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Research Article

Networked Control System for the Guidance of a Four-Wheel Steering Agricultural Robotic Platform

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A current trend in the agricultural area is the development of mobile robots and autonomous vehicles for precision agriculture (PA). One of the major challenges in the design of these robots is the development of the electronic architecture for the control of the devices. In a joint project among research institutions and a private company in Brazil a multifunctional robotic platform for information acquisition in PA is being designed. This platform has as main characteristics four-wheel propulsion and independent steering, adjustable width, span of 1,80 m in height, diesel engine, hydraulic system, and a CAN-based networked control system (NCS). This paper presents a NCS solution for the platform guidance by the four-wheel hydraulic steering distributed control. The control strategy, centered on the robot manipulators control theory, is based on the difference between the desired and actual position and considering the angular speed of the wheels. The results demonstrate that the NCS was simple and efficient, providing suitable steering performance for the platform guidance. Even though the simplicity of the NCS solution developed, it also overcame some verified control challenges in the robot guidance system design such as the hydraulic system delay, nonlinearities in the steering actuators, and inertia in the steering system due the friction of different terrains.

1. Introduction

Agribusiness is an activity of great importance to Brazil's economy and is responsible for more than 30% of the Brazilian gross domestic product (GDP). This economy sector has a great interest in providing solutions for sustainable agricultural development through the development and transfer of technology. The application of management techniques such as the precision agriculture (PA) aims at better utilization of the cultivated area and opens opportunities for technological development applied to the agricultural sector. References [1, 2] discussed about the new technologies and recent trends which will be required by the future in the agricultural area and the green farm concepts.

New agricultural practices related to PA have enhanced the importance in the research of embedded sensors and communication networks [3, 4] for the study of spatial variability and for the application of inputs using variable rate technology (VRT). New technologies and devices for real-time data acquisition and actuation have been released to equip agricultural machinery to support and automate these practices [5, 6]. The use of PA makes possible the culture management that seeks to maximize productivity considering spatial variability of the area, as opposed to traditional management, which applies the same amount of input for the whole area, may be resulting in better use of the chemical products, increase of productivity and reduced costs for the producer [7].

The use of robots as autonomous agricultural vehicles has an interesting potential as a valuable technological tool for PA, bringing the advantage of applying several robotic control theories for applications in various other areas [8]. This recent trend of development of mobile robots and autonomous vehicles for application in specific tasks is driven mainly by the requirement to improve the efficiency and provide better results (soil compactation reduction and machine operator absence) when compared with the use of traditional large tractors and machinery [9].

A current related trend is on the design of specific robotic platforms for autonomous vehicles and agricultural mobile robots [10, 11]. Recent applications of mobile robots have used distributed architectures based on fieldbus networks [12, 13]. Fieldbus-distributed control systems have replaced the traditional centralized control systems because of several benefits such as reduced cost and amount of wiring, increased reliability and interoperability, improved capacity for system reconfiguration, and ease of maintenance [14]. Although the fieldbus-networked control systems offer several advantages over traditional centralized control systems, the existence of communication networks makes the design and implementation of these solutions more complex. Networked control systems (NCSs) impose additional problems in control applications with fieldbus: delays, jitter, bandwidth limitations, and packet losses [15]. And the network delays may be constant, random, or time varying [16, 17]. Between the several fieldbuses, the controller area Network (CAN) protocol is the most common technology applied on embedded electronics and also in agricultural robots [18].

A common approach when designing NCS is to analyze and model the delays and missing data aiming to develop more robust control strategies [19, 20]. A control strategy is required to handle the network effects improving the performance and guaranteeing the stability of the NCS. An increasing research effort has been devoted to the PID control design for NCS. Reference [21] develops a robust $H\infty$ PID controller for NCS such that load and reference disturbances and also measurement noise can be attenuated with a prescribed level by incorporating this information in the closed loop state model. The theory of robust static output feedback (SOF) control for NCS is investigated and employed to design a remote PID controller for motor systems in [22]. In this paper the effectiveness of the proposed strategy is proved using simulations for a case study of a NCS subject to network delays and missing data.

Based on this research focus, the project "Agribot: Development of a Modular and Multifunctional Robotic Platform for Data Acquisition in Precision Agriculture" currently funded by FINEP (research and projects financing) in Brazil is developing an agricultural mobile robot called Agribot. This research and development project is a partnership among the University of São Paulo at São Carlos, the Brazilian Agricultural Instrumentation Research Corporation (Embrapa Cnpdia), and the company Máquinas Agrícolas Jacto.

In this paper a simple networked control system (NCS) solution is presented using the CAN network, for the four-wheel hydraulic steering and guidance of this agricultural robot. The correct steering control of the wheels is required for a suitable robot guidance and movement and needs to overcome some verified control challenges such as the hydraulic system delay, nonlinearities in the steering actuators, and inertia in the steering system due to the friction of different terrains. The NCS control strategy developed, centered on the robot manipulators control theory, and is based on the difference between the desired and actual position and considering the angular speed of the wheels. Experimental results with the robot demonstrated that the NCS solution for the distributed control was simple and efficient, providing suitable steering performance for the robot guidance.

