DESIGN AND DEVELOPMENT OF THE ARCHITECTURE OF AN AGRICULTURAL MOBILE ROBOT

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ABSTRACT: Parameters such as tolerance, scale and agility utilized in data sampling for using in Precision Agriculture required an expressive number of researches and development of techniques and instruments for automation. It is highlighted the employment of methodologies in remote sensing used in coupled to a Geographic Information System (GIS), adapted or developed for agricultural use. Aiming this, the application of Agricultural Mobile Robots is a strong tendency, mainly in the European Union, the USA and Japan. In Brazil, researches are necessary for the development of robotics platforms, serving as a basis for semi-autonomous and autonomous navigation systems. The aim of this work is to describe the project of an experimental platform for data acquisition in field for the study of the spatial variability and development of agricultural robotics technologies to operate in agricultural environments. The proposal is based on a systematization of scientific work to choose the design parameters utilized for the construction of the model. The kinematic study of the mechanical structure was made by the virtual prototyping process, based on modeling and simulating of the tension applied in frame, using the.

KEYWORDS: precision agricultural, CAD, CAE, ISOBUS, robotic, sensor.

PROJETO E DESENVOLVIMENTO DA ARQUITETURA DE UM ROBÔ AGRÍCOLA MÓVEL

RESUMO: Parâmetros, como tolerância, escala e agilidade empregados na amostragem de dados para uso em Agricultura de Precisão, exigem um expressivo número de pesquisas no desenvolvimento de instrumentos e técnicas para automação. Destacam-se a utilização de metodologias em sensoriamento remoto utilizadas em conjunto com o Sistema de Informação Geográfica (SIG), adaptados ou desenvolvidos para o uso agrícola. Visando a isso, a aplicação de Robôs Agrícolas Móveis é uma forte tendência, principalmente na União Europeia, EUA e Japão. No Brasil, pesquisas são necessárias para o desenvolvimento de plataformas robóticas, que sirvam de base para sistemas de navegação autônomos ou semiautônomos. O objetivo deste trabalho é descrever o projeto de uma plataforma experimental para a aquisição de dados em campo para o estudo da variabilidade espacial e desenvolvimento de tecnologias para operação de robôs em ambiente agrícola. A proposta baseia-se em uma sistematização de trabalhos científicos que norteiam a escolha dos parâmetros de projeto utilizados para a construção do modelo. O estudo cinemático da estrutura mecânica foi feito pelo processo de prototipagem virtual, baseado na modelagem e simulação das tensões aplicadas no chassi, utilizando o método dos elementos finitos, em função dos conceitos básicos de cinemática de robôs móveis e experiências em trabalhos anteriores.

PALAVRAS-CHAVE: agricultura de precisão, CAD, CAE, ISOBUS, robótica, sensor.

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INTRODUCTION

The idea of robotic agriculture (agricultural environment serviced by smart machines) is not a new one. Many engineers have developed driverless tractors in the past, but they have not been successful as they did not have the ability to embrace the complexity of the real world. Most of them assumed an industrial style of farming, where everything was known beforehand and the machines could work entirely in predefined ways. The approach nowadays is to develop smarter machines that are intelligent enough to work in an unmodified or semi natural environment. These machines must exhibit sensible behavior in recognized contexts. In this way they should have enough intelligence embedded within themselves to behave sensibly for long periods of time, unattended, in a semi-natural environment (BLACKMORE et al., 2005).

Autonomous vehicles have been widely used in industrial production and warehouses, where a controlled environment can be guaranteed. In agriculture, research into driverless vehicles has always been a dream but serious research started in the early 1960's (FOUNTAS et al., 2007). In recent years, the development of these vehicles has experienced increased interest. This development has led many researchers to start developing more rational and adaptable vehicles. In the field of agricultural autonomous vehicles, a concept is being developed to investigate if multiple small autonomous machines would be more efficient than traditional large tractors (BLACKMORE et al., 2004). These vehicles should be capable of working 24 hours a day all year round, in most weather conditions and have the intelligence embedded within them to behave sensibly in a semi-natural environment over long periods of time, unattended, while carrying out a useful task (PEDERSEN et al., 2005).

In scientific literature can be found a large number of studies that seek to adapt commercial agricultural machinery in autonomous agricultural platforms (vehicles or autonomous agricultural mobile robots) as in REID et al., 2000, KEICHER & SEUFERT, 2000, HAGUE et al., 2000, HAGUE & TILLETT, 1996, MOGENSEN et al., 2007, RESKE-NIELSEN et al., 2006, and BLACKMORE et al., 2007. A more recent trend is the development of platforms built specifically for agricultural autonomous vehicles or robots, as can be seen in ÅSTRAND & BAERVELDT, 2002, BAK & JAKOBSEN, 2004, MOORE & FLANN, 2000; SOUTHALL et al., 2002; BISGAARD et al., 2004; JØRGENSEN et al., 2007, BAKKER et al., 2006, BAKKER, 2009, and the utilization of sensors or images for determining management zones (GROHS et al., 2009 and BAESSO et al., 2007). In the second case, it identifies two challenges: developing a physical structure suitable for the agricultural environment, and develop architecture to integrate the various electronic devices in systems allowing its expansion through the addition of new devices.

