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A design and analysis of an autonomous ground vehicle to automate the process of transplanting rice

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Abstract– ***Precision agriculture brought with it the implementation of new digital technologies, mainly autonomous vehicles, satellite images, IoT and artificial intelligence, to provide economic, productive, and environmental benefits in the agricultural field. However, the main applications are focused on data management and monitoring of crop fields, so agricultural processes such as planting and harvesting are not yet fully automated. A clear example of this occurs in the cultivation of rice, which despite being one of the most important agricultural products in the world, the manual production method continues to predominate in developing countries. This work presents a design of an autonomous terrestrial vehicle capable of carrying out the rice transplantation process, having as its main characteristics its ability to move in the field of cultivation at a speed of 0.75m/s, transport a payload of up to 20kg and possess an autonomy of 1 hour. Which translates into an effective field capacity (EFC) of 0.21 ha/h, an operational equivalence of 7 workers/hour and an increase in the productivity of the transplant process of 200% with respect to the manual process. It seeks to provide farmers in developing countries with an affordable option, supported by numerical simulations, with which they can obtain the benefits of precision agriculture in the process of transplanting rice. In such a way, that the manual production of rice and its disadvantages such as low productivity, the physical consequences for the farmers and the limitations against expensive machinery are replaced by the automation proposal.***

Keywords-- Precision agriculture, rice transplantation, UGV, autonomous vehicle, skid-steering mobile robot, numerical simulation.

I. INTRODUCTION

Rice is one of the most important crops in Peru, which has become one of the pillars of national food security, and one of the most important products of Peruvian cuisine [1]. In April 2022, rice production amounted to 330,825 tons, a volume 32.5% higher than that reported in the same month of the previous year, 249,692 tons [2]. However, most of the farmers in Peru continue to use the manual production method, which requires high consumption of time, energy, and resources [3]. Specifically, rice transplantation is the most important and demanding process of the crop, and thanks to the mechanized agricultural revolution, rice production was significantly optimized, mainly due to the precision in the distances between rows and rice seedlings [4]. In addition, for developing countries, one of the main obstacles in the implementation of the mechanized process is the lack of technical skills of the users with agricultural machinery, the most common being 4-row transplanting machines [5]. The theoretical transplanting speed of this type of machine varies according to its type, number of rows and the power of its combustion engine; being the most common 0.75 m/s which corresponds to an effective field capacity (EFC) of 0.18 [6]. Regarding the production requirements, they vary according to the geography and type of process (manual or mechanized), for this reason there are methods that standardize these requirements, such as the SRI, which indicates that for favorable climatic conditions and the mechanized transplant process, should establish a distance between rows and seedlings of 20 x 25 cm and a minimum transplant depth of 2 cm [7].

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During the last years, designs of different rice transplanting machines have been carried out, as well as studies on the efficiency of commercial models. However, commercial models represent a high initial investment for farmers in developing countries such as Peru, and current autonomous vehicle designs do not satisfactorily integrate commercial model mechanisms.

Jie He [8] developed a positioning correction method for transplanters, eliminating the inclination error when performing the linear trajectory of the process. The study obtained a significant improvement by standardizing the transplantation process through a satellite navigation system. However, this method focuses on automating commercial transplanters, adding new components such as GPS modules, which increases the price and complexity of using the transplanting machine.

Marzuki et al. [9] designed and simulated a mechanism based on four links to carry out the process of transplanting rice. The design has a trajectory that simulates that carried out manually and can be coupled to manual tractors with a 9.5Hp Diesel engine. However, this design does not include integration with other necessary mechanisms that a transplant machine has, so the dimensions of the links and the shape of the end effector must be adapted to a specific design.

Meris et al. [10] developed a two-row rice transplanter machine in the Philippines. The design has a transplant mechanism like the one proposed by [8], with a static seedling support, a vehicle with differential 3-wheel drive. However, the type of traction presents a greater instability and sensitivity to noise than one based on 4 wheels, in addition to having a fixed seedling support, it presents an inefficiency in the use of raw material, which is reduced with a mobile platform like the of commercial machines.