This paper is organized as follows. After this introduction and literature review in Section 1, Section 2 presents a description of the agricultural robotic platform developed focusing on the mechanical structure and electronic devices. Section 3 presents the details of the wheel steering system and discusses the challenges faced to develop its control. A description of the NCS solution developed in this paper is given in Section 4, focusing on the NCS architecture, the Agribot kinematic model, and the NCS control strategy proposed. The results are resumed in Section 5, and finally some conclusions are outlined in Section 6.

2. Agribot Description

The project aims to develop a modular robotic platform able to move around in typical Brazilian agricultural environments with the main purpose of in-field data acquisition and new technologies research for sensing in agricultural area. Its main features are the robustness, mobility, high operating capacity, and autonomy consistent with agricultural needs. The robotic platform will feature a multifunctional structure to allow the coupling of different data acquisition modules to study spatial variability through embedded sensors and portable equipment. The proposed platform is composed of two main subsystems: the robotic platform subsystem and the modules subsystems. This paper focuses on the robotic platform subsystem.

2.1. Robotic Platform Description. The robotic platform subsystem, presented in Figure 1, consists of a mechanical structure and the electronic system and is able to move effectively in adverse agricultural environments. It has been manufactured by the company *Máquinas Agrícolas Jacto* and is based on the structure of a portico agricultural mobile robot developed previously [13, 23] by the research institutions.

The mechanical structure has a rectangular portico configuration with headroom of 1.8 m (Figure 1). The frame has an adjustable gauge of 2.25 m to 2.80 m, which means that it is possible to change the distance between the wheels in function of the characteristics of the field or culture. As a mobile robotic platform designed to operate in the main Brazilian agricultural environment, in almost all the growth and postharvest cycles, it requires a versatile structure. To provide this versatility, the robotic platform system was designed in separate modules, denominated as

(i) Main Frame Module, in which the main engine, fuel tank, the tank of hydraulic oil, hydraulic pumps and hydraulic cylinders are fixed;

Figure 1: Agricultural robotic platform: Agribot.

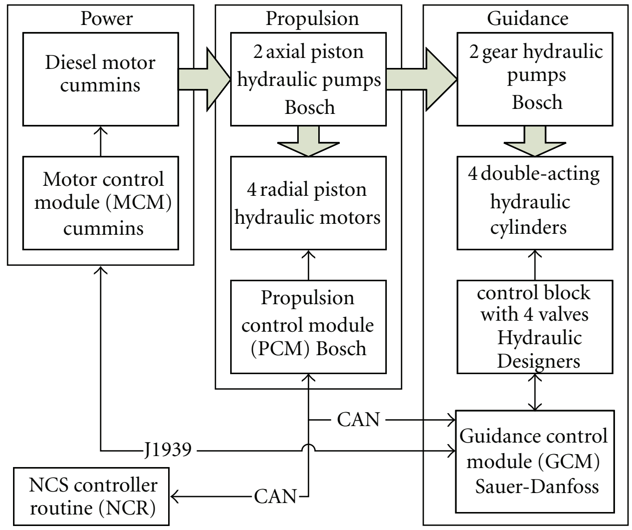

Figure 2: Electromechanical schematic view of the robotic platform.

(ii) Wheels Module, composed by a hydraulic propulsion motor, one 9.5″×24″ agricultural tire fixed directly in the hydraulic motor, steering system, pneumatic suspension system, and a telescopic rod for fixation and control the adjustment of the gauge in the main frame.

Above of the main frame a refrigerated case is located to accommodate the navigation and control systems, as well other electronic components which compose the robot. The weight of the platform is around 2800 kg.

Figure 2 presents a schematic view of the electromechanical system of the robotic platform. The main power source is a turbocharged Diesel 4-stroke engine with an electronic injection system, manufactured by *Cummins Inc.*, which provides 80 hp at 2200 RPM. The main characteristics of this kind of power source are autonomy, which in this case can reach up to 20 hours, and the ability to refuel quickly. The fuel tank has capacity of 140 liters of oil Diesel. There is also an electric power system composed by three batteries with 12 VCC and 170 Ah, connected in parallel, totaling 510 Ah, and feedbacked by one alternator fixed in the Diesel engine.

The management and the control system of the Diesel engine are owner of *Cummins Inc.* and use a SAE J1939 high layer communication protocol, based on CAN, with data transmission rate of 250 Kbit/s. The electronic control system requires the transmission of some periodic messages (by the user), otherwise the engine is turned off automatically. The input data of the system is the RPM of operation, and the output is fault alarms and some engine operating parameters.

The hydraulic propulsion system consists of two variable axial piston pumps with electronic proportional control by solenoid manufactured by *Bosch Rexroth AG*. The nominal pressure of the pump is 300 bars and maximum flow rate is 28 cm^3 per revolution, and the maximum speed at maximum flow rate is 4000 RPM. The pumps are connected in series and attached directly in the Diesel engine. The pumps feed four radial piston hydraulic motors with two speeds, also manufactured by *Bosch Rexroth AG*, and the maximum speed in 1/2 piston displacement is 465 RPM which results in a displacement speed up to 24 km/h. The nominal flow is of 470 cm^3 per revolution, and nominal and maximum torques are, respectively, 1680 Nm and 3030 Nm. The hydraulic motors are equipped with static brake with torque of the 2200 Nm and encoders for speed control.