A trend that can assist in the development of more complex machines that meet the needs of the new practice in agricultural area is the Virtual Prototyping (VP). VP is a computer-aided design process concerned with the construction of digital product models and realistic graphical simulations that addresses the broad issues of physical layout, operational concept, functional specifications, and dynamic analysis under various operating environments (HUANG et al., 2007 and SHEN et al., 2005). This consists of many capabilities, which the best known is the creation and viewing of three-dimensional solid models with various colors and surface textures. A Virtual Prototype may be represented as a series of graphical images or Computer Aided Design (CAD) and Computer Aided Engineering (CAE) models, in animated or still format, created in the form of mathematical models and stored digitally in computer usable memory (ZORRIASSATINE et al., 2003).

Considering the context presented, the purpose of this study is to present a mechanical structure to form an Agricultural Mobile Robot, developed with Virtual Prototyping, including a CAD model and a finite elements analysis at the normal operating conditions and the worst-case conditions. The Agricultural Mobile Robot can be developed to test different sensor systems and tools in the field, and should be able to work under field conditions. In this study, the principal parts that compose the set of the Agricultural Mobile Robot and its functions were described.

MATERIAL AND METHODS

The Agricultural Mobile Robot is designed to sensing agronomic parameters of most important Brazilian culture (maize, sugar cane, soybeans, and orange) during almost the entire cycle of growth and post harvest in large areas. It does not require actions that demand high power, as in agricultural operations, but only moving efficiently in this environment. According to MADSEN & JAKOBSEN, 2001 the considerations made about the principles of the vehicle and the choices of concept for the mobile robot were: traction, steering, dimensions, frame, motors and power supply. The mechanical structure was designed by the studying of working conditions required in field and desired characteristics of the project, using the steps of processes described in Figure 1.

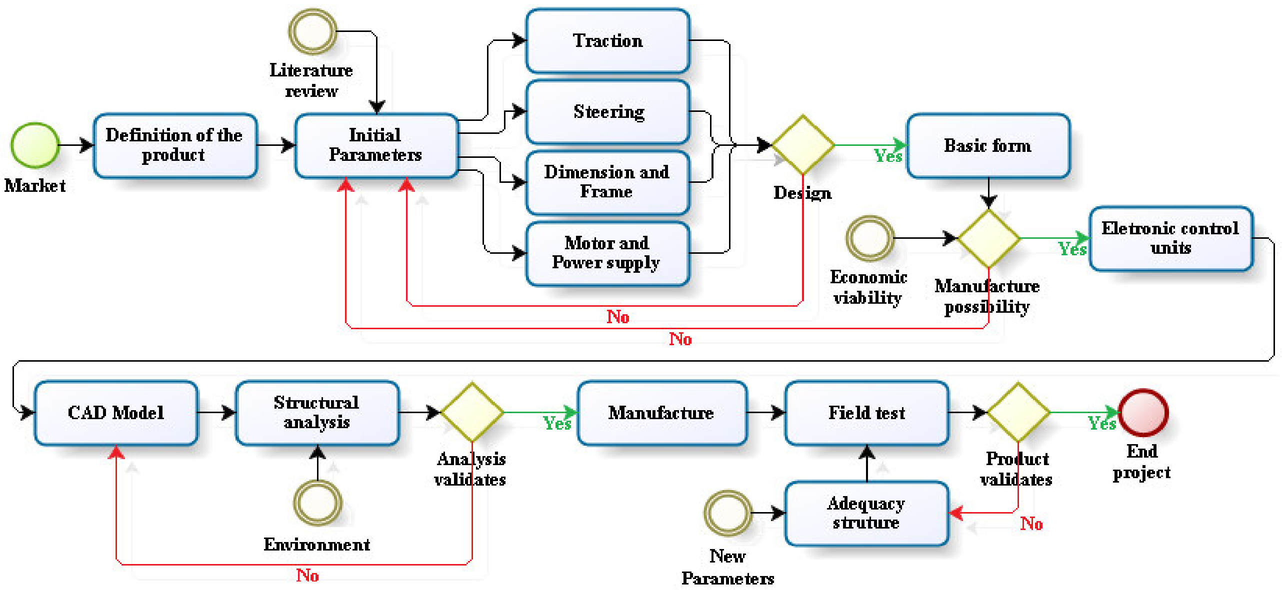

FIGURE 1. Flowchart of agricultural mobile robot design.

Dimensions and Frame

It has been established that the structure needs to be capable of operating in cultures up to 1.8 m of height, with variable intra-row spacing. In order to reach this requirement, the frame format adopted was the portico one, with adjustable gauge which is light and flexible when compared with the commercial agricultural vehicles, with the possibility of inserting new sensors and actuators.

