program modifies the pulse width, and the voltage that the device delivers to the speed controller for each axis corresponds to a type II system of a second order. Therefore, the control speed and the direction of travel can be managed at the same time by a two-way bit that is implemented on a port of the microcontroller. This scheme allows the detection of skids or improper turn situations, which are communicated to the operator. In addition, the vehicle's control can perform automatic decisions to restore normal operation. A relay output allows the switching of an actuator for spraying a pump. E.g. If the vehicle is ordered by the operator to move forward, but it detects an obstacle, it automatically stops and informs the operator through the console, that it has stopped; if it was spraying also this task will be stopped automatically. The system returns control to the operator only when the command is for an appropriate movement, obstacles free. All scenarios are programmed in the vehicle automaton, and can be modified by reprogramming depending on the work environment.

In our development, see Fig. 2, given the low vehicle speed, a proportional controller for the vehicle automaton drives was implemented that provides the setpoint of engine power. The vehicle rolls at 2.9 m/s corresponding to 10.44 km/h guaranteeing an effective spray treatment. In the literature, a Proportional Integral Derivative (PID) type controller was more convenient for faster vehicles (Fazeli et al., 2012).

3.1. States encoding

The vehicle moves at slow or moderate speeds; anyway it was programmed for four speeds (very-slow, slow, middle, and high) and the stop state. These are adequate for manoeuvre in greenhouse. With minor modifications, for other types of vehicles this development can be extrapolated.

The codification of the states constitutes a finite automaton, so their entries correspond to the steering levers, the speed selector and the interrupter of the trigger sprayer pump. The entry alphabet

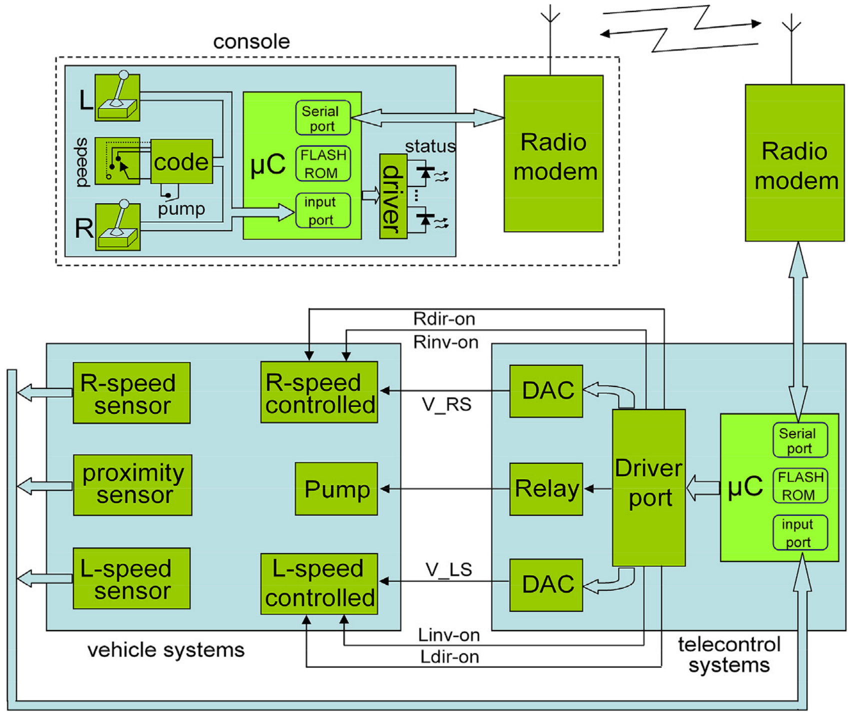

Fig. 2. Block diagram of the intelligent telecontrol system.

Σ consists of three subsets: the first one, with respect to the direction Σd = {d11, d10, d01, d00, d0-1, d-10, d-1-1, d1-1, d-11}, specifies the action performed by the steering levers. Thus, the entry d11 indicates the two levers forward, d00 stop, d01 left lever stop and right lever backward, etc. The second encoding table refers to speed Σs = {s00, s01, s10, s11} with the correspondence as follows: s00 → vslow, s01 → slow, s10 → medium and s11 → high. A third encoding table has been considered for the actuator with an alphabet Σa = {a0, a1, p0, p1, f0, f1}, and the correspondence is x0 → no action, x1 → action (for x = a, f, p), where a encodes relay on in task spraying, f encodes stop due fail communication and p encodes stop due to a obstacle. Table 3 summarizes the states defining the actions of the vehicle movements and for the operation of the actuators (spraying in our case).