The propulsion control system of the engines is owner of *Bosch Rexroth AG*. The electronic control system of the hydraulic system uses the CAN ISO11898 protocol with data transmission rate of 250 Kbit/s and 29-bit ID. The input data of the system are the displacement direction, speed of the motors, and static brake status, and the output data are motor speed and transmission fault alarms.

3. The Challenges of the Four-Wheel Steering Control

The use of four-wheel steering enables parallel displacement of the vehicle and facilitates maneuvering. The steering on all wheels also minimizes side slip of the wheels resulting in reduced wear on the vehicle and less damage to the culture [24]. Many works [24–26] highlight the use of robots with independent steering on all four-wheel and the development of control solutions for them. The wheel steering system of the robotic platform is described here together with the discussion of the challenges which will be faced by the NCS control development.

3.1. Details of the Wheel Steering System. The hydraulic guidance system consists of two gear pumps manufactured by *Bosch Rexroth AG*. The nominal pressure of the pump is 250 bars, maximum flow rate is 11 cm^3 per revolution, and the maximum speed is 3500 RPM. The pumps are connected in series and fixed directly after the propulsion system pumps. The pumps feed four double-acting hydraulic cylinders, which are controlled by a control block with four proportional valves with eight ways (two for each cylinder) driven by solenoid, manufactured by the *Hydraulic Designers* company. Each hydraulic cylinder is connected in a rack, which drives a pinion, converting linear motion into radial motion, allowing that the wheel turns to 133° until −133°. The position feedback of each cylinder is made by a linear potentiometer by *Gefran SpA*.

Figure 3 presents the details of a wheel module and the parts that belong to the guidance system, like cylinder, potentiometer, and motor, clarifying the operation of the robot wheel steering system.

The control system of the guidance hydraulic cylinders is done by an electronic control unit (ECU) manufactured by *Sauer-Danfoss* that was denominated as guidance control module (GCM). The GCM operates the solenoid of the *Hydraulic Designers* control block. The input data of the system are the PWM values (0–100%) that command the opening and closing of the valve of each hydraulic cylinder. The output data are the analog values read from the linear potentiometers.

The GCM is able to communicate in the CAN ISO11898 and SAE J1939 protocol, and, for this reason, this system was configured to receive and transmit the messages addressed to the Bosch (propulsion) and Cummins (engine) control modules. This fact transforms the GCM in a message center, enabling the user to exchange messages only with this module.

The schematic of the robotic platform guidance system composed by four-wheel modules is shown in Figure 4.

The GCM acts with an electrical signal on the four solenoids. The solenoids command the actuation of the four proportional valves. Each of the four valves has two ways that determine the direction of the movement of the wheel. The opening of valve releases the fluid that carries out the linear movement of hydraulic cylinders. The coupled system of racks and pinions, connected to the hydraulic cylinders, transforms the linear motion into radial motion of the wheels as explained in Figure 3.

3.2. Problems Related with the Steering System. There are some problems related to the robot wheel steering system which bring challenges to the development of the control system. Among these verified problems are the hydraulic system delay, the nonlinearities in the steering actuators, and inertia in the steering system due to the friction of different terrains. Therefore, a discussion of these problems and its influence on the control of the steering systems is presented.

The first problem is due to the hydraulic system delay. Differently of electric and pneumatic actuators that usually provide fast actuation on the controlled process, the hydraulic system used in the robot guidance has a slow response time and high inertia. These characteristics influence the system performance and consequently the controller's choice and design.

The nonlinearities in the steering actuators are another important problem. The opening action of the valves uses a PWM signal to activate the solenoids and actuate on the wheels position using the hydraulic cylinders. But there is a dead zone and a saturation limit in each cylinder, which respectively means that the cylinders do not start operating until an approximate control signal of 30% of the PWM value, and their actions saturate at approximately 90% of the PWM value. Additionally, the change on the wheels position is not linear to the applied control signal in this range. Another issue related to the steering actuators is the difference between the areas in the two sides of the piston of the hydraulic cylinder as one side has the piston rod and the other does not. It results in a different strength for the same pressure of fluid. This fact must be considered by the control system because the same PWM control signal will provide more force in one sense of displacement than the other. This last issue also hinders the use of a single controller (usually a PID) to each wheel of the robot as the control action would be different for each side of wheel movement.

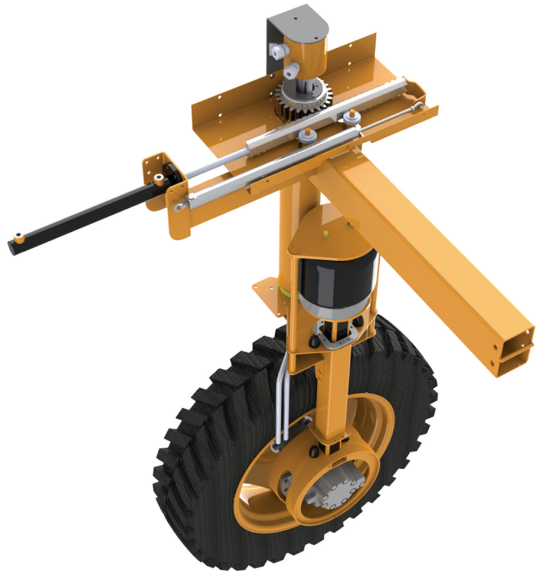

Figure 3: Representation of a wheel module of the robot steering system.