Four wheels have been placed in each corner of a rectangle with the length parallel to the crop rows chosen for the vehicle, that configuration provides great stability. The system has been designed in independent modules (side frame and top frame), with telescopic bars, to be applied in the maximum possible situations. The steering module, the propulsion module and central box complete the system. As the work speed of the Agricultural Mobile Robot is low, there is no need to design a suspension or compensation system.

Traction

The most common traction systems found are wheels and tracks. The tracks system has better distribution of load on the soil, significantly reducing compaction and disturbance in the soil, and more traction capability especially in loose soils. This system is common utilized in large equipment or those who require high performance, however, they have high cost for manufacturing and maintenance. For the Agricultural Mobile Robot, these properties are not very important, but accuracy in direction, low power consumption and low cost are desirable. Systems with wheels are cheap and, in function of the low need for traction and load to be distributed, attend the needs of this project. In this project, it was adopted a four wheels system and to increase the ability of vehicle to pull in adverse conditions, and independent traction in each wheel; primarily the system was dimensioned with full traction.

Steering

Among the steering systems found, there are differential steering, articulated steering and wheel steering. Differential steering works by the difference between the speed of rotation of right and left wheels or track. Advantages are the simple transmission manufacture, due to the fact that the wheels of the same side turn at the same speed and the position and orientation of the wheels are fixed. The disadvantage of this system is that when the vehicle turns around a vertical axis wheels sliding sideways, which means spending too much power. Articulated steering works change the angle between the front and the rear axle of a vehicle. This is a system by which a four-wheeled drive vehicle is split into front and rear halves which are connected by a vertical hinge. For big machines, the disadvantage of this system is the complexity of construction.

The methodology of wheel steering or Ackerman steering geometry is the most used by road vehicles for steering. This methodology describes the relation between the outside and inside angles of the wheel in a turn. As for the choice of structure configuration and capability of adjustment of the gauge, a system that could be independent for each wheel, with easy construction and accuracy of steering was chosen, and therefore we opted for the system Ackerman geometry in front wheels.

Motors

The motors for the vehicle must be easy to control, to supply and to install. It is also preferred that they could be used indoors for tests. Therefore, electrical motors for the steering and propulsion systems have been chosen because they attended all the necessary requirements. The most common types of electric motors are the AC (alternate current) or DC (direct current) motors. The disadvantages of the AC motor for the application in this project are the difficult control and the need of frequency inverters. The advantages of a brushed DC motor include low cost, high reliability, and simple control of motor speed. In this case, the DC motor which attends better the above demands can be used indoors and can be supplied by battery and power amplifiers, which makes it a flexible and easy solution to install. The power supply should be able to drive the electronic components, computers and motors.

Power supply

Batteries have been chosen for the vehicle, because they are easy to install and should be able to deliver power for the necessary time to do the analyses on the field. Traction battery is the term relates to all batteries used to power supply electric vehicles. They are designed to be fully discharged and recharged daily, can withstand thousands of discharge cycles. For this works eight batteries of 12 V and 70 Ah for traction, four batteries of 12 V and 10 Ah for the steering system and one battery of 12V and 50 Ah for the computing system are used.

RESULTS AND DISCUSSION

Mechanical structure of the robot

Mechanical structure of the Agricultural Mobile Robot has been designed using the virtual prototyping methodology which is a step in the process of product development. It involves using CAD and CAE software to validate a design before committing to make a physical artifact. This is done by creating computer generated geometrical shapes (parts) and also combining them into an assembly and testing different mechanical motions, fit and function or just aesthetic appeal. The assembly or individual parts could be opened in CAE software to simulate the different stresses that the product may encounter in the real world. The development of the project followed the flowchart shown in Figure 1.

FIGURE 2A shows the isometric view of the Agricultural Mobile Robot with all its components: (1) side frame, (2) fork, (3) wheel, (4) batteries, (5) propulsion system, (6) steering system, (7) side box, (8) top frame, (9) central box and (10) telescopic bar. The gauge of the robot can be regulated, the highest gauge is 2,0 meters and the minimum is 1,2 meters. It may be observed that heavier items such as batteries and propulsion and steering systems are at least one meter from the soil, which contributes to lower center of gravity of the structure, thus increasing its stability on slop capability.

