

## USE OF VIRTUAL PROTOTYPING FOR EVALUATION OF MECHANICAL BEHAVIOR OF AN AGRICULTURAL MOBILE ROBOT

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**Abstract.** The Precision Agriculture demands an expressive number of researches in developing instruments for automation. Among them, highlights the use of remote sensing techniques based on the use of on-the-go sensor technology, which coupled to a Geographic Information System (GIS) has been adapted and developed for agricultural use. Aiming this, the application of Agricultural Mobile Robots is seen as a strong tendency, mainly in the European Union, USA and Japan. In Brazil researches are necessary for the development of robotics platforms, serving as basis for semi-autonomous and autonomous navigation systems, facilitating the operations of data acquisition in the field. This work aims the project of a robot for remote sensing in agricultural area. The robot presents structure in portico format and steering systems and propulsion system organized in modules. 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. Was utilized the finite elements method, based on basic concepts of kinematics of mobile robots and previous experiences. The mechanical parameters of tension and deformation were obtained according to the different kinds of efforts applied in struture of the robot. Due scarcity of models to be used for comparison, during the manufacturing process, the virtual prototyping process is presented as a great methodologist for authenticate the mechanical structure operation in different conditions. Results obtained by the agricultural robot presented great potential for data acquisition and development of robotics and navigation technologies.

**Keywords:** *precision agricultural, finite elements method, robot control*

### 1. INTRODUCTION

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 find studies that seek to adapt business agricultural machinery to make autonomous agricultural platforms (vehicles or autonomous agricultural mobile robots) as can be seen in REID *et al.*, 2000 and KEICHER & SEUFERT, 2000. 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 and SOUTHALL *et al.*, 2002. In the second case, it identifies two challenges: developing a physical structure suitable for the agricultural environment, and develop an architecture to integrate the various electronic devices in systems allowing its expansion through the addition of new devices.

It is widely known that mobile robots are designed, built and experimented with all over the world. However, despite this popularity, the work discussing the underlying structural and functional complexity is frequently neglected (DENG *et al.*, 2000). 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. This consists of many capabilities, the best known of which 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) models, in animated or



still format, created in the form of mathematical models and stored digitally in computer usable memory. Virtual Prototyping is about presentation, testing and analysis of three-dimensional CAD models prior to creating any physical prototypes. The technology for using virtual prototypes was pioneered and adopted initially by large automotive and aerospace industries (ZORRIASSATINE *et al.*, 2003).

With the rapid increase in both computing power and sophistication of computational methods and models of physical phenomena and the growing ability to transport results between various models are improving the scope of applications, robustness, accuracy, realism and cost effectiveness of Virtual Prototyping technology at an incredibly fast pace (MILLER, 1998).

Other familiar examples of Virtual Prototyping include digitally generated animations of mechanisms, finite element analysis (FEA) and computational fluid dynamics (CFD) of mechanical products and structures (ZORRIASSATINE *et al.*, 2003). The finite element method (FEM) is the most popular simulation method to predict the physical behaviour of systems and structures. Since analytical solutions are in general not available for most daily problems in engineering sciences, numerical methods have been evolved to find a solution for the governing equations of the individual problem. Although the finite element method was originally developed to find a solution for problems of structural mechanics, it can nowadays be applied to a large number of engineering disciplines in which the physical description results in a mathematical formulation with some typical differential equations that can be solved numerically (WANG & NELSON, 2004).

Considering the context presented, the purpose of this work is the development of a mechanical structure to form an Agricultural Mobile Robot, with Virtual Prototyping including a CAD model and a finite elements analysis at normal operating conditions and worst-case conditions. The autonomous vehicle will be developed to test different sensor systems and tools in the field. The vehicle should be able to work under field conditions, where it can be disturbed by irregularities, when following a specified path.

## 2. MATERIAL AND METHODS

The Agricultural Mobile Robot is designed to do the sensing of agronomic parameters of most important Brazilian culture in large areas. It doesn't require actions that demand high power, as in agricultural operations, but only moving efficiently in this environment. The mechanical structure was designed by the studying of work conditions required in field and desired characteristics of the project, using the process steps described in Figure 1.