The third problem to be considered is the inertia in the steering system due to the friction between the wheel and different terrains such as earth, pasture, and asphalt. The minimum value needed for the beginning of the steering movement is not constant and depends on the amount of inertia which is being submitted to each wheel and also depends on the robot mass distribution among the wheels. Moreover, there is a difference between the inertia related to static (when the robot is stopped) and dynamic friction (when the robot is moving).

The cited problems represent challenges to the development of the steering control that must be considered and which somehow restrict the choice of the steering control strategy. On the other hand, it is desirable when designing a control system a flexible architecture and a simple algorithm which can be easily implemented and no cost computing.

4. Description of the NCS Solution

Aiming to deal with the robotic platform (Agribot) requirements and control problems, a NCS control architecture was adopted. NCS can provide efficiency, flexibility, and

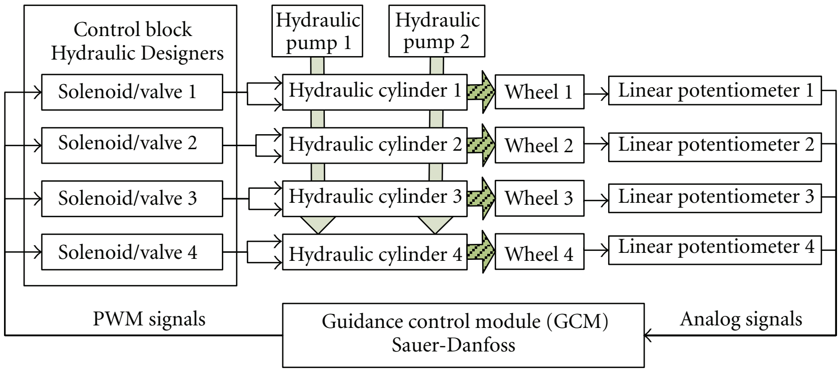

Figure 4: Schematic of the robotic platform guidance system.

reliability of distributed control system through distributed intelligence [15]. Furthermore, the concepts of robot manipulators control theory [27] were used as a basis for the development of the wheels steering control strategy. This chosen was driven by the fact that the robot manipulator control theory could be a simple solution to deal with the verified problems in the wheel steering control.

4.1. Architecture of the Agribot Guidance Control. In NCS, the controller, the sensor, and the plant are physically separated from each other and connected through a communication network such as CAN. The control signal is sent to the controller by a message transmitted over the network while the sensor samples the plant output and returns the information to the controller also by transmitting a message over the network. The architecture developed for the robotic platform (Agribot) follows this structure as shown in Figure 5. The NCS controller routine (NCR) was developed with *LabVIEW of National Instruments* and operates in an industrial PC that establishes communication with the guidance control module (GCM) using the CAN ISO11898 network with 250 kbit/s.

In accordance with Figure 5, the guidance commands are the inputs of the Agribot kinematic model. These guidance commands can be given by the user through teleoperation or the by embedded autonomous navigation system. Some outputs of the Agribot kinematic model are the required steering position for the four-wheel of the robot. This steering position is given by the wheel angle and direction of movement. The angle of the wheel is defined in relation to the main axis from the robot, all the wheels in parallel to this axis represents the zero angle position. Steering movement from zero to left represents negative angle. Steering movement from zero to right represents positive angle. In addition, these steering positions for the wheels are used as the reference for the NCS control strategy which controls the four-wheel of the robot.

The NCR receives the CAN messages from the GCM with the sensor information (wheel angle of the potentiometer) of each wheel module, computes the algorithm of the control strategy, and sends the CAN messages to the GCM with the calculated actuators control signals (PWM values for the valves). For each of the four-wheel steering NCS that composes the robotic platform, the GCM time-driven sensors sample the wheel periodically within a sampling time of 100 ms. The threads executing in the NCR and GCM actuators are both event driven. The four closed loop NCSs in the robotic platform are sharing both limited CAN network bandwidth and NCR CPU.

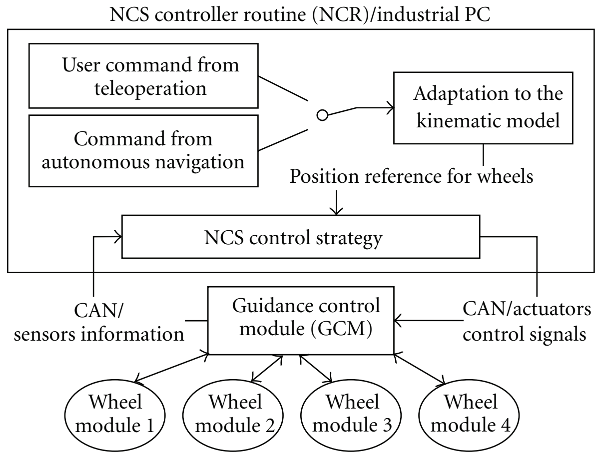

Figure 5: NCS architecture proposed for the Agribot Guidance Control.