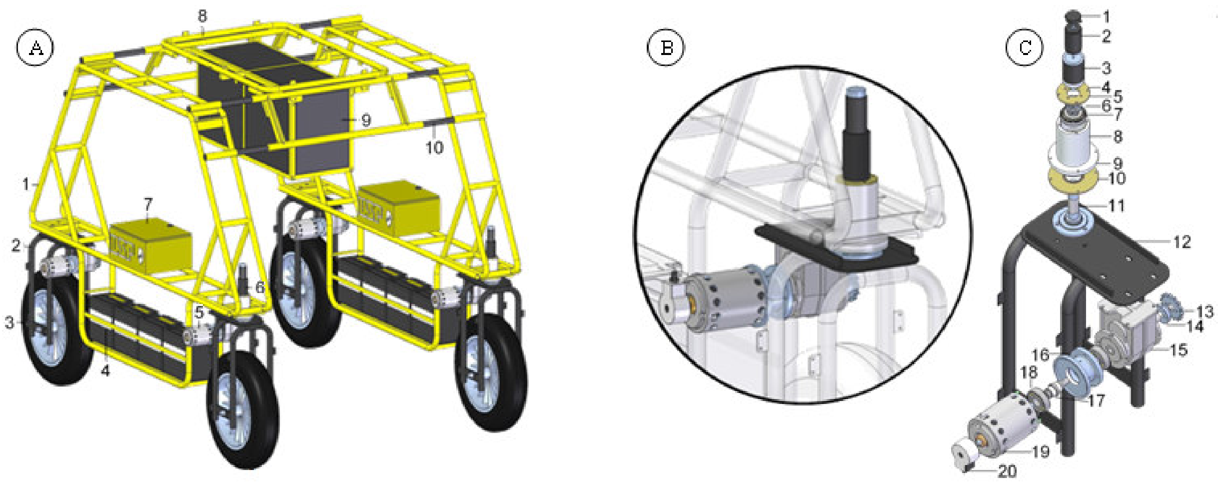

FIGURE 2. Agricultural Mobile Robot: (A) Isometric view of the (B) Detail of the front wheel module; (C) Propulsion and Steering system.

In highlight

FIGURE 2B shows a detail of the results of development of propulsion and steering system assembly fixed in front fork and how they are fixed in the side frame of the Agricultural Mobile Robot.

FIGURE 2C shows an exploding view of the components of the steering and propulsion system, where: (1) encoder, (2) DC motor, (3) reducer, (4) top flange, (5) nut, (6) lock washer, (7) bushing, (8) bearing, (9) bottom flange, (10) retainer, (11) shaft, (12) fork, (13) gear, (14) gear support, (15) reducer, (16) bushing, (17) shaft, (18) bearing, (19) DC motor and (20) encoder.

At the base of the side frame, where the front wheels are fixed, there is a hole through which the bushing with the DC motor and reducer of the steering system are inserted from bottom to top. This set is designed to support all loads and impacts bound for the wheel and that would be easy to maintain. The reducer used has a reduction rate of 1:230 and the transmission of torque to the shaft is made by pin. The system allows turning radius of 180° degrees, resulting in large capacity of maneuvering. The propulsion system consists of a DC motor and a coupling system that is coupled to a reduction with rate of 1:25 (item 15 of

FIGURE 2C). The system is fixed in the base of the fork. Torque transmission between the output of the set motor-reducer and the shaft of the wheel of propulsion system is based on the sprockets and chain, with rate reduction of 1:3, resulting in total reduction of 1:75.

Both the transmission and the wheels and tires are components used in commercial motorcycle, with features of mixed use (on-road and off-road). It was chosen to adapt the project to commercial use of mechanical components, reducing costs of design and of parts manufacture. Propulsion system is similar to the front back, except for the absence of steering system.

Four engines of 24 V and 750 W which were responsible for propelling the robot have been used, as can be seen in item 19 of

FIGURE 2C. Measurement of engine rotation was made by an incremental encoder with resolution of 100 pulses per revolution fixed in motor shaft (item 20 of

FIGURE 2C). During robot traffic, the power required for its displacement will fluctuate depending on the condition of the land, acceleration parameters and speed required, so it is necessary a constant monitoring and adjustment of the power for each engine, aiming to obtain the required parameters. Thus, a power controller equipped with two independent channels has been used, which was responsible for controlling front and rear motor of corresponding side. Control is done according to data obtained by the encoder, which is processed according to the PID programming included in system or in dynamic mode by use of a remote control. A tolerance for this control has been attributed in order to avoid overloading of the system with little variations, which do not influence in operation performance.

In order to provide the steer of the front wheels, two engines of 48 V and 150 W have been used, (Item 2 of

FIGURE 2C). The measurement of engine rotation is provided by an incremental encoder with resolution of 500 pulses per revolution fixed in motor shaft (item 1 of

FIGURE 2C). Observe that, for small changes in the angle of the wheels of steer, a large amount of points are generated, which ensures accuracy that is more than necessary for the great functioning of steering system. In this case, a condition of tolerance was inserted, so the system cannot work overloaded. The main feature of the steering system is the necessity to position the motor so that the wheels of the steering system are positioned at a correct angle; so it is important that the two steering systems are calibrated with the same tolerance and working synchronization. If any system presents a failure there may be damage in the structure.

Interconnected with the set, a security system that has the task of cutting controllers and motors power in case of any accident or unforeseen has been installed. This system consists of a button fixed in a strategic place of robotic structure which, when activated, interrupts system power.

Kinematic model of the robot

The following is a brief presentation of the kinematic model of the vehicle. For the implementation of the kinematic model it is necessary to know the relation between the outside and inside angles of the wheel in a turn. Some relevant parameters used to understand the model, as a global reference and site reference can be seen in

FIGURE 3.