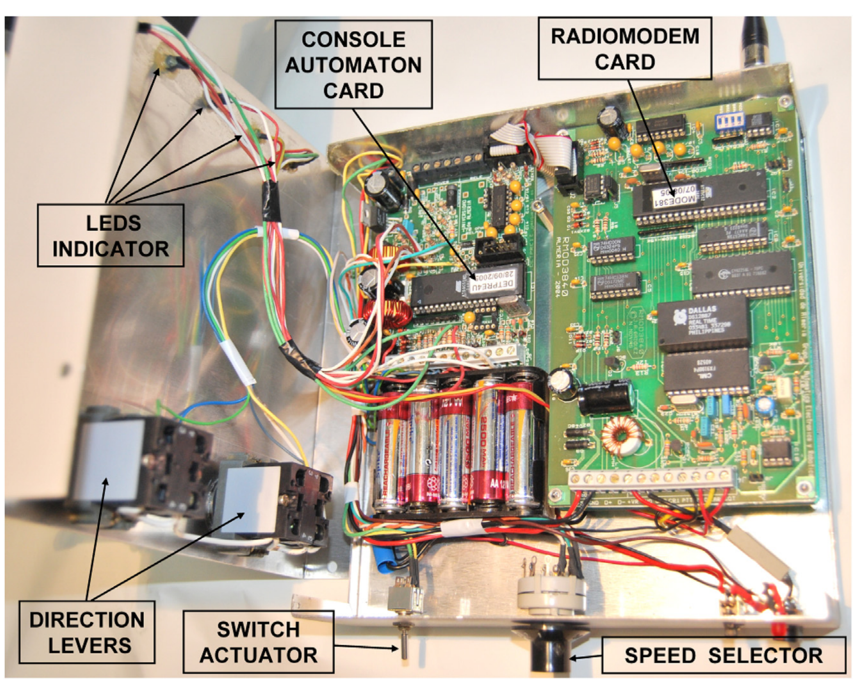

Fig. 3. Main components inside the console.

3.2. Console automaton

The guidance system by automaton improves the behaviour of the vehicle in adverse conditions (Mars et al., 2014). So, the console is the man–machine interface that detects manoeuvring that man wants to do at every moment and encodes it in one of the allowed states. The automatons improve the safety of control systems (Yu and Xu, 2010). The console automaton interprets the orders made by the operator using the aforementioned tables. Not all actions indicated by the console sticks are allowed. For instance, if the current state is S1 (corresponding to proceeding straight ahead), we cannot pass to state S5 (proceeding backwards and turning right). Therefore, control sticks define the meaning, direction and mode of action for nine different states with transitions between them in order to allow an appropriate operation.

The sticks left back and right in the neutral position that generate input d-10 are not accepted and would require a pass through state S0 to stop so that input d-10 defined by state S5 could be accepted. The speed information and orders to perform do not pass through this automaton. Instead, the speed information and orders are transmitted directly after codification, so the control system interprets them. The operator, always from his control room, can receive the video coming from the camera for a better control of the system. Fig. 4 shows the automaton that represents the functioning of the console (Table 3).

3.3. Vehicle automaton

The controllers for the vehicle's engine actuators have been implemented with a microcontroller of the same type as the console with another form of automaton. This automaton regulates the functioning of the vehicle to prevent inappropriate speed variations. Some authors also use finite automaton as tool for the formation in the control (Yan et al., 2014). Additionally, this automaton has entries that affect the safety of manoeuvring the vehicle (like obstacle detection or loss of communications) and provides a transition to the S0 state, such as stopping the vehicle until a problem is resolved. Packets sent by the console are inputs of the automaton. They are joined with the sensorial information about direction, speed of the vehicle and the proximity of obstacles to the vehicle. This serves to determine the next state of the automaton.

Proximity detectors in the vehicle generate the entries $\Sigma p = \{p0, p1\}$, where p0 indicates a path without obstacles, and p1 indicates that an obstacle has been detected and that the vehicle should be stopped.