4.2. Agribot Kinematic Model. The Agribot kinematic model is required for the correct guidance commands which are used as the references for the wheels steering NCS and consequently to achieve a suitable robot movement. The information is based on the dimension and the position of the wheels in relation with the center of mass (CM) of the robotic platform. To determine the CM, four scales are placed under the four-wheel with the robot. Equivalent masses are calculated for all sides, and the proportion between them gives the position of the center of mass. It is assumed for the kinematic model that the orientation of all wheels is perpendicular to the instantaneous center of rotation (ICR) and that there is no lateral sliding during the movement. The inputs of the system are the following:

(i) Turn radius (TR);

(ii) Orientation of the TR in relation to the frame (β), which assumes values to $-\pi/2$ until $\pi/2$;

(iii) Scalar velocity of the platform (V_{CM}).

The outputs are the following:

(i) Angular velocity of the platform (W_{CM});

(ii) Orientation (δ_i) and of angular velocity (rot_{W_i}) of the four-wheel.

Figure 6 presents the position of the variables of the kinematic model in relation to the robotic platform frame.

It is assumed for the kinematic model that the CM is the origin of the coordinated system. The ICR can be calculated by

$$X_{\text{ICR}} = \text{TR} \cdot \cos\left(\beta + \frac{\pi}{2}\right),$$
$$Y_{\text{ICR}} = \text{TR} \cdot \sin\left(\beta + \frac{\pi}{2}\right). \quad (1)$$

With the ICR position it is possible to determine the steering angle of the wheels. Two vectors for each wheel (Figure 6) are used for this calculation. The vector $\vec{m}$ has origin joined with the position of the wheel that desires to find the steering angle (W_i) and end in the position of the ICR. The vector $\vec{n}$ has origin in the same point of $\vec{m}$ and is oriented parallel to the frame ending in the opposite wheel (W_j). The signal of the determinant of the matrix M_i in (2), which is formed by the position of the two vectors, is used to determine the orientation of the angle. We have

$$M_i = \begin{bmatrix} (X_{\text{ICR}} - X_{W_i}) (Y_{\text{ICR}} - Y_{W_i}) \\ (X_{W_j} - X_{W_i}) (Y_{W_j} - Y_{W_i}) \end{bmatrix}. \quad (2)$$

The angle (γ_{W_i}) between the vectors $\vec{m}$ and $\vec{n}$ can be calculated using one of the properties of vector product as presented in

$$\gamma_{W_i} = \arccos\left(\frac{\vec{m} \cdot \vec{n}}{\|\vec{m}\| \cdot \|\vec{n}\|}\right) \cdot \frac{|\det[M_i]|}{\det[M_i]}. \quad (3)$$

Next step is converting the angle between the vectors (γ_{W_i}) to the steering angle of the wheels (δ_i). For this purpose, some logic notations are made in function of the TR and the angle γ_{W_i}, increasing or decreasing $\pi/2$ to the final result. For the case illustrated in Figure 6, the steering angle of the wheel (δ_1) is given by

$$\delta_1 = \gamma_{W_1} + \frac{\pi}{2}. \quad (4)$$

The angular velocity of the center of mass (W_{CM}) in rad/s is calculated by

$$W_{\text{CM}} = \frac{V_{\text{CM}}}{\text{TR}}. \quad (5)$$

The maximum angular velocity allowed to the platform is 0.8 rad/s. The scalar velocity of the platform will be automatically reduced for values bigger than this maximum. With the position of each wheel in relation to the CM and the position of the ICR, the radius of the patch realized for the wheel can be calculated using

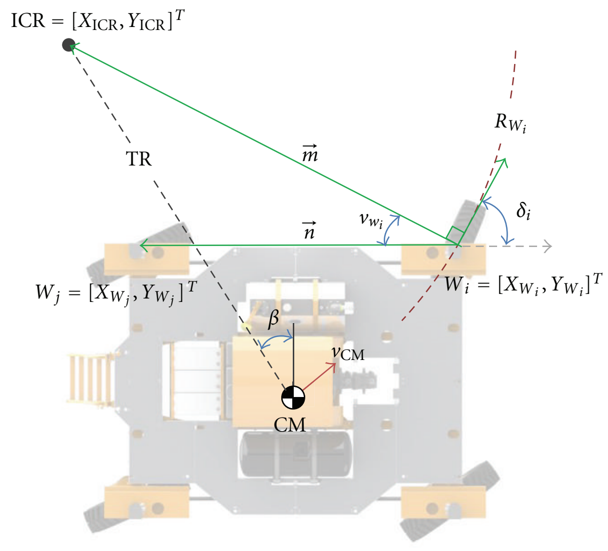

Figure 6: Variables in the Agribot kinematic model.

$$R_{W_i} = \sqrt{(Y_{\text{ICR}} - Y_{W_i})^2 + (X_{\text{ICR}} - X_{W_i})^2}. \quad (6)$$

Using the angular velocity (W_{CM}), the radius of the patch of the wheel (R_{W_i}) and the diameter of the tire (d_W), the speed of the wheel, in RPM, can be calculated by

$$\text{rot}_{W_i} = \frac{|(W_{\text{CM}} \cdot R_{W_i} \cdot V_{\text{CM}})|}{\pi \cdot d_W \cdot V_{CM}} \cdot 60. \quad (7)$$

All the calculations are made for the four-wheel. Finally, with the Agribot kinematic model, the desired angles (δ_i) for the four-wheel are used as the setpoints for the NCS steering control system.