The global reference is represented by the axes X and Y. The site reference is represented by the center of mass (CM) located on board of the vehicle. In this case, the location of the CM is in the middle of the vehicle due to the symmetrical and modular configuration. Ackermann steering geometry is determined by the steering angle of the vehicle (α) in relation to its center of mass. With this, the instantaneous curvature radius of the vehicle (Cr) is determined as shown in Figure 3 and described by equation 1.

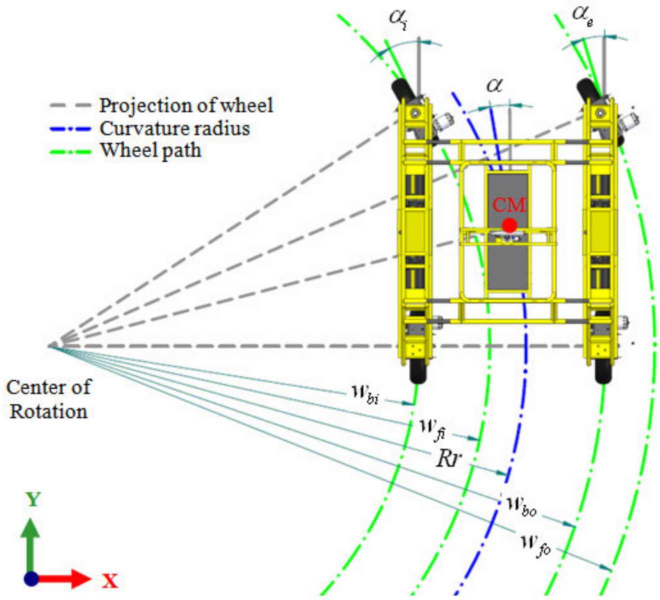

FIGURE 3. Ackermann steering geometry.

All equations presented in this research are in function of length (C) and width (L) of the vehicle. The maximum steering angle is limited by mechanical parameters of the vehicle. The maximum steering angle of the inside wheel (α_i) has been established as 45º, thus, the minimum steering angle of the vehicle has been obtained as well as the minimum instantaneous radius of curvature.

$$Cr = \sqrt{\left(\frac{C}{\tan\alpha}2\right)^2 + \left(\frac{C}{2}\right)^2} \quad (1)$$

Equations 2 and 3 represent the steering angle of the inside wheel (α_i) and the steering angle of the outside wheel (α_e) respectively.

$$\alpha_i = \arctan\left(C / \left[\left(\frac{C}{\tan\alpha}2\right) - \frac{L}{2}\right]\right) \quad (2)$$

$$\alpha_e = \arctan\left(C / \left[\left(\frac{C}{\tan\alpha}2\right) + \frac{L}{2}\right]\right) \quad (3)$$

Equations 4 to 7 represent the proportion of the speed rotation, in percentage, of each wheel of the robot in function of its steering angle. Equations 4, 5, 6 and 7 demonstrate, the speed of the inside front wheel (w_{fi}), outside front wheel (w_{fo}), inside rear wheel (w_{bi}) and external rear wheel (w_{bo}), respectively. The path of each wheel is show in FIGURE 3.

$$w_{fi} = \left[\left(\sqrt{\left(\left(\frac{C}{\tan\alpha}2\right) - \frac{L}{2}\right)^2 + C^2}\right)100\right] / \left[\left(\left(\frac{C}{\tan\alpha}2\right) + \frac{L}{2}\right)^2 + C^2\right] \quad (4)$$

$$w_{fo} = 100 \quad (5)$$

$$w_{bi} = \left[\left(\left(\frac{C}{\tan\alpha} 2 \right) - \frac{L}{2} \right) 100 \right] / \left[\left(\left(\frac{C}{\tan\alpha} 2 \right) + \frac{L}{2} \right)^2 + C^2 \right] \quad (6)$$

$$w_{bo} = \left[\left(\left(\frac{C}{\tan\alpha} 2 \right) + \frac{L}{2} \right) 100 \right] / \left[\left(\left(\frac{C}{\tan\alpha} 2 \right) + \frac{L}{2} \right)^2 + C^2 \right] \quad (7)$$

Structural analysis

The material properties which were utilized in finite elements analyses were obtained from the manufacturing, where: Young's Modulus: 200 GPa; Poisson's Ratio: 0.3; Density: 7.85 . 10^6 kg mm^{-3}; Tensile Yield Strength and Compressive: 250 MPa; Tensile Ultimate Strength: 460 MPa. In order to simplify the model, elements that have no structural function as central box, batteries, motors and steering system have been removed from analysis. Only the side and top frame have been kept and duly established by telescopic tubular bars. Removed items have been replaced by resulting forces. Simulation has been performed considering the structure under condition of dynamic strain in three severe conditions of use: steering system badly calibrated; across obstacle; traffic with lateral inclination. The details of the structure with the forces applied are presented in Figure 4.