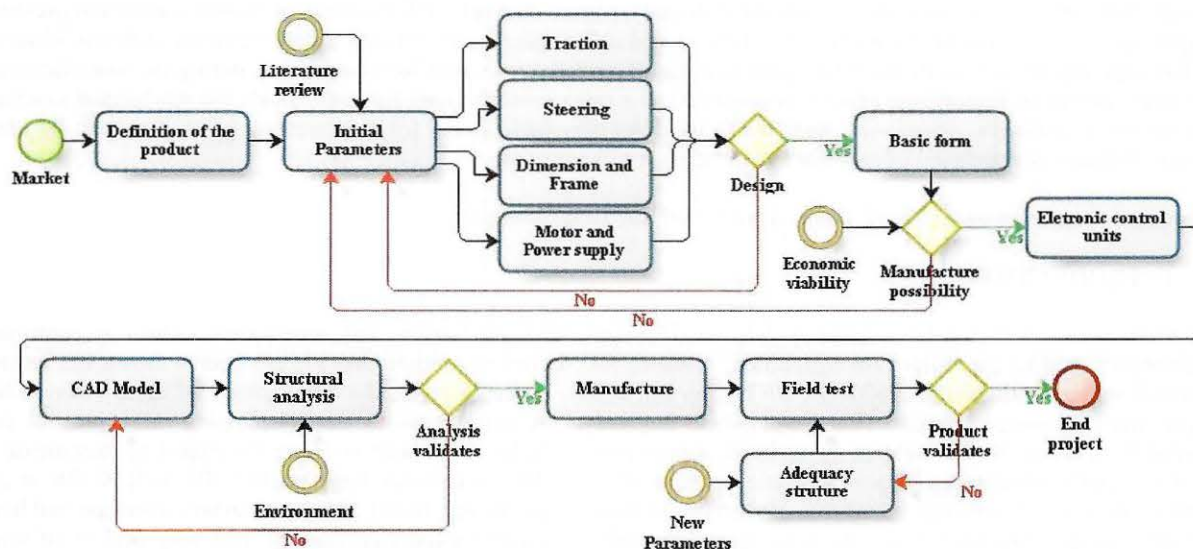


Figure 1. Flowchart of Agricultural Mobile Robot design.

### 2.1. Mechanical design

It was established that the structure should be in portico, capable of operating in cultures up to 1.8 m of height, with adjustable gauge to operate in various row spacing cultivation and should be light and flexible compared with commercial agricultural vehicles, with the possibility to insert new sensors and actuators. According 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.

**Dimensions and Frame:** Four wheels were placed in each corner of a rectangle with the length parallel to the crop rows were chosen for the vehicle. This configuration provides a great stability and the rear wheels can run in the tracks of the front wheels, which decreases the rolling resistance.

As the Agricultural Mobile Robot is designed to operate in the main cultures of Brazilian agricultural sector, during almost the entire cycle of growth and post harvest, it requires versatility of the frame, aiming to meet all situations. It



was established that the structure would be in portico with 2m of height, and according to the different distances between rows of crop plants, it was chose a frame where the gauge could be adjusted. To accomplish this, the system was designed in independent modules (side frame and top frame), together by telescopic bars, to meet the maximum possible situations, as shown in Figure 3. The steering module, the propulsion module and central box complete the system.

Due to the Agricultural Mobile Robot height, distance between axles must allow overcome ramps commonly found in agricultural environments. The short wheelbase improves the maneuverability of the vehicle, but also makes it harder to control. Our goal is to build a flexible vehicle, the wheelbase is therefore chosen, so that it will just leave room for tools and give the best maneuverability. As 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, more traction capability especially in loose soils. This system is common utilized in large equipment or those who require high performance, however, 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, meet the needs of this project. In this project, we adopted a four wheels system and to increase the ability of vehicle pull in adverse conditions, we adopted independent traction in each wheel; primarily system will be 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, frequently utilized for vehicles that should be very maneuverable, can turn on the own axis. The transmission is simple to manufacturing, in function of the wheels of the same side turning at the same speed and the position and orientation of the wheels are fixed. The disadvantages of this system is which the vehicle turns around a vertical axis with the wheels slid sideways, which means spends too much power.

The principle of articulated steering is to change the angle between the front and the rear axle of a vehicle. This is a system by which a four-wheel drive vehicle is split into front and rear halves which are connected by a vertical hinge. The front and rear halves are connected with one or more hydraulic cylinders that change the angle between the halves, including the front and rear axles and wheels, thus steering the vehicle. An advantage of this system is the simplicity of construction.