4.3. NCS Control Strategy for Steering Control. The Agribot guidance is linked to the correct positioning control of the robot four-wheel. In the NCS architecture developed for the Agribot (Figure 5), there is one controller (NCR) responsible for the steering control of the four-wheel. Besides there is the fact that the control strategy needs to deal with some steering problems explained in Section 3.

Investigating a solution that was at the same time simple to implement and robust against the problems, in this paper a NCS control strategy centered on the robot manipulators control theory [27] was proposed. This NCS control strategy uses a position/velocity control idea [28] to calculate the control signals, based on the difference between the desired and actual position and considering the angular speed of the wheels. The fluxogram in Figure 7 details the NCS steering control algorithm developed.

The idea of the simple control strategy presented in Figure 7 is explained as follows. It is important to understand

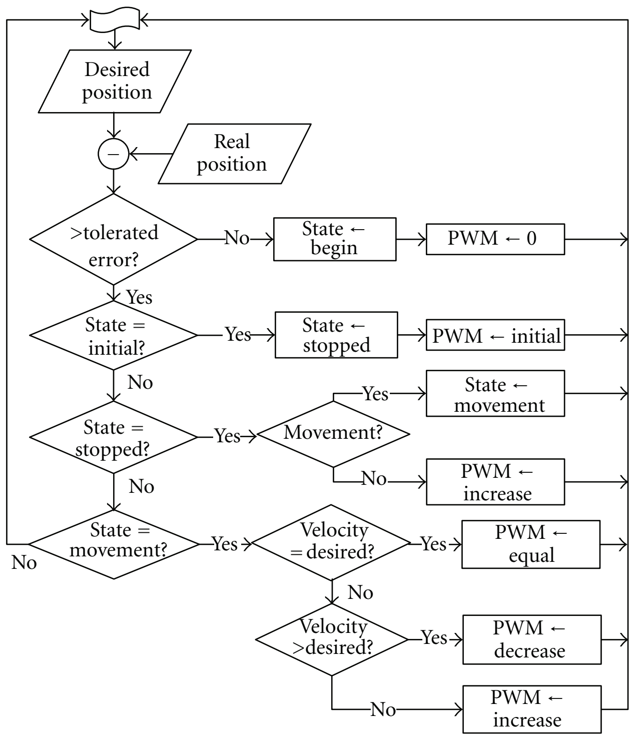

Figure 7: Fluxogram of the NCS control strategy developed.

that this control strategy is simultaneously applied to the steering control of the four-wheel of the platform. As a result, the actions outlined are implemented for each of the four-wheel. The steering control action begins with the comparison among the desired positions (received from the kinematic model) and the actual position of each wheel. If the difference is bigger than a maximum error tolerated (defined by the user), the control strategy will act to reduce this error. The first step is to apply an initial PWM. This value is subsequently incremented until the wheel starts its angular movement.

The wheel motion detection is done by comparing the last two readings of the wheel (angular) positioning. If the difference is bigger than the maximum tolerated, then it is considered that there is movement. After this first movement, it must be considered that the speed with which this movement is occurring. The intention is getting the slowest speed that could be constantly applied to the movement of the wheel, and keep this speed constant. To do it, a calculation is made using the previous readings of the wheel positioning, as each reading occurs every 100 ms. If the wheel speed is higher or lower than a specified value, the increment or decrement of the control signal (PWM applied to the valves) is implemented. The control algorithm runs until the error between the desired and actual position for each wheel is smaller than the error tolerated.

After some study of the robotic platform mechanical structure capabilities to deal with forces and deformations related to the requirements of its adequate guidance, the following parameters were defined for operation. A 2% of the total PWM step value to increase or decrease the control signals. An initial PWM value of 30%, in consequence to the actuators dead zone. A tolerated error is of 2 degrees for the wheel positioning and a tolerated error of 1 degree for the wheel motion detection (i.e., movement is detected if there is a difference greater than or equal to 1 degree positioning between readings).

The NCS control solution proposed in this paper for the four-wheel steering and platform guidance simplifies the control system design and implementation as only one controller can be applied to control all the wheels with a simple algorithm.

5. Results

We performed field tests using the robotic platform (Agribot) to evaluate the NCS guidance architecture and steering control strategy proposed. In the experiments, the user controls (teleoperates) the Agribot navigation and the feedback information is analyzed to check the operability and accuracy of the robot movement.

Tests were conducted on different soil types and with the robot in movement or stationary, to identify differences in the system behavior against the inertia offered by each state. The steering movement angle leaving and going from 0° to 90° represents a clockwise motion and motion from 0° to −90° a counterclockwise direction.