The vehicle automaton regarding communications state generates the entries $\Sigma f = \{f0, f1\}$, where f0 indicates that the last two packets have been received with a right checksum and f1 indicates that two consecutive errors of checksum are present in the packets or that they have not been received (cf. Table 3). If the vehicle does not receive two packets of orders consecutively (failed transmission), the automaton proceeds to an inactive state.

Fig. 5 represents the transition between speed states that are mapped on the states of direction Sj, depending on the codified selector on the console Σs, the proximity detectors Σp and the state of communications Σf (Table 3).

The vehicle automaton shows five speed states for each direction state, Sj: from Stop to High. Thus, each of these states has mapped the set of states defined by the information encoded on the console for directions and actions that affect the state for a given speed. For example, Sj10 is complemented with information that could be “going forward and turn right” and spraying actuator ON.

This state can be defined as nested within each other. The actuator case is also mapped as two sub-states: one sub-state as an actuator switch on and one sub-state as a switch off. If additional speed levels were needed, the automaton would have more states: one state per additional level, from state Sj11 to the left (Fig. 5).

If a failure occurs in communications, in Fig. 5 is represented as an entry d00, p1, f1, any state makes a transition to state S0 corresponding to stop. Likewise occurs with an obstacle on the road.

Table 3
Directional states encoding.

Directional states encoding			
dL	dR	State	Effect
1	1	S1	Straight
1	0	S2	Front-right
0	0	S3	Front-left
0	0	S0	Stop
0	−1	S6	Reverse-left
−1	0	S5	Reverse-right
−1	−1	S4	Reverse-straight
1	−1	S7	Turn on clockwise direction
−1	1	S8	Turn on anti-clockwise direction

Speed states encoding				
Code	Speed	PWM	PWM′	Km/h
s00	vslow	07	04	1.2
s01	slow	23	17	3.0
s10	medium	77	68	6.0
s11	high	E5	D3	9.0

Sensor/action states encoding		
Code	Action	Case
p1	stop	Obstacle
f1	stop	Fail communication
a1	relay on	Spraying

3.4. Communication system

The vehicle's actions have been encoded using four ASCII characters (American Standard Code for Information Interchange). The main reason for this decision was for the possible use of command generators and visualisations in any PC, especially at the setup phase. Additionally, the bandwidth use would not be significantly improved with binary encoding. Table 4 shows an example of the encoding used in several states for tracked vehicles with a spraying system. The low bandwidth requirements of the system (compared to classical telecontrol) allow the use of a 4800 b/s bit rate, which is sufficient for bidirectional communication. A narrow-band radio modem in the UHF band was used. Aside being powerful and reliable, this radio-modem is low speed which represents its main advantage. Therefore, it is used in industrial applications requiring high security in manoeuvres (actuating of gates in marshes, actuating valves and motors in plants water, etc). The narrowband used for the implementation supplies sufficient, stable and long reliability communication.

Fig. 6 shows an example of a chronogram for an information exchange between the vehicle and the control console: operative commands sent by the console and the corresponding response of the vehicle's state. All radio communication systems are susceptible to a loss of information due to interferences, electrical noise, etc. After two consecutive failures, the vehicle proceeds to a stop state and restarts only after receiving another valid command from the console.

3.5. Security of communications

Protecting communications from outsiders may be of crucial importance in some cases as mentioned in Section 2. When attempting to define an appropriate algorithm to perform this