The methodology of wheel steering or Ackerman, is the most used by road vehicles for steering. This methodology describes the relation between the angles of outside and inside the wheel in a turn. However, this criterion is very difficult to implement mechanically, because it is a nonlinear model. Therefore, on most vehicles, steering angles only approximate for small steering angles, however, deviations do not necessarily mean that the steering geometry is not optimal under real driving conditions. In function of the choice of the structure configuration and the capability of adjust of the gauge, it was chosen a system that could be independent for each wheel, with easy construction and accuracy of steering, so we opted by the system Ackerman 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. To attend this requisites was opted electrical motors for the steering and propulsion system. The most common types of electric motors are the AC (alternate current) or DC (direct current) motors. The AC motor consists of a stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft that is given a torque by the rotating field. There are two types of AC motors (synchronous and induction), depending on the type of rotor used. Disadvantages for application in this project are the difficult control and the need of frequency inverters. The brushed DC motor generates torque directly from direct current power supplied to the motor by using internal commutation, stationary permanent magnets, and rotating electrical magnets. Advantages of a brushed DC motor include low cost, high reliability, and simple control of motor speed. The DC motor which has the best meets above demands can be used indoors and can be supplied by battery and power amplifiers, which makes it a flexible and easy to install solution. The power supply should be able to drive the electronics components, computers and motors.

**Power supply:** Batteries where chosen for the vehicle, because they are easier to install and should be able to deliver power for 2 - 4 hours of testing, without getting to heavy. The number of times a battery can be discharged is known as its cycle life, and this is what determines its suitability for use how power supply in electric vehicles. For this application a battery needs to be capable of being discharged many times, this type is known as a deep-cycle battery. Car batteries are the most common type of lead-acid battery, but will survive only 5 or 10 cycles so are unsuitable for our purposes. 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.

## 2.2. Virtual prototyping

Mechanical structure of the Agricultural Mobile Robot was 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 physical artifact. This is done by creating computer generated geometrical shapes (parts) and either 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 different stresses that product may encounter in the real world. The development of the project followed the flowchart shown in Figure 1. A detailed solid model was design in Solid Edge (Siemens Corp.) (SIEMENS, 2010), CAD commercial software. By using this model, finite element model was constructed. Deformation and stress analyses were performed via ANSYS Workbench V11.0 (ANSYS, 2010) commercial finite element software. Housing material properties which were utilized in finite elements analyses were obtained from ANSYS library, where: Young's Modulus:  $2.10^5$  MPa; Poisson's Ratio: 0.3; Density:  $7.85.10^6$  kg mm<sup>-3</sup>; Tensile Yield Strength and Compressive: 250 MPa; Tensile Ultimate Strength: 460 MPa. The structure was developed using the Solid Edge and ANSYS software. To simplify the model, elements that have no structural function as central box, batteries, motors and steering system were removed from analysis, only side and top frame stayed duly established by telescopic tubular bars. Removed items were replaced by resulting forces. Simulation was performed considering the structure under condition of dynamic strain in three severe conditions of use.

Steering system badly calibrated: 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: 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: 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.

### 2.3. Electronic control units

Between the several fieldbuses, a technology that is widespread to be applied on these devices interconnection is the distributed communication based on the Controller Area Network (CAN) protocol. In the agriculture area, the chosen of the CAN protocol (BOSCH, 2010) as communication network due to its low cost of development and large acceptance and success for embedded electronics in the automotive area. The implementation of the ISO11783 standard, also called ISOBUS, represents the standardization of the CAN protocol to the agricultural area and constitutes the main target of development as described in BENNEWEIS, 2005.

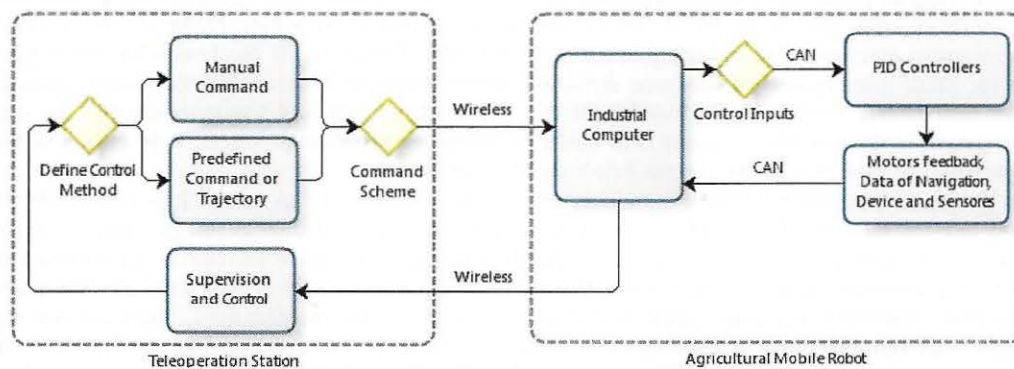


Figure 2. Flowchart of Agricultural Mobile Robot control system.