The defined steering control requirements for the platform guidance are slow movement speed and preferentially no overshoot on the wheel steering response, because of the great time to invert the control action on the hydraulic cylinder. Figures 8 to 11 present the accuracy of the steering wheel responses related to the setpoint required. These graphs demonstrate the steering movement of the front right wheel, front left wheel, back right wheel and back left wheel, successively.

The graphs of Figures 8 to 11 are shown separately as the setpoints, in accordance with the platform kinematic model, are different for each of the wheels. The upper graphs show the command values for the desired position and the readings values for the actual position.

At most times no steady-state error and overshoot can be verified, and an appropriate low speed was achieved for the Agribot guidance movement. These results indicate the correct design of the NCS control strategy for the wheels steering and platform guidance. The bottom graphs show the PWM value being applied by the system. These graphs of the PWM values present the dynamics of the control strategy aiming to maintain a constant speed steering (Figure 9).

Analyzing the wheel steering control graphs, it is possible to verify that the time taken to leave the actual position until the desired position changes along the platform operation and sometimes is greater in one direction of movement. This difference of values can be also seen when looking for the initial PWM values of the control signals graphs. This behavior was expected with the corrected operation of the proposed control strategy and can be explained by some facts such as the constructive characteristics of the cylinder, the different inertia related to the friction on the terrain, and the Agribot mass distribution along the wheels. These factors

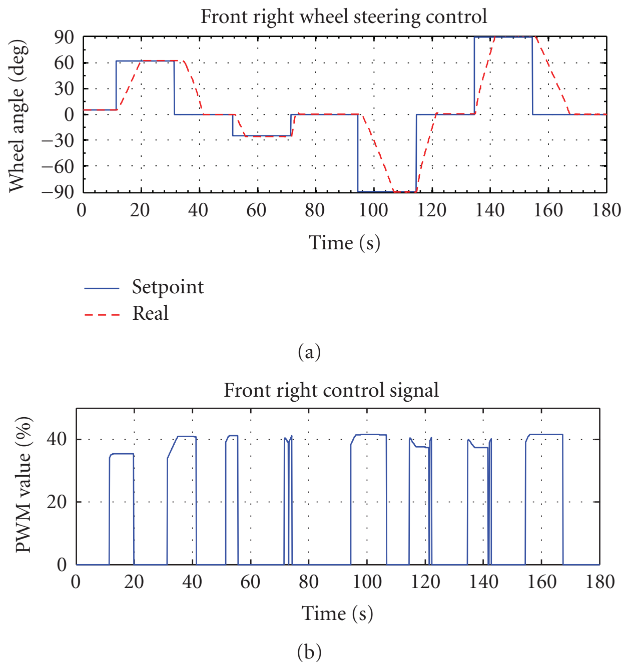

Figure 8: Front right wheel. (a) Wheel steering response comparing desired and real position. (b) Dynamic of PWM applied.

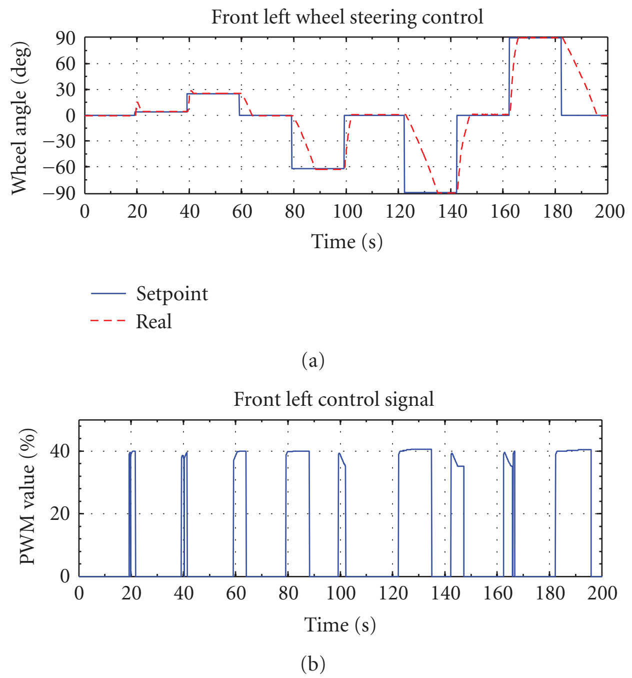

Figure 9: Front left wheel. (a) Wheel steering response comparing desired and real position. (b) Dynamic of PWM applied.

demand different control actions and consequently different steering outputs accordingly to the platform navigation.

Delays in the system response are, in part, attributed to the exchanging of messages through the CAN network, and in most part, attributed to the response time of the hydraulic system, which is slow and with high inertia (Figure 10).

The developed NCS control solution for the four-wheel steering and Agribot guidance simplified the control system design and implementation because only one controller was applied to control all the four-wheel. In addition, the proposed control strategy with a simple algorithm provided an ease implementing and no cost computing solution for the wheel steering control.

Despite the simplicity of the NCS control strategy, it was an effective solution to overcome the verified problems and challenges in the steering control design. However, it is important to emphasize that the control strategy could be designed for the robotic platform because of its guidance and control requirements including the slow response and movement speed.