Chaitanya et al. [11] designed a simple and cost-effective rice transplanter. The design is characterized by having a straight transplant trajectory, thanks to a mechanism like that proposed in [8]. However, this design is only capable of operating one row and requires propelling by a user, which in terms of physical effort is still inefficient.

Miranda-Caballero et al. [12] evaluated the quality of mechanized transplantation in Cuba. The study used a transplanting machine model predominant in the market and concluded that standardizing the distances between rows, seedlings, and transplanting depth increases crop efficiency. In addition, he stressed the importance of the mobile system that stores the raw material and guarantees the efficiency of the transplant process, as well as the elaboration of the raw material that will be entered into it (carpets of rice seedlings). However, the inclination of the terrain was not considered in the calculations, but rather it was assumed as parallel to the water sheet and perpendicular to the ground.

Finally, to validate the design, two types of analysis will be carried out. On the one hand, for the mechanical design of the proposal, finite element analysis (FEA) will be used, which is a numerical simulation technique used to simulate the response of physical systems. This method is based on decomposing a system into a series of smaller and simplified elements, where their type and size will define the precision of the results of modeling and analyzing the behavior of the system in question. For this, graphs of parameters such as Von Mises Stress, maximum deformation and safety factor will be used, which will be provided by the Autodesk Inventor 2021 software, where [13].

On the other hand, to guarantee that the mobile robot is autonomous, its controllability will be analyzed through concepts of kinematics and dynamics. Kinematics focuses on the study of the position, speed, and acceleration of robots, without considering the forces that produce them; while the dynamics focuses on the study of the forces that generate the movement of the robot, considering the mass, inertia and the interaction with the environment. For this, a kinematic simulation will be carried out with a trajectory similar to the one required and a Lyapunov first-order control, which is a control technique used in robotics to control the speed of a robot, and through the dynamic model of the vehicle it is will calculate the power required by the electric actuators to move the vehicle at the required speed [14].

II. METHODOLOGY

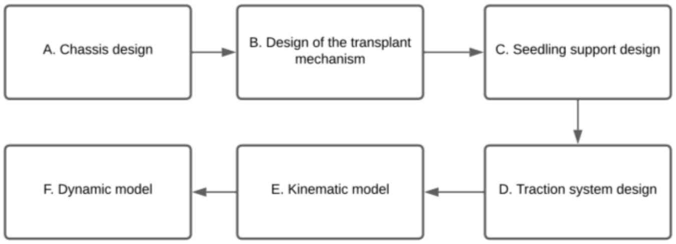


Fig. 1 Block diagram of the process.

The autonomous vehicle design was developed using Autodesk Inventor 2021 software with an educational license. Likewise, the plans of the manufacturers of the different materials and components used, such as DC and stepper motors, spindle, aluminum profiles, etc., were considered. In addition, for all component selection parameters, a safety factor of 5 is being used to guarantee correct operation. While, in the structural analysis of the chassis, finite beam elements with a size defined by the software used were used, since they guarantee better precision when analyzing structural profiles such as the V-slot; and for the FEA in the design of the transplant mechanism, hexahedral elements were chosen, since the geometry of the links does not represent a high complexity. However, since it has a circular shape, an element size of 0.5 mm was chosen to better capture the details of the geometry.

The autonomous vehicle design has dimensions of 780 mm x 460 mm x 300 mm and a total weight of 46 kg. It is characterized by being low cost, capable of moving at 0.75 m/s and transplanting two rows of rice 20 cm apart using 4-link mechanisms, a mobile system that supports the raw material (rice seedling mats) and is synchronous. to the movement of the mechanisms, and a 4-wheel drive system with skid steer since robots of this type have greater robustness and ability to operate in difficult terrain such as sub-arctic and arctic areas [15].

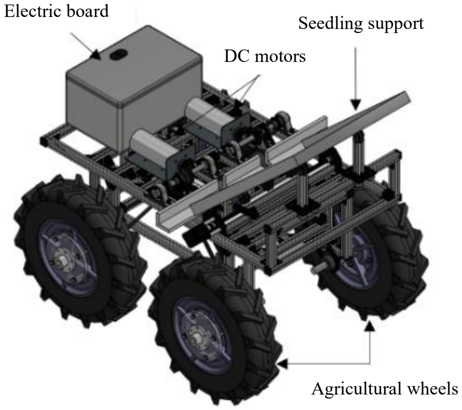


Fig. 2 UGV design.