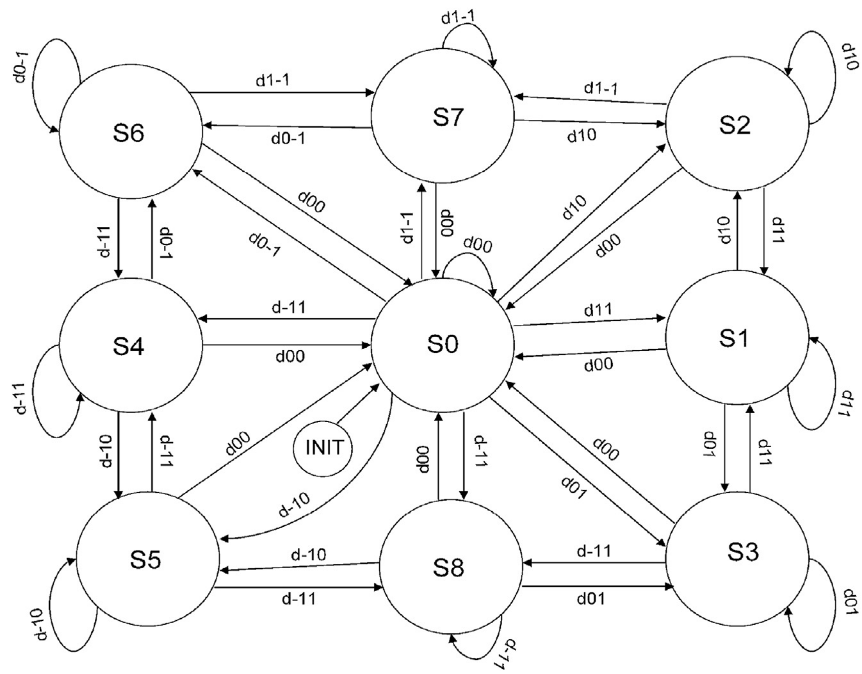

Fig. 4. State diagram of the automaton (Directional States Encoding) implemented by the console automaton.

task, we must consider different variables, such as the level of required security, the speed and the bandwidth of communication or the computing speed of the devices for implementing the algorithm.

For real-time communications and due to the characteristics of the devices, an efficient and light algorithm is needed. We use a list of keys (256 Bytes) in both parts of the communication, such as the console and the vehicle that are in the memory code of the

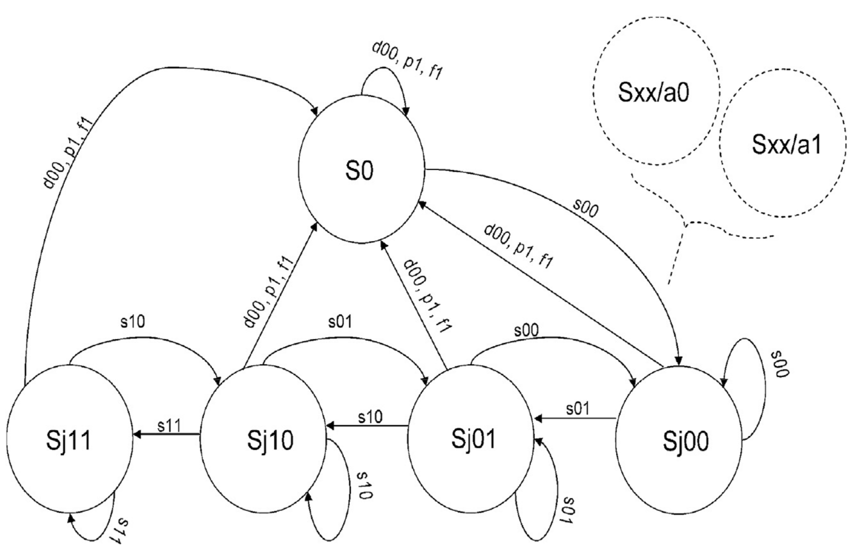

Fig. 5. State diagram of the automaton (Directional States Encoding) implemented by Vehicle automaton.

Table 4
Example of state encoding.

4 bytes	1 bit	1 bit	1 bit	1 bit	1 bit	2 bytes	Action
COM	Rdir	Rinv	Ldir	Linv	Pump	Speed	
0000	0	0	0	0	0	00	Stop
AA01	1	0	1	0	0	01	Run forward slow speed
BB23	1	0	1	1	1	23	Run forward normal speed pump
GC17	0	1	0	0	0	17	Run reverse normal speed
AD07	1	0	0	0	0	07	Run turn left slow speed
AB97	1	0	0	0	0	07	Turn on its axis slowly