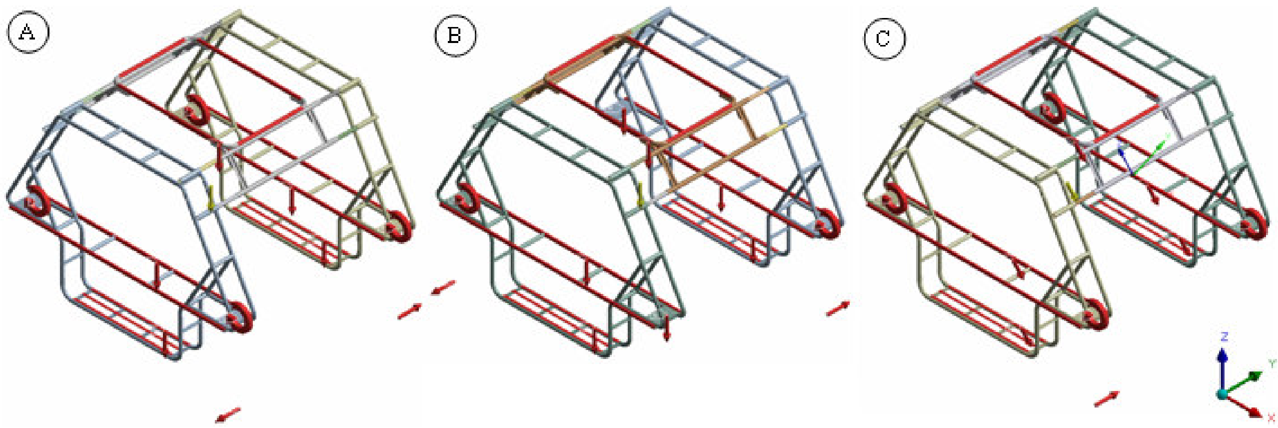

FIGURE 4. Loads applied on the structure: (A) Steering system badly calibrated, (B) Across obstacle, (C) lateral inclination 25º.

Steering system badly calibrated (A): In this case the robot is operating in ramp angle of 0° (inclination to be overcome for the vehicle subdue in the direction of displacement) and 0° lateral inclination (inclination to be overcome by the vehicle perpendicular to the displacement), with four wheels supported on the soil, with angle of divergence (angle of opening formed by the plans of the two wheels of the same directional axis) of the front wheel raise, causing strength for opening the structure of 500 N in each direction.

Across obstacle (B): In this case the robot is operated with a ramp angle 0° and 0° lateral inclination, with two wheels supported in the soil, (front right and rear left) and lateral strength on each wheel support, to open the structure of 500 N.

Traffic with lateral inclination (C): In this case the robot is operated with a ramp angle 0° and 25° lateral inclination, with the convergence angle (angle of closing formed by the plans of the two wheels of the same directional axis) of the front wheel moderate, causing strength for closing the structure of 500 N in each direction. The result of simulation, containing data of total deformation and equivalent stress (von-Mises) are presented in Figure 5, 6 and 7. It is necessary to emphasize that the scale of deformation used in the figures is increased to facilitate viewing.

FIGURE 5 shows the result of the system simulation in situation A (badly calibrated steering system). It is possible to observe that most of the deformation occurred in the lower area of the frame, but without compromising the performance of the set. Regarding tension, points of stress accumulation occurred at the junction between the top and side frame, but not enough to generate disruptions.

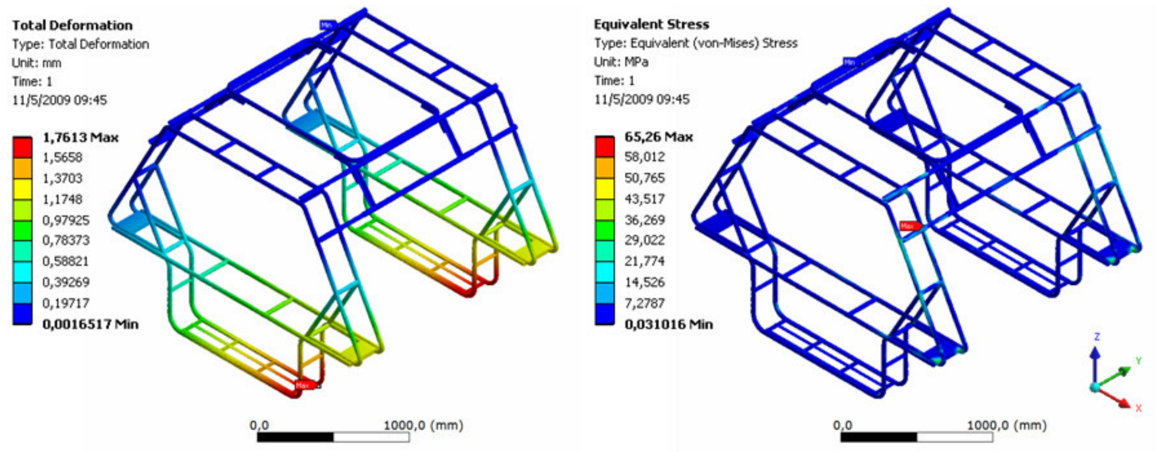

FIGURE 5. Total Stress and Deformation of the structure in the situation A (Steering system badly calibrate).