For integration between electronic devices, it was deployed a network CAN in the Agricultural Mobile Robot. The network developed not only enables the integration of sensors, actuators and computer systems relative with tasks of steering and navigation, but also enables integration of devices relate of data acquisition of agronomical variables, which will eventually compose the system. The steering controllers have an embedded can interface and are direct connected to the network. The propulsion controllers use a can interface, developed to communicate with the network. For viability of robotic structure operation in the field 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.

## 3. RESULTS AND DISCUSSION

### 3.1. Mechanical structure of the robot

Figure 3 shows the assembly and size of Agricultural Mobile Robot. Figure 3A shows the front view. It is possible modify the gauge of the robot through of telescopic bar which conect the side frame and the top frame (item 10 of Figure 3C). Figure 3B shows side views of the set, highlight batteries positioning, format of side and top frame, connected by tubular bar and the central box where there are the electronic devices to control. Figure 3C shows the



isometric view of the Agricultural Mobile Robot with all its components were: (1) side frame, (2) fork, (3) wheel, (4) batteries, (5) propulsion system, (6) steering system, (7) side box, (8) top frame, (9) central box, (10) telescopic bar. It is observed that heavier items such as batteries and propulsion and steering systems are at least one meter of the soil, which contributes to lower the structure center of gravity, increasing its stability on sloping land. Figure 3D shown an explode 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.

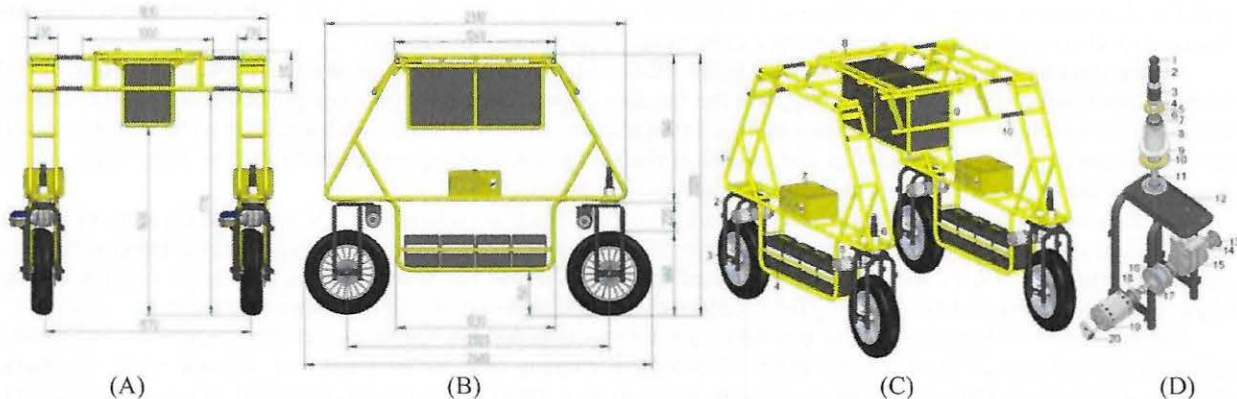


Figure 3. Agricultural Mobile Robot views; (A) Front view; (B) Side view. (C) Isometric view (D) Propulsion and Steering system.

At the base of the side frame, where the front wheels are fixed, there is a hole through which the bushing of the steering system is inserted in order from bottom to top, and fixed by four screws. After assembly of the bearings in the bushing, the fork that supports the wheel is fixed to the shaft of the steering system by three screws. This set is designed to support all loads and impacts bound for the wheel and that would be easy to maintain. Finally the set reducing-motor-encoder is fixed to the bushing by four screws. The reducer used has a reduction rate of 1:230 and the transmission of torque to the shaft made by pin. It is essential that no gap exists between the bushing and the motor to be possible the control of the steering with the desired precision. The system allows for turning radius of  $90^\circ$  and  $-90^\circ$  degrees, resulting in large capacity of maneuvering.