A. *Chassis design*

For the design of the chassis, the use of Vslot 20x20 aluminum 6063-T5 structural profiles was chosen, whose tensile elastic limit is 145MPa. Considering a safety factor N=2 for the design, the maximum effort in the Y axis would be:

$$\sigma_{maxy} = \frac{\sigma_{yAluminum6063-T5}}{N} \qquad (1)$$

Where:

σ_{maxy}: $Maximum\ effort\ in\ Y[Mpa]$; N: $Security\ factor$; $\sigma_{yAluminum6063-T5}$: $Tensile\ elastic\ limit\ [MPa]$

Then:

$$\sigma_{maxy} = 72.5\ MPa$$

While the critical deformation in the horizontal axis, for a profile with two supports and a system load of 20 kg, considering the design presented in Fig. 2, would be:

$$Maximum\ deflection = \frac{F \times L^3}{48 \times E \times I} \qquad (2)$$

Where:

F: $Load\ on\ the\ beam$ $[N]$; L: $Beam\ length$ $[m]$;
E: $Modulus\ of\ elasticity$ $[Pa]$; I: $Transverse\ moment\ of\ inertia$ $[m^4]$

Then:

$$Maximum\ deflection = 0.55386\ mm$$

B. Design of the transplant mechanism

Taking the kinematic model proposed by Marzuki [7] as a reference, the lengths of the mechanism and the ergonomics were adapted to integrate them into the chassis design.

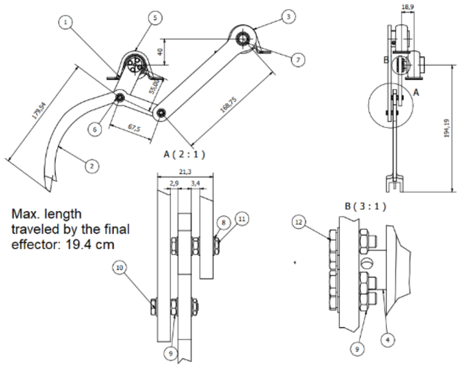


Fig. 3 Design of the transplant mechanism.

To verify that the established lengths do not interfere with the desired trajectory, Grashof's Law will be used, which guarantees a continuous movement in the effector, provided that the sum of the smallest link with the largest link is less than the sum of the two other links:

$$s + l < p + q \qquad (3)$$

Where:

s: $Shortest\ link$ $[mm]$; l: $Longer\ link$ $[mm]$;
p: $Intermediate\ link\ 1$ $[mm]$; $Intermediate\ link\ 2$ $[mm]$

Then:

$$55\ mm + 179.54\ mm < 67.5\ mm + 168.75\ mm$$
$$234.54\ mm < 236.25\ mm$$

C. Seedling support design

It is required to mobilize the payload of 20 kg, rice seedlings, a necessary distance to optimize the use of raw material of each row. Considering [5], the mechanisms must be separated by 20cm, therefore a distance of double this parameter, 40cm, is determined.

To meet this requirement, a power screw linear actuator was selected, which transfers the rotation of a stepper motor to linear movement, this system is characterized by its self-locking capacity and does not require constant maintenance.

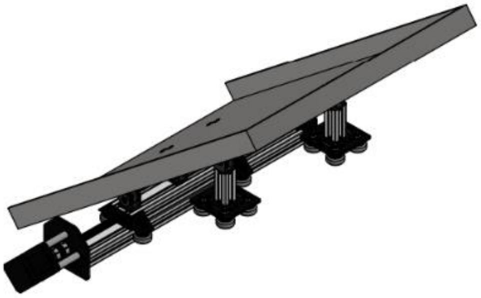


Fig. 4 Rice seedling support design.