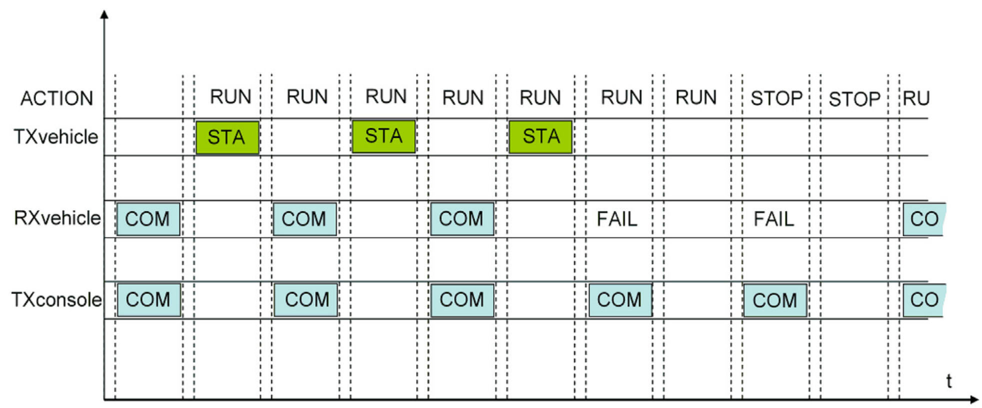

Fig. 6. Example of sequence for communication packets: when communications fail the robot changes the action to stop and will resume when the comuncación operated remote controlled operation becomes.

corresponding microcontrollers with only execution access. The key selection from these lists is performed through a Linear Feedback Shift Register (LFSR), see Fig. 7, whose initial state or seed is communicated at the beginning of every message. To avoid an attack based on the Berlekamp–Massey algorithm (Chen et al., 2011), we also consider, as part of this algorithm, a non-linear filter to avoid the linearity of the output for the LFSR (Deepthi and Sathidevi, 2009; Vaidya et al., 2011; Qu et al., 2013).

In these 256 8-bit numbers randomly generated will integrate the list of keys. The sequence to run over the list of keys or key selection method is obtained from a non-linear filter generator, composed of an LFSR of 8 stages and a filter function defined by a Boolean function that will be used to generate numbers in the range 1–255 as output. The LFSR will be determined by a primitive polynomial of degree 8. In this case the primitive polynomial is: $X8 + X4 + X3 + X2+1$, which means that the value of a0 a1 … a7 in Fig. 7 is 10001110.

When we want to encrypt a message coming from an information source, we need hierarchy in the structure of this message. The message is divided into bytes (bits), each byte will be encrypted by performing the exclusive OR with the byte value that is in a certain position of the key table. First, a random number of k bits (8 in our case) is calculated and is entered into the LFSR $S0\ S1 \ldots S_K$. the result $B0, B1, \ldots, B_j$. is the position of the first key with that the first byte of the message is encrypted. The following bytes of the message is encrypted with the key defined by the new value of the B0, B1, …, B7 to feedback S7 LFSR with the result of the last operation and shift S7 → S6 → S5 → S0. And so on until encrypt every byte of the message. A combinational logic circuit is responsible for obtaining the number of bits required to obtain the address of the key table B_0 to B_j, as $J \le K$. In our case, it is not necessary since $K = J$. To decrypting, the procedure used is the same as for encrypting, since the system is symmetric; if message is cipher twice, the original message appears. This cipher system is very safe, because the key is secret and being an embedded system, the key can not be read; only the procedure is executed.

4. Evaluation and discussion

The final configuration was performed after a series of tests and trainings including the speed coefficient for each axe and each of the possible combinations. Results turn out that the vehicle is allowed to manoeuvre safely.

For instance, at a predetermined speed such as medium speed, a right or left turn has a determined velocity and an optimum turning radius that are experimentally obtained and programmed depending on the dimensions and weight of the vehicle with possible corrections including whether the vehicle has cargo. Additionally, the coefficients for both axes were adjusted so that the vehicle moved in a straight line for a long path because the asymmetry of the vehicle structure could not be adjusted with the feedback from the speed turn sensor. Another adjustment was performed for the automatic stop system against obstacles to avoid sudden stops that could unbalance the vehicle load during turns for

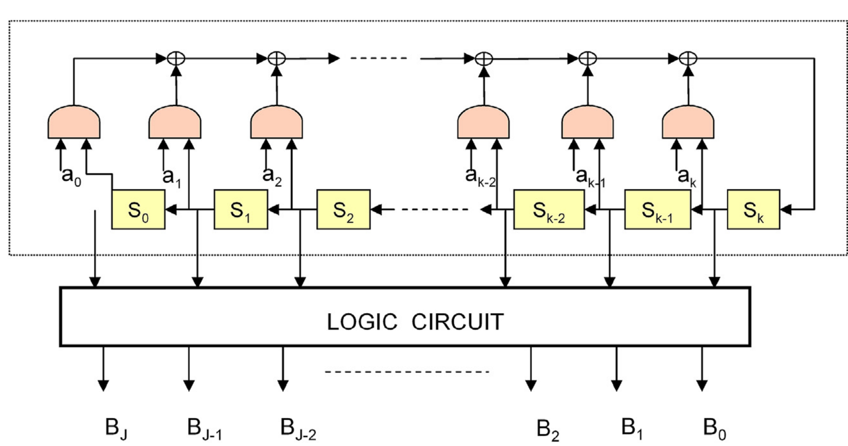

Fig. 7. Scheme of the key selection method.

a smooth and gradual stop without collision with the obstacle. For efficiency and security matter, adjustments were made to the spraying pump for real environments manoeuvres used for spraying greenhouses.