The propulsion system consists of a DC motor that is coupled to a reduction with rate of 1:25 (item 15 of Figure 3D). As the reduction used in the propulsion system has no bearing of its internal components, it was necessary to build the coupling system shown below (item 16 of Figure 3D). This aimed to ensure the alignment between the motor and reducer, avoiding stress accumulation in any component and premature wear of the system. The system is fixed by four screws connecting the reducer to 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 pinion / chain / crown, with rate reduction of 1:3, resulting in total reduction of 1:75.

Both the transmission system (crown, pinion, chain, shaft and bearing) and the wheels and tires are components used in a 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.

Table 1 shows the estimated weight of the components that constitute the Agricultural Mobile Robot, obtained by the Solid Edge software, in function of the mechanical properties of the materials used to build the model and the information contained in the manuals of the items used. Draws attentions to the weight percentage of the batteries, which corresponds to 27% of the total weight of the robot.

The robotic structure was designed symmetrically between right and left sides, which allows the homogenous distribution of weight, simplifies the development of the project, reduces design time and costs, build, install and accomplishes the maintenance of electromechanical components installed in the system. All these characteristics reflect in programming and operation of propulsion and steering systems controls, since these are independent of each side. The following will describe the electrical equipment that comprises each side of the structure and its function. Table 2 presents the main components used in the project.

It were used four engines of 24V and 750W which were responsible for propelling the robot, as can be seen in item 19 of Figure 3D. 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 3D). 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 constantly monitoring and adjustment of the power for each engine, aiming to obtain required parameters. Thus it was used a power controller equipped with two independent channels, installed inside the side box (item 7 of Figure 3C) for each side of the robot, 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. It can also be attributed a tolerance for this control to avoid overloading of the system with little variations, which do not influence in operation performance.

To provide the steer of the front wheels we used two engines of 48V and 150W, as can be seen in item 2 of Figure 3D. 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 3D). Observe that, for small changes in the angle of the wheels of steer, it is generated a large amount of points, which ensures an accuracy more than necessary for the great functioning of steering system. In this case, it is inserted a condition of tolerance, 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 correct angle; so it is important that the two steering systems are calibrated with the same tolerance and working synchronized. If any system present a failure may occur damage in structure.

All the electronic systems are accommodated in a metal box fixed by screws on the side frame of the Agricultural Mobile Robot (item 7 of Figure 3C). They have the function of protecting electronic components from weather and are positioned to facilitate maintenance of the system. In central box (item 9 of Figure 3C), are inserted the computers that do the processing of the collected data and control of the navigation, steering and position system. For electric cables passage it is used a flexible electric duty attached to structure robotics.

For the power of the controllers and motors we used eight traction batteries of 12V and rated capacity of 70 Ah, arranged four on each side as seen in item 4 of Figure 3D. Each propulsion motor uses two batteries connected in series and the steering motor uses four batteries connected in series. To load the system, it was developed a circuit to load eight batteries at the same time, reducing the time to recharge and ensuring that all batteries receive the same load.

Interconnected with the set, it was installed a security system that has the task of cutting controllers and motors power in case of any accident or unforeseen. This system consists of a button fixed in a strategic place of robotic structure which, when activated, interrupts system power, in function of the amperage demanded we developed a circuit to disarm the system.

### 3.2. Structure analysis

Table 1 shows the estimated weight of the components that constitute the Agricultural Mobile Robot, obtained by the Solid Edge software, in function of the mechanical properties of the materials used in building the model and the information contained in the manuals of the items used. Draws attentions to the weight percentage of the batteries, which corresponds to 27% of the total weight of the robot.

Table 1. Weight of the components of the agricultural mobile robot.

Item	Nº items	Unitary weight (kg)	Total weight (kg)	% total weight
Side frame	2	66,34	132,68	22,61
Top frame	1	33,18	33,18	5,65
Central box	1	18,40	18,40	3,13
Telescopic bar	8	1,78	14,24	2,43
Fork	4	9,57	38,28	6,52
Tyre and cube	4	8,54	34,16	5,82
Steering system	2	6,30	12,60	2,15
Propulsion system	4	19,60	78,40	13,36
Battery	8	20,00	160,00	27,26
Electronic system	1	65,00	65,00	11,07
<b>Total</b>			<b>586,94</b>	<b>100,0</b>

The details of the structure with the forces applied to the three tests are presented below (Figure 4). For the three situations are common following loads, however the situation C was rotation of coordinate system in 25° in Y axis, to represent the lateral inclination of the ground.