The torque required to mobilize a load of 200 N, using a THSL-400-8D power screw, with an external diameter of 8 mm, advance of 2 mm, coefficient of friction between materials equal to 0.1 and a transported length of 400 mm would be:

$$T = \frac{F \times dm \times (1 + \pi \times u \times dm)}{2 \times (u \times L - u \times dm)}; dm = de - p \qquad (4)$$

Where:

T: $Required\ torque$ $[Nm]$; F: $Burden$ $[N]$;
de: $Screw\ outer\ diameter$ $[m]$; p: $Advance$ $[m]$;
u: $Friction\ coefficient\ between\ materials$ $[m]$;
L: $Transported\ length$ $[m]$

Then:

$$T = 0.04393\ Nm$$

Considering a safety factor equal to 5, there would be a required torque equal to 0.22 Nm. To meet this requirement, a stepper motor with a nominal torque of 0.5 Nm was selected, a THSL-400-8D spindle with a feed rate of 0.002 m and 90% efficiency is considered. With these data, the axial force that the motor would generate is calculated.

$$Fa = \frac{T \times 2 \times \pi \times n}{l} \qquad (5)$$

Where:

Fa: $Axial\ force$ $[N]$; T: $Supplied\ torque$ $[Nm]$;
n: $Engine\ efficiency$; l: $Advance [m]$

Then:

$$Fa = 565.48\ N$$

The linear actuator has a 20x40 Vslot profile as a mobile component, so it must be able to support, the torque will be supplied by the Nema 23 motor, the axial force, and the weight of the payload.

D. Traction system design

The humid terrain of the process was considered, for this reason it is necessary that the motors are in the upper part of the chassis. To transmit the power and movement to the wheels, a system with transmission chains and bevel gears was designed.

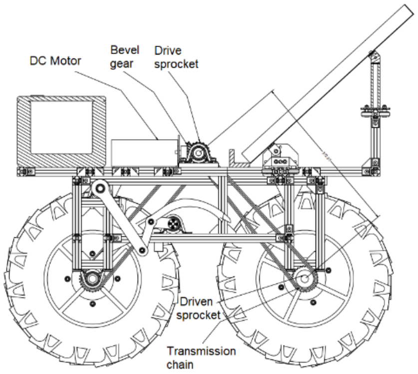


Fig. 5 Traction system design.

The design contemplates two DC motors with planetary gearboxes, which will transmit the mechanical power through bevel gears and chains with a ratio of 1: N, where N represents the total ratio of the number of teeth of the gears and sprockets of the chain. While the length between the driving pinion and the driven pinion would be:

$$X_0 = 2\frac{C_0}{p} + \frac{z_1 + z_2}{2} + \frac{p\left(\frac{|z_2 - z_1|}{2\pi}\right)^2}{C_0} \tag{6}$$

Where:

X_0: $Number\ of\ links$; C_0: $Distance\ between\ centers$ $[m]$; p: $Chain\ pass$ $[m]$; $z1$: $N°\ of\ teeth\ of\ the\ driving\ pinion$; $z2$: $N°\ of\ driven\ pinion\ teeth$

Then:

$$X_0 = 139\ links$$

E. Kinematic model

The designed mobile robot is of the 4-wheel sliding steering type, and its behavior is given by the kinematic model, where only speeds intervene. This type of vehicle has already been extensively studied in [16], [17] and [18].

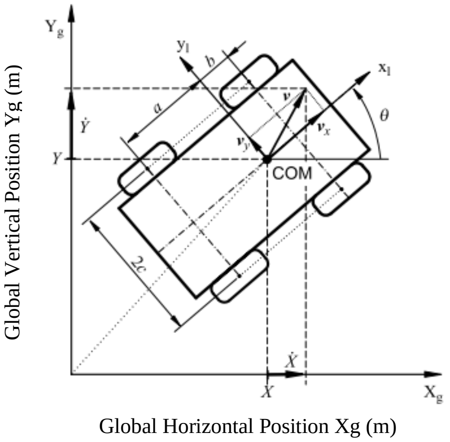


Fig. 6 Kinematic model [13].

$$\dot{q} = R(\theta) \times n \tag{7}$$

Where:

$\dot{q}$: $Vector\ of\ global\ velocities$; R: $Rotation\ matrix$
n: $Vector\ of\ local\ velocities$

Then:

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos\theta & -a\sin\theta\\ \sin\theta & a\cos\theta\\ 0 & 1\end{bmatrix}\begin{bmatrix}v\\ w\end{bmatrix} \tag{8}$$

Where:

$\dot{X}$: $Speed\ in\ X\ [m/s]$; $\dot{Y}$: $Speed\ in\ Y[m/s]$;
$\dot{\theta} = w$: $Angle\ speed[rad/s]$;
θ: $Rotation\ angle[rad]$; v: $Linear\ speed[m/s]$

Equation (8) relates the linear speed of the robot; however, the selection of geared DC motors is usually found in revolutions per minute.

$$Nr = \frac{60 \times v}{2 \times \pi \times r} \tag{9}$$

Where:

v: $Linear\ speed\ [m/s] = 0.75m/s$;
r: $Wheel\ radius[m] = 0.2m$

Then:

$$Nr = 35.81 \cong 35\ rpm$$

The actuators are required to have a nominal speed of 35rpm for the mobile robot to be able to move at 0.75m/s.

F. Dynamic model

To determine the power of the actuators and optimize trajectory control, it is necessary to evaluate the dynamic model of the vehicle. As with the kinematic model, there are already references to previous studies in [14], [15] and [16], so the behavior of the dynamic system is represented by the following equation:

$$M(q)\dot{n} + C(\dot{q})n + R(\dot{q}) = B(q)\tau \qquad (10)$$

Where the matrices M, C, R and B are:

$$M = \begin{bmatrix} m & 0 \\ 0 & ma^2 + I \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & ma\dot{\theta} \\ -ma\dot{\theta} & ma\dot{a} \end{bmatrix}$$

$$R = \begin{bmatrix} F_{rx}(\dot{q}) \\ aF_{ry}(\dot{q}) + M_r \end{bmatrix}$$

$$B = \frac{1}{r}\begin{bmatrix} 1 & 1 \\ -c & c \end{bmatrix}$$

While 2c is the width of the vehicle, m represents the mass of the robot, I is the moment of inertia of the robot with respect to the COM, r denotes the radius of the wheel, the coordinate of the instantaneous center of rotation (ICR) is defined as (a, b), $F_{rx}(\dot{q})$ and $F_{ry}(\dot{q})$ are the resultant forces expressed in the inertia frame, and $M_r(\dot{q})$ is the resisting moment about the center of mass and τ is the torque vector right and left. With this relationship it is possible to calculate the torque required for the design, which turns out to be 22Nm per motor.

III. RESULTS

A. Structural analysis

A structural analysis was carried out using Autodesk Inventor 2021 to verify the deformation and the safety factor of the chassis design, where the loads of the mechanisms and raw material were entered. A maximum stress equal to 34.73 MPa and a maximum deformation of 0.554mm was obtained. Which agrees with what was designed and is within the design safety parameters.

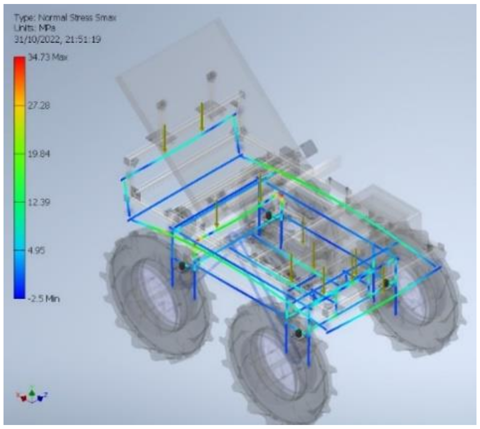


Fig. 7 Maximum normal stress on the chassis.

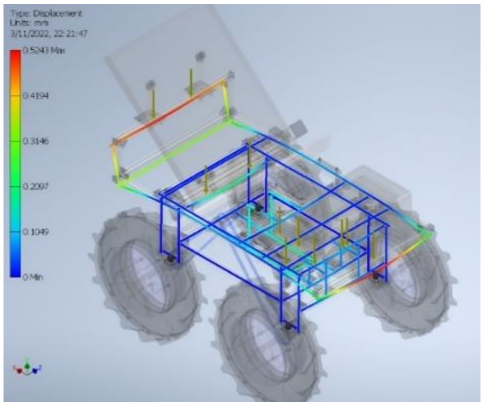


Fig. 8 Maximum displacement in the chassis.