Fig. 8 shows the implementation of this system: the control system, the antenna and the console (held by the operator) and the vehicle (platform for greenhouse spraying). The string length is 2.5 m, and the distance between them is 0.7 m. The path where the vehicle is telecontrolled in an outdoor environment can be seen in the appendix section or through the link <http://www2.ual.es/te/icons/televeh1.MPG>.

As an example of system operation, a path on a flat surface which is usual slope inside greenhouses, is analysed over 50 s at different speeds and with several turns. The centre point of the vehicle is acquired twice per second. Fig. 9 shows the path; the numbers next to the points indicate the instant of time corresponding also to Fig. 10. Fig. 10 shows for this path (Fig. 9) the angular speed for the left and right motors of the tracked vehicle with respect to the different manoeuvres. First (1–10 s), the vehicle starts moving straight at a slow speed from a detention state, one can see how the rpm for right direction decrease from 20 to 9 rpm, instead the left direction keep the speed. Next (1–15 s), the vehicle starts turning right with a wide turning angle and continues again moving straight (16–20 s), the rpm for both direction axis are close to 20 rpm. After at 20 s, the vehicle speed increases to medium, 38 rpm, and it lowers, turns left (36–39 s), as we can see at this medium speed both direction decrease, letf axis decrease to 19 rpm instead right axis only do to 30 rpm, this is due that at medium speed the vehicle could dump, so a decreasing both axis is advisable. Finally (40–50 s) continues moving straight and then stops (54 s). We can check the corresponding state encoding in Tables 3 and 4. We have to emphasise that during this manoeuvre, the operator only sends directional orders for medium speed.

This Intelligent Telecontrol is a hybrid between classical telecontrolled and autonomous vehicles and offers the following conceptual advantages from Classical Telecontrol: avoiding the difficulty of learning and managing (Kruse et al., 2013), providing a complete knowledge of the state of the vehicle at every moment because communications are bidirectional and avoiding erroneous functions in situations that could become dangerous. These features differentiate the developed system from other previous systems (Schmidt and Boutalis, 2012; Courbon et al., 2013) added to the fact that it is provided with low cost material as it will be dissected later. Another enhancement that we achieve with this system for the classical telecontrolled vehicles is the possibility of providing a straight-ahead march in an automatic way or choosing an adequate radius for turning depending on the speed to avoid a possible vehicle rollover due to the inherent uncertainty in the environment (Hiremath et al., 2014a). Other systems as Autonomous Vehicles, are more expensive, e.g. 40,400 € for electronic systems + GPS (Pedersen et al., 2005), complex (have a complex sensorial system) and need beforehand mapping performed on the new work environment (Gopalan et al., 2012; Gasparetto et al., 2012). The system developed for Intelligent Telecontrol including two radio-modem, console and vehicle microcontroller, has the following cost analysis: the 2× UHF Narrow Band Radiomodem cost 2500 €, the 1 Console microControlled costs 600 €, the 1× Actuator interface costs 700 €, the 1 set sensor collision costs 300 € which makes a total of 4100 €.

On the other hand, the main advantage of the narrow band developed system compared to wideband is to realize stable long-range and reliability communication (Shao-Hua et al., 2010). In addition, the carrier purity of transmission spectrum is very good; therefore it is available to manage an operation of many radio devices within near frequency at same time. In real scenarios working, the vehicle can operate monitored by a TV camera from an office near the greenhouse. This could allow managing multiple vehicles on the same farm. Since the operator is always available at his control room, he is responsible of monitoring the vehicles, and keeping control over their track. While the systems are semi-autonomous, the operator can handle monitoring several vehicles at a time since his work is limited to observing and maintaining communication with the console of the vehicles that sends continuous information about the state and the situation of the vehicle.