- Standard Earth gravity: acceleration of  $9,8 \text{ m.s}^{-1}$  in -Z direction operating on entire surface;
- Batteries: concentrated force of 1200 N in -Z direction inserted at the bottom of the side frame on both sides;
- Side Box: concentrated force of 500 N in -Z direction inserted in the middle bars of the side frame on both sides;
- Central Box: concentrated force of 1000 N in -Z direction inserted bottom of the top frame;
- Wheel module: moment of 3,5 N.mm in Y direction inserted in the base of the wheel support module, in the four wheels for situations A and C. In situation B the support is made only in two wheels (front left and rear right) to represent the seesaw effect that the structure is subject to cross an obstacle.
- Support system: were utilized to dislocate support in 880 mm of the base of each wheel module, with two degrees of freedom, X and Y.

Two loads of 500 N are specific to the situation A, applied in the side frame, the right side in Y direction and the left side in -Y direction, fix to 880 mm in -Z direction of the base of the front wheel module.

For situation B, two loads of 500 N, applied in the side frame, the right side in Y direction fix to 880 mm in -Z direction of the base of the front wheel module and the left side in -Y fix to 880 mm in -Z direction of the base of the rear wheel module; two loads of 1500 N applied on the side frame, both in -Z direction, fixed at the base of the left front



wheel module and on the rear right wheel module representing the weight in the wheel module, which are not in contact with the ground.

For situation C, coordinate system was rotated by  $25^\circ$  in the Y axis to represent the side inclination of the land. It were placed two loads of 500 N, applied in the right side frame in Y direction, fix to 880 mm in the -Z direction of the base of the wheel modules.

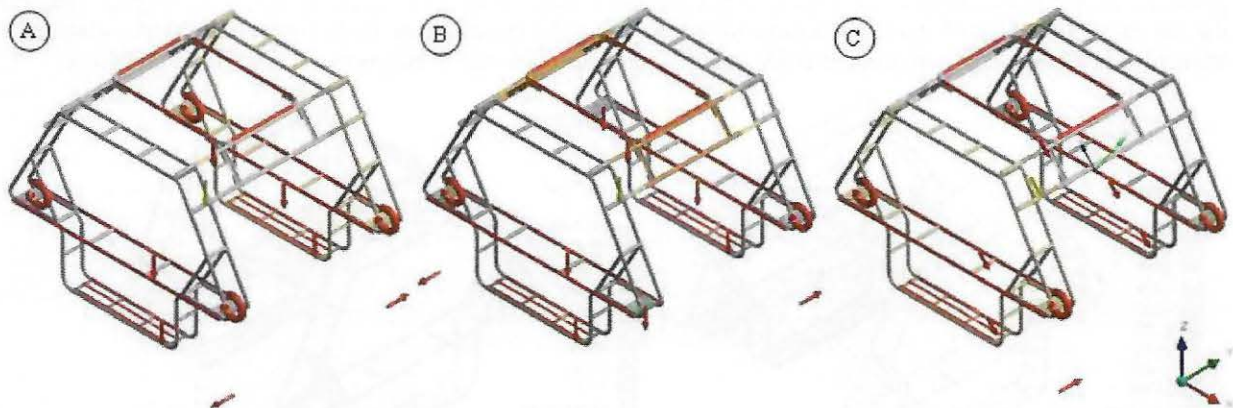


Figure 4. Loads applied on the structure: (A) Steering system badly calibrated, (B) Across obstacle, (C) lateral inclination  $25^\circ$ .

The result of simulation, containing data of total deformation and equivalent stress (von-Mises) are presented below. It is emphasized that the scale of deformation used in the figures is increased to facilitate viewing. In Figure 5 appears the result of the simulation of the system (steering system badly calibrated). It is observed that most deformation occurred in the lower area of the frame, but without compromising the performance of the set, regarding tension, it occurred points of stress accumulation at the junction between the top and side frame, but not enough to generate disruptions.