B. Dynamic simulation

A dynamic simulation was carried out using Autodesk Inventor 2021 to verify what was established in (3). To do this, a speed of 25 rpm was entered into the driving mechanism and the trajectory of the end effector was analyzed, as well as the torque required to move the mechanism at that speed.

In addition, factors such as gravity and the pressure exerted by the ground on the effector were considered and a required torque of 0.2 Nm and a maximum longitudinal distance of 19.4 cm were obtained.

Fig. 9 End effector trajectory.

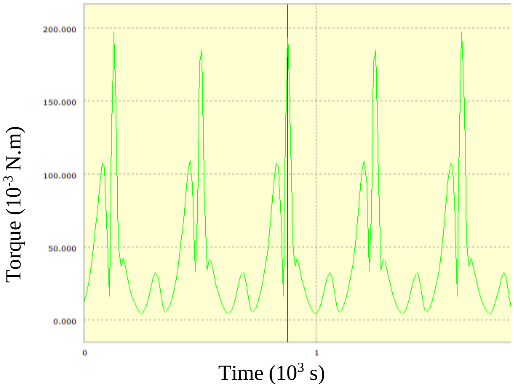


Fig. 10 Required torque.

C. Stress analysis

A finite element simulation was carried out using Autodesk Inventor 2021 to verify if the ABS 3D printing material, selected for the mechanism, can withstand the pressure exerted by the cultivated land and the torque found in Fig. 10. It was obtained a maximum stress of 1.241 MPa and a maximum deformation of 0.6772 mm, which guarantee that the selected material is optimal for the process in which it will be used, since the tensile strength of the material is considerably higher than that obtained in it, since this varies between 35 and 50 MPa depending on the grade of ABS used and the processing conditions.

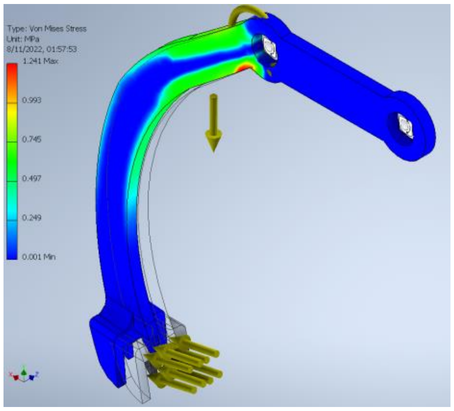


Fig. 11 Von Mises stress.

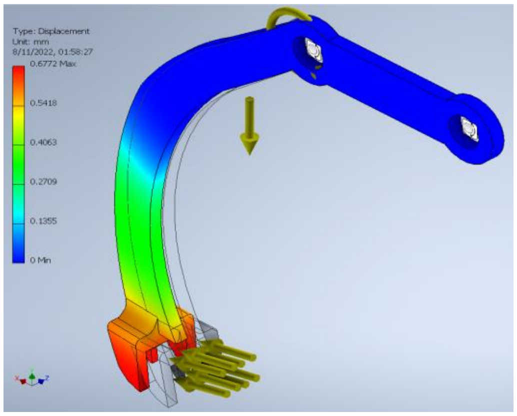


Fig. 12 Maximum displacement.

D. Kinematic simulation

For a sinusoidal trajectory, with an amplitude of 5 m and the parameters of the designed robot mentioned above, width of 0.46m, length of 0.78m, and a linear speed of 0.75m/s. The kinematic model with a Lyapunov controller was simulated using MATLAB, obtaining global position errors close to 0.

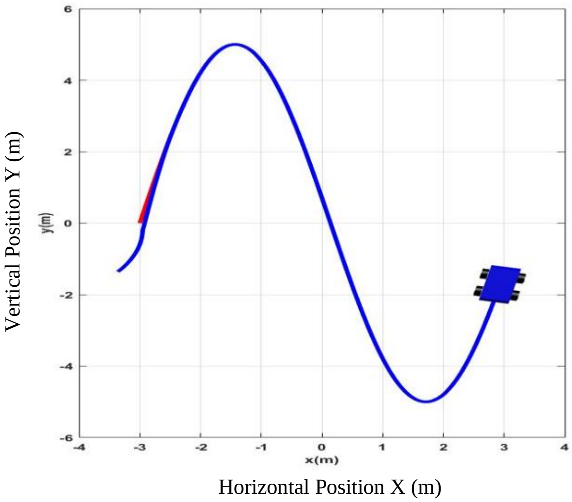


Fig. 13 Kinematic simulation.