Finally the results of the tests prove that the NCS architecture and control solution for the Agribot are reliable and satisfactory. Even though it may be desirable to improve the wheel steering control, the present level of accuracy is sufficient for the Agribot guidance, and the results indicate that the developed NCS architecture and the distributed control strategy are useful for agricultural mobile robot operations.

Future work will be done to improve the robotic platform guidance by the study of timed control solutions to synchronize the steering movements among the four-wheel. Non synchronism among the wheels was verified in the performed tests with the Agribot and is not desirable if higher navigation speed is required for the Agribot guidance.

Another interesting point would be the application of fuzzy systems [29] to deal with the Agribot steering control challenges discussed in this paper. Reference [30] attests that T-S fuzzy models can be very efficient in characterizing and dealing with nonlinearities.

6. Conclusion

In this paper a networked control system (NCS) solution was presented for the guidance of a four-wheel steering robotic platform for agricultural applications called Agribot. The solution is composed by the NCS architecture with hardware and software structure, the Agribot kinematic model used to obtain the platform guidance inputs, and the NCS control strategy, centered on the robot manipulators control theory, for the four-wheel hydraulic steering control.

The results demonstrated that the NCS solution was simple and efficient, providing suitable steering performance for the Agribot and overcoming the discussed control challenges in the robot guidance system design such as the hydraulic system delay, nonlinearities in the steering actuators and inertia in the steering system due the friction of different terrains.

The application of the NCS technology with CAN protocol provided a flexible architecture to perform the distributed control of the Agribot. The Agribot NCS architecture with distributed intelligent units (ECUs) reduced the computational load of the industrial computer and simplified the data communication among the devices of

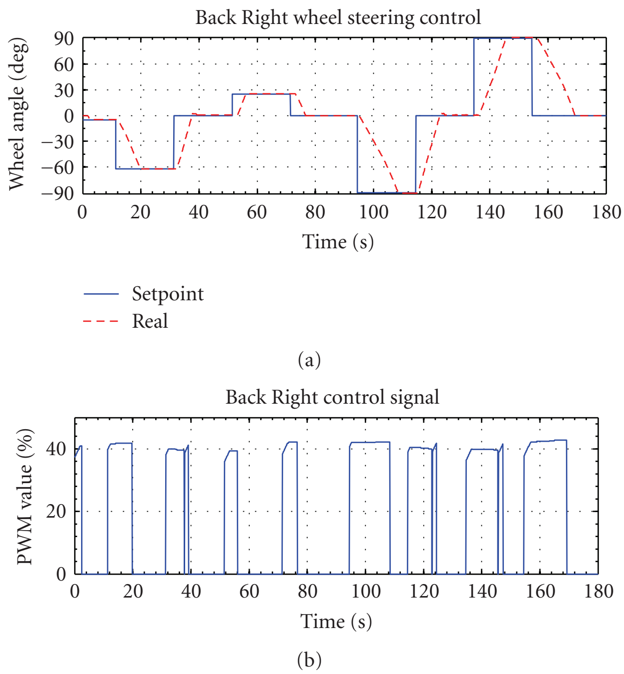

Figure 10: Back right wheel. (a) Wheel steering response comparing desired and real position. (b) Dynamic of PWM applied.

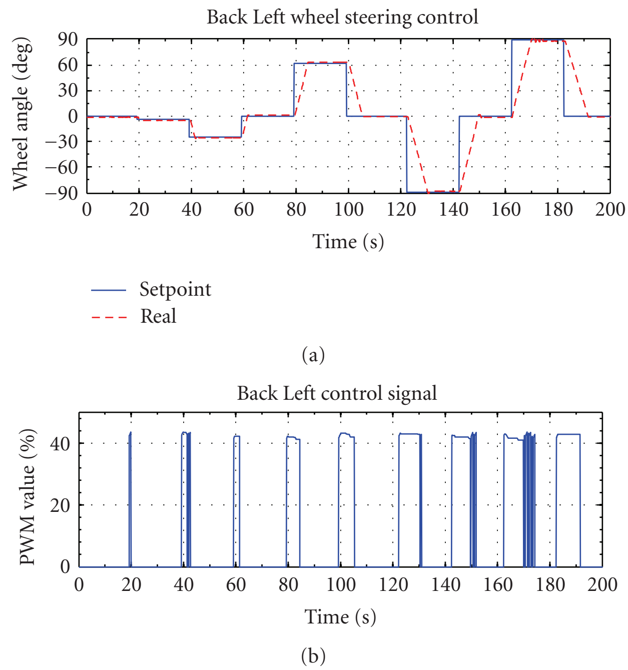

Figure 11: Back left wheel. (a) Wheel steering response comparing desired and real position. (b) Dynamic of PWM applied.

the robotic platform. Another advantage was the possibility to use only one controller to control the four-wheel of the Agribot. The NCS control strategy was developed using a simple (ease implementing and no cost computing) position/velocity control algorithm based on the difference between the desired and actual position and considering the angular speed of the wheels. This approach was proved very effective for the wheels steering control providing a proper and precise operation for the Agribot navigation.

Furthermore the NCS solution developed in this paper for the Agribot can be applied for distributed control of agricultural and other mobile robots meeting the requirements for a reliable and accurate robot movement.

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