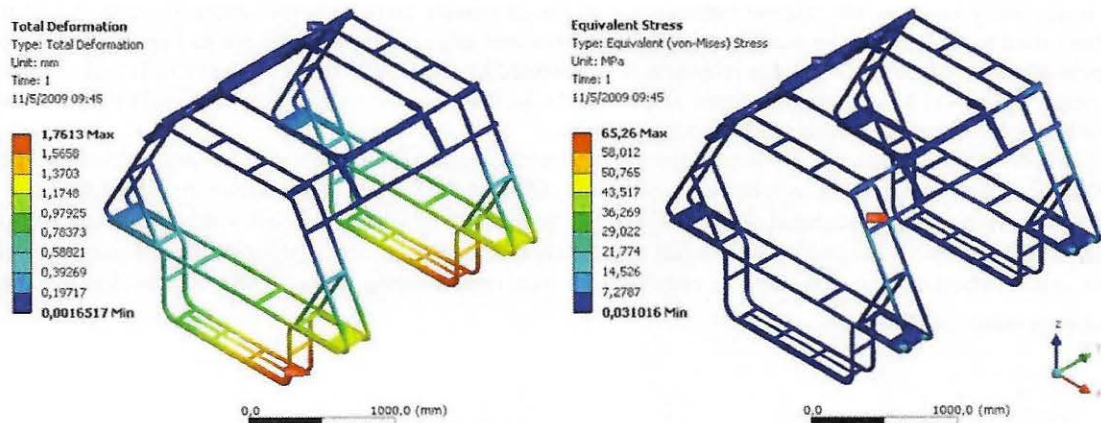


Figure 5. Total Stress and Deformation of the structure in the situation A (Steering system badly calibrate).

In Figure 6, we show the result of simulation B (across obstacle). Compared with situation A, deformation was larger, tending to twist the structure. With respect to stress, it was increased significantly due the twist of the structure, focusing on the same point of the situation A.

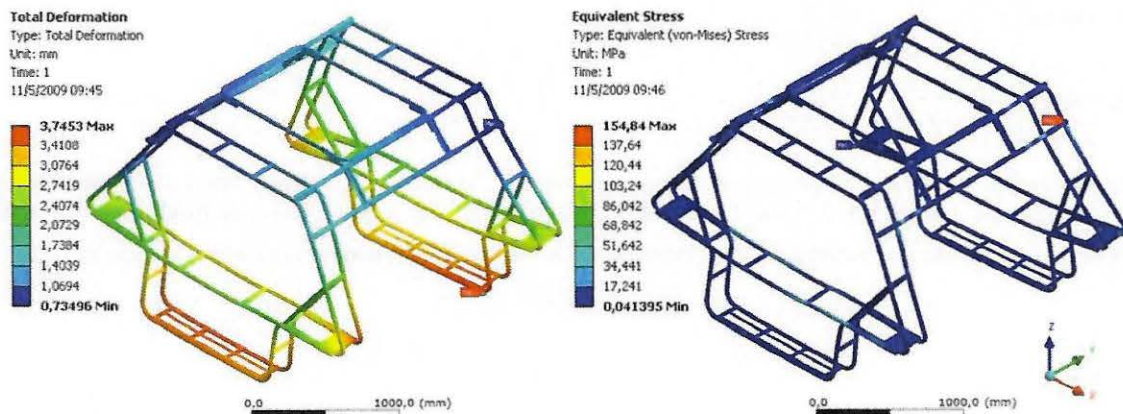




Figure 6. Total deformation and Stress of the structure in situation B (crossing obstacle).

Figure 7 shows the result of simulation of situation C (traffic with lateral inclination). Note that this is the most severe situation which structure was submitted. Strain was superior to 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 320% compared with the situation A. With the use, it may occur appearing of cracks in this region due to change in efforts to traction and compression.