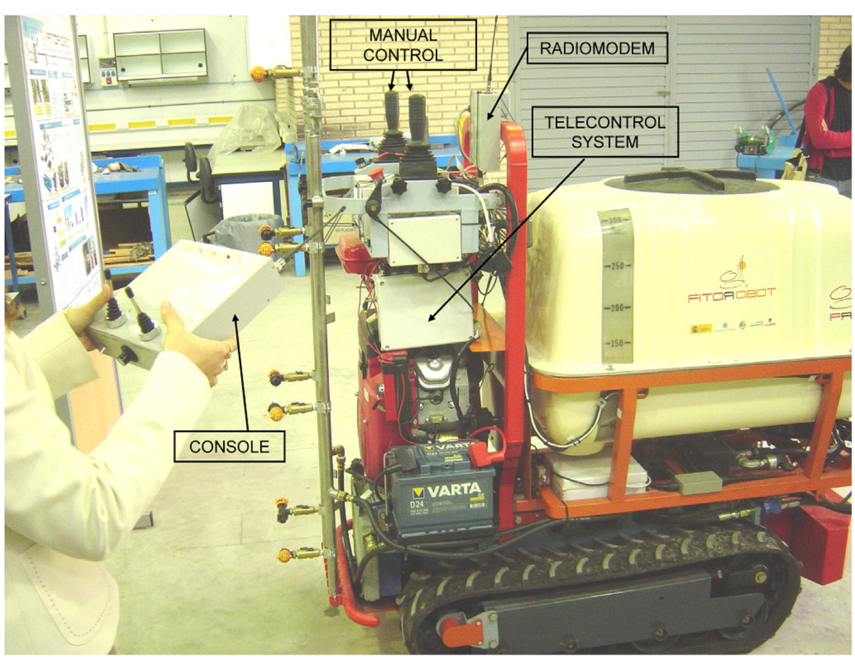

Fig. 8. Main components of intelligent telecontrol system and agricultural vehicle.

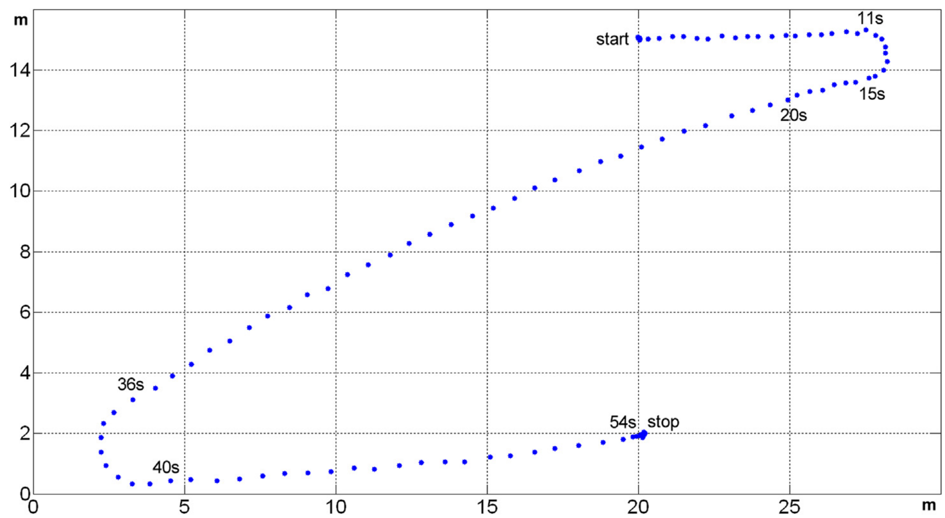

Fig. 9. Analysed path X–Y axis of the vehicle, time 0–54 s.

A security improvement is developed in the system. The vehicle automaton was programmed to stop when a danger of collision is detected by the sensors. Other authors also foresee limitations in the autonomous functions of the vehicle in this situation (Ogren and Leonard, 2005). The operator console receives information that the vehicle is stopped. Also the automaton is programmed in the case that interference will occur in communication via radio or communication is lost by excessive distance between console and vehicle, the vehicle will stop and alert to operator console the communication failure, because the console reports to the operator the action that this vehicle performer in real time. Because the console sends operating commands constantly to the vehicle, the vehicle is programmed to respond to each command console and therefore it can response to the operator via LED on the console over communications failure. In this way, when a failure in communication happens, the vehicle is stopped, and the operator is alerted through the console.