FIGURE 6 shows the result of simulation of situation B (across obstacle). Compared with situation A, the deformation was larger, tending to twist the structure. Regarding stress, it has significantly increased due to the twist of the structure, focusing on the same point of the situation A.

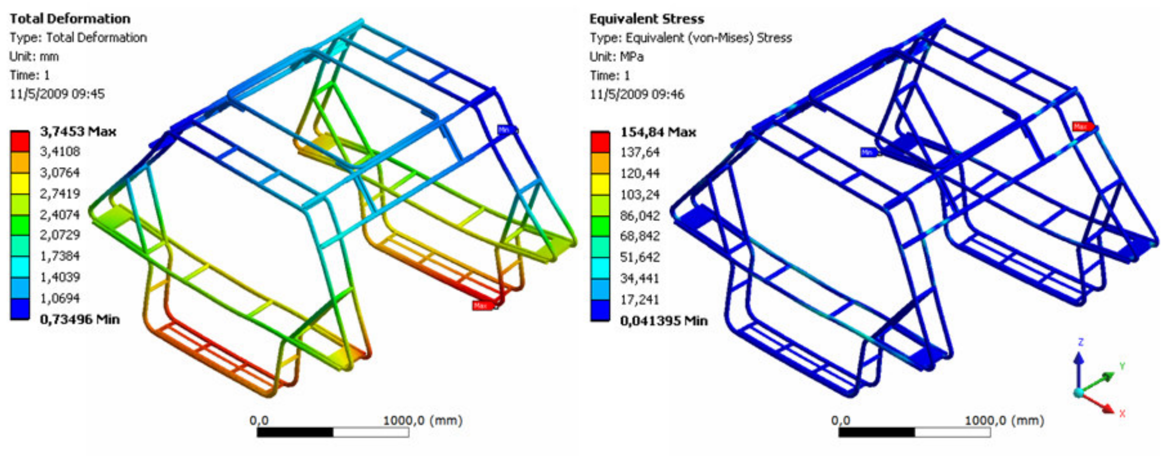

FIGURE 6. Total deformation and Stress of the structure in situation B (crossing obstacle).

FIGURE 7 shows the result of simulation of situation C (traffic with lateral inclination). Note that this is the most severe situation to which structure was submitted. Strain was superior to the ones in the two previous cases, and showed an increase of 290% compared with situation A. In this case, forces tend to close the structure. We believe that there would be problems with the navigation of the vehicle in this condition, because the front and rear wheels are aligned. Note that the site of accumulation of strain is the same of the above, so the increase was of 320% compared with the situation A.

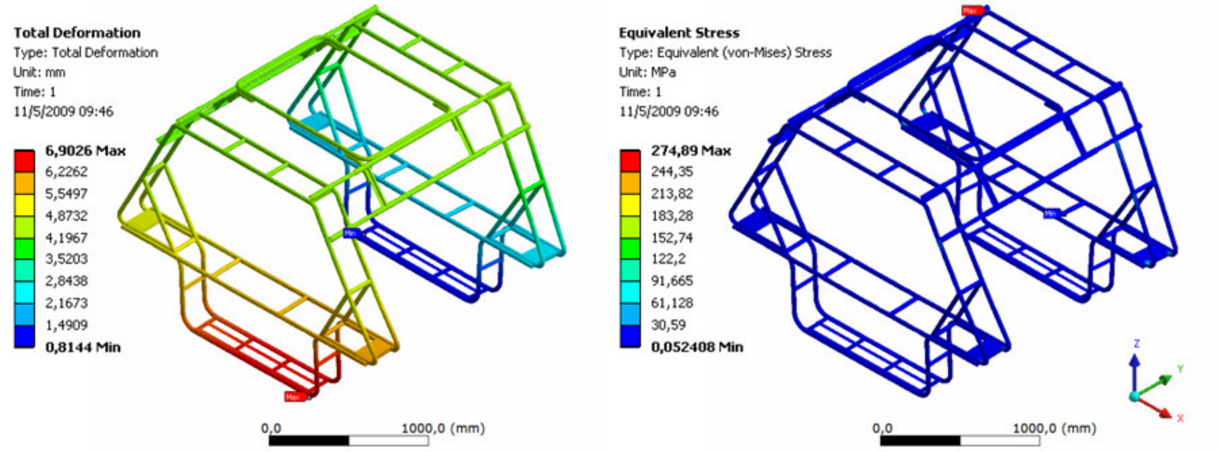

FIGURE 7. Total deformation and Stress of the structure in situation C (traffic with lateral tilt).