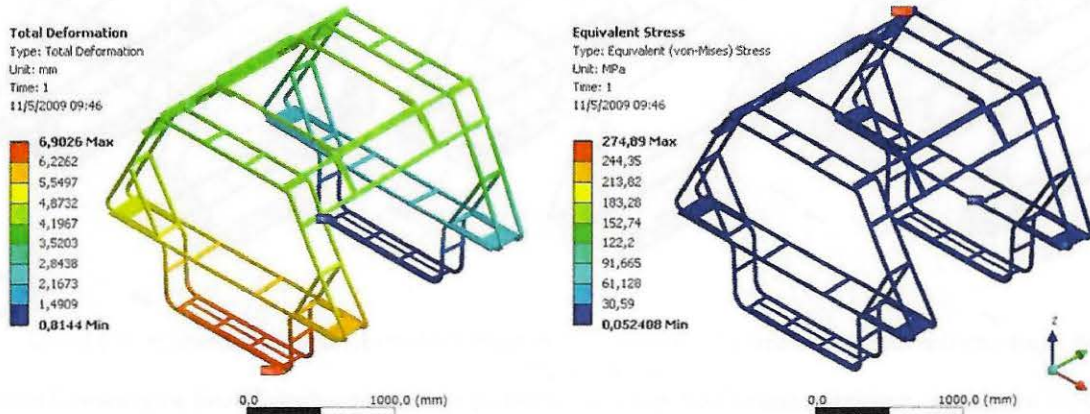


Figure 7. Total deformation and Stress of the structure in situation C (traffic with lateral tilt).

### 3.3. 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 is necessary to know the relation between the angles of outside and inside the wheel in a turn. Some relevant parameters used to understand the model, as global reference and site reference can be seen in Figure 8. **Fonte de referência não encontrada.** The global reference is represented by the axes X and Y. The site reference is represented by the center of mass (CM) locating on board of the vehicle. In this case, the localization of the CM is in the middle of the vehicle due the symmetrical and modular configuration.

Ackermann steering geometry, is determined by the steering angle of the vehicle ( $\alpha$ ) in relation with its center of mass. With this, is determined the instantaneous curvature radius of the vehicle ( $C_r$ ), shown in Figure 8 and described by equation 1. 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. Are established that the maximum steering angle of inside wheel ( $\alpha_i$ ) is  $45^\circ$ , thus, is obtained the minimum steering angle of the vehicle and the minimum instantaneous radius of curvature.

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

The equation 2 and 3 represent respectively the steering angle of the inside wheel ( $\alpha_i$ ) and the steering angle of the outside wheel ( $\alpha_e$ ).

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

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

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. Equation 4, 5, 6 and 7 demonstrate, respectively, the speed of the inside front wheel ( $w_{fi}$ ), outside front wheel ( $w_{fo}$ ), inside rear wheel ( $w_{bi}$ ) and external rear wheel ( $w_{bo}$ ). The path of each wheel is show in Figure 8.



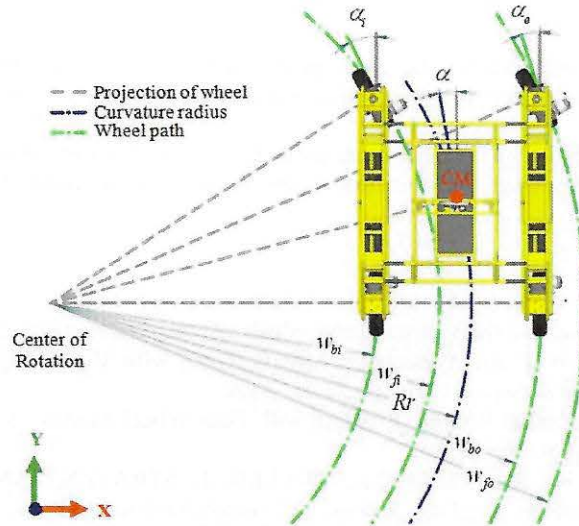


Figure 8. Ackermann steering geometry.

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

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

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

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

### 3.4. Robot operation

With the teleoperated architecture implemented in the mobile robot and the controllers designed to the CAN network, the mobile robot operation could be evaluated. We performed field tests using the mobile robot to evaluate the architecture (response time of user commands and quality of motors control). In experiments, the user controls (teleoperates) the mobile robot navigation and the feedback information is analyzed to check the operability and accuracy of the robot movement. The architecture time delay (response time of user commands transmission and feedback information for supervision) is also evaluated to verify its possible influence on the robot operation and supervision. The results of the tests demonstrated that the developed fieldbus architecture can be applied for teleoperation and distributed control of agricultural mobile robots meeting the requirements for an accurate robot movement and an acceptable response time for control commands and supervision. In Figure 9 is showed views of the Agricultural Mobile Robot.



Figure 9. Views of the Agricultural Mobile Robot.



#### 4. CONCLUSION

The methodology was efficient for the development of robotic structure, the values found for strain and stresses are within the required tolerance. It is hoped that, with the construction of the prototype and the beginning of tests, the model can be validated.

The robot was manufacture based on the parameters presented. The preliminary tests indicated that the structure met the requirements originally proposed. The kinematic model and the control system showed good performance during the activities.

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#### 6. RESPONSIBILITY NOTICE

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