The system is considered to be semi-autonomous, the control system can be stated as a teleoperated agriculture vehicle system. Although no GPS is required, the entire field can be covered and that could be achieved by establishing marks or beacons in the workplace which will tell the operator the path, this is very different from the proposal of other authors that use GPS to locate the vehicle (Gomez-Gil et al., 2011; Corpe et al., 2013; Ryan and Bevly, 2014). The robot proves the real applicability of the operator being always able to be observed by the vehicle. First, the vehicle can be seen by TV camera, from a control room that can even serve several vehicles. Most important of all, it can be operated in unsuitable environments for people such as excessive noise or use of pesticides. The ranges of the speed listed from very slow to slow, medium and high are enhanced according to Table 1 by incorporating the linear velocity. The LEDs are provided to report about the current state of the vehicle such as its start, stop and pump status. Moreover, they can inform about the state of communications such as the vehicle communication failure console and can alarm about any collision in case it happens.

The novelty of the “Intelligent telecontrol” is that it is much more efficient and safer than vehicles with standard remote and not much more expensive than these. While other systems are much more complex and expensive, the implemented intelligent robot is a lot simpler and less expensive. As future research, this system is expected to be used as alternative control of unmanned

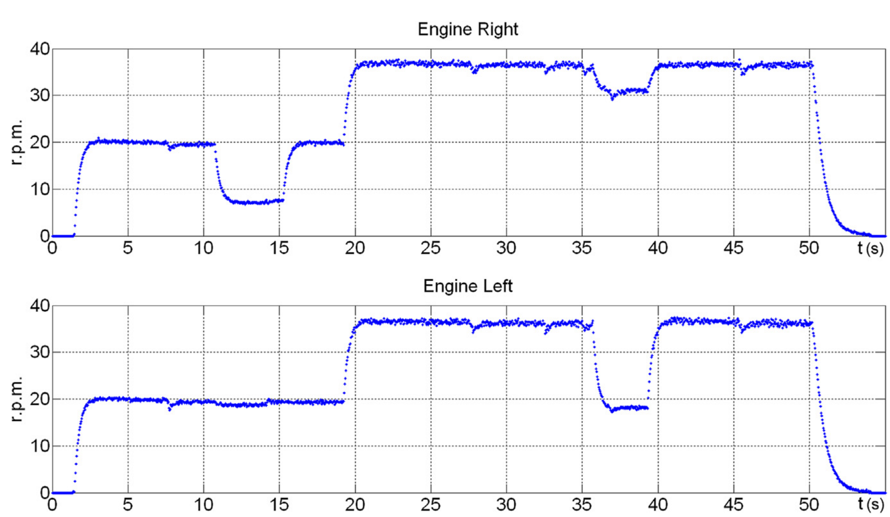

Fig. 10. Representation of the angular speed in a path of Fig. 9.

aerial vehicles. E.g. If the UAV looses this communication, it can fly around its current position in order to avoid the lost of the vehicle.

5. Conclusions

The system presented was implemented in vehicle for greenhouse spraying where the environment is quite harmful during this task. A new intelligent telecontrol system for vehicles based on finite automaton and with a secure communication system that allows the control of vehicles for different purposes in an easy and safe mode has been introduced compared to classical telecontrol. The system implemented mainly for spraying function in an agriculture environment can be placed in some other situation to provide other precise duties. The development is low cost, less complex and does not need beforehand mapping performed on the new work environment compared to Autonomous systems. The main advantage of this intelligent telecontrol is that it does not require the use of sophisticated systems that need careful maintenance or a complete knowledge of the vehicle workspace. At the same time, the functions provided by the designed automaton show an easily operated vehicle and an acceptable level of security. This automaton diminishes concerns of a possible loss of control due to a high security level for communication, due the narrow band, which prevents possible interferences or outsiders after a lengthy testing period. Additionally, we can observe that during the turns, both motors reduce the speed automatically to avoid vehicle rollovers when vehicle goes at medium or high speed. The main advantage of the narrow band developed system is to realize stable long-range and reliability communication. In addition to that, the purity of transmission spectrum is very good; therefore it allows managing an operation of many radio devices within near frequency at the same time. This system also opens new perspectives in the field of unmanned aerial vehicles telecontrol.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.11.015.

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