Electronic control units

For the integration between electronic devices, a CAN network based on ISO11783 protocol, also called ISOBUS, in the agricultural mobile robot has been placed (GODOY *et al.*, 2009). An electronic control unit (ECU), or CAN interface, was used for these devices integration. The microcontroller that has been used was the PIC18F258. This chip provides the logic operations for the CAN protocol communication and implements the programs for data acquisition of the devices connected to the I/O ports, such as sensors and actuators. A MCP2551 transceiver was incorporated into the ECU to provide switching between the digital TTL logic of the microcontroller and the differential output required on the CAN bus. And a MAX232 transceiver provides switching between the TTL logic and the output required by the serial RS232 port.

In order to communicate according to the ISO11783 standard, a microcontroller library was developed and inserted in the ECU. This microcontroller library was developed according to the specifications of parts 1 to 11 of ISOBUS documents. The implementation of the high-level ISOBUS functions (initialization, management and communication) was in C language and used as a basis a J1939 library for the Microchip microcontroller. The developed network not only enables the integration of sensors, actuators and computer systems relative with tasks of steering and navigation, but also enables integration of devices related to data acquisition of agronomical variables, which will eventually compose the system.

Teleoperation system and distributed control

For the viability of robotic structure operations in the field, it is necessary to develop a base station that has the function of managing the operations performed by robots or receive data from the analysis, permitting planning, controlling and monitoring tasks in real time via digital link for data communication.

FIGURE 8 presents the flowchart of the distributed control in the mobile robot.

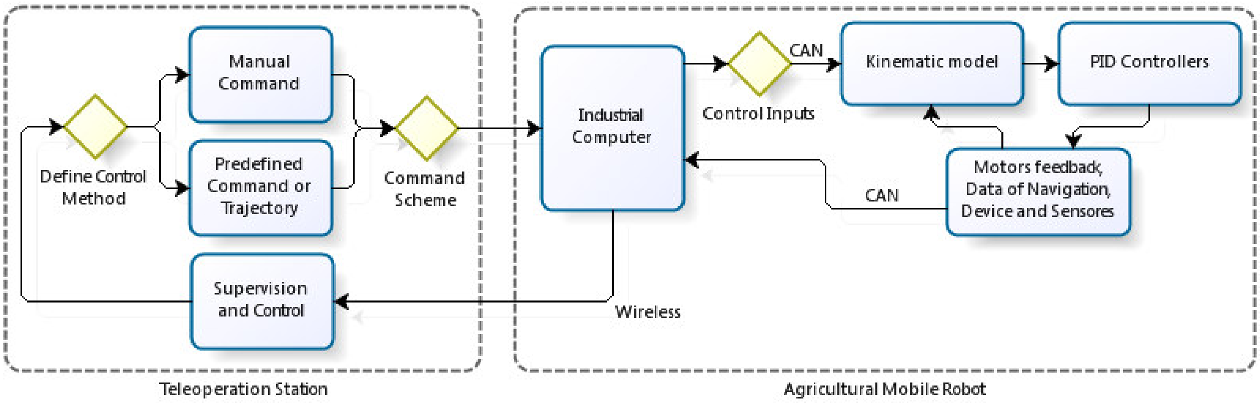

FIGURE 8. Flowchart of Agricultural Mobile Robot control system.

According to the flowchart, the used cans teleoperated the robot by selecting the control methods and sending manual commands or setting predefined commands to control the mobile robot. The predefined commands do not allow autonomous navigation but only defined trajectories that simplify the necessary user commands to be sent to the robot. All commands defined by the user are transmitted to the mobile robot via a wireless digital link based on IEEE 802.11 standard performed by a VNC connection. All control inputs received by the industrial computer in the mobile robot are processed according to the kinematic model. The kinematic parameters supply the control system for the steering and propulsion motors, which in this work, are a discrete-time PID.

The results of the adopted control methodology are transmitted by messages in the CAN network. The ECUs in the robot receive the CAN messages with the control data and act in the motor of the robot. The motors feedback (encoder information about traction speed and steering position) and the data from other devices and sensors connected in the robot are also transmitted via the CAN bus to the industrial computer. This information feedback both the PID controller and the kinematic model it is also sent back, via wireless network, to the computer in the teleoperation station and it is presented in the supervision and control software. By using of the information about the robot, the user can decide how to act and control the robot movements.

Robot operation

The robot was manufactured based on the parameters presented. Currently, communication and navigation modules are in development. Preliminary tests indicated that the structure reached the originally proposed requirements.

FIGURE 9 shows views of the Agricultural Mobile Robot.

FIGURE 9. Views of the Agricultural Mobile Robot.

CONCLUSION

The study showed the possibility of the robot application for carrying out remote sensing in agricultural environments. Initially the possible areas of activity and the main consumer markets have been identified. The operations that could be performed as well as the most important features that make up the agricultural environment have been defined. With these data the technical options available have been selected, in view of the set of parameters of operation, and among those, the one that best fits the prerequisites of the project. Computational modeling and later simulation and validation of the structure designed by specific software have been performed. With the manufacture of the platform it has been possible to find that the methodology used to develop the agricultural robot has been efficient, according to all the needs.

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