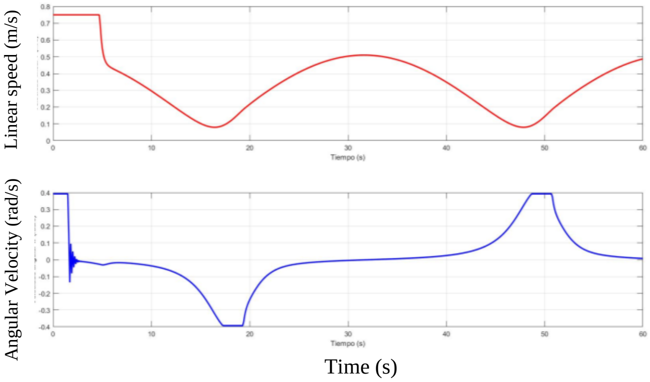


Fig. 14 Linear and angular velocity.

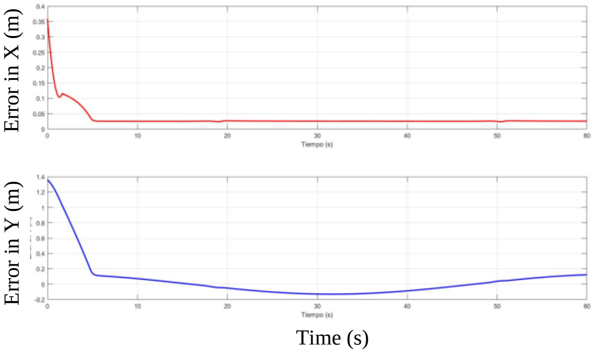
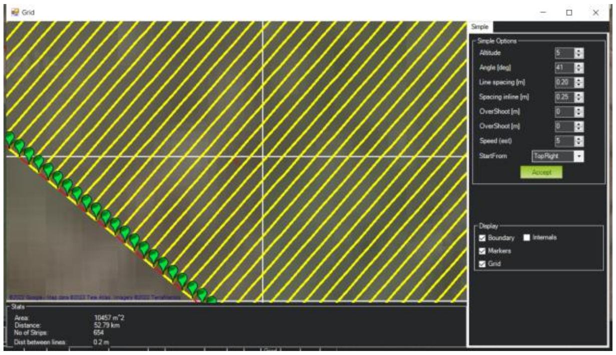


Fig. 15 Error in global positions.

So, with a better quality and affordable controller, like a low cost Pixhawk 2.4.8 autopilot, based on a PID controller and two Kalman filters which optimize information from an inertial measurement system, a GPS, an accelerometer, and gyroscope it is possible for the design to be capable of autonomous missions, using an open-source mission planner such as MissionPlanner.



Altitude 5
Angle [deg] 41
Line spacing [m] 0.20
Spacing inline [m] 0.25
OverShoot [m] 0
OverShoot [m] 0
Speed (est) 5
StartFrom TopRight

☑ Boundary ☐ Internals
☑ Markers
☑ Grid

Area: 10457 m^2
Distance: 52.79 km
No of Strips: 654
Dist between lines: 0.2 m

Fig. 16 Mission planned on 1 hectare with MissionPlanner.

Finally, by adding an SBC (System Board Computer) card, such as a RaspberryPi, to the mechanical system and autopilot, it is possible to implement technologies such as AI to optimize navigation control, acquire data through a webcam and recognition of desired objects for others. Applications. As well as, monitoring the operating parameters and data acquired by the vehicle through a database in the cloud and show it to farmers through images and dashboards in an easy-to-use mobile application.

IV. CONCLUSIONS

It was possible to design an autonomous land vehicle capable of carrying out the rice transplant process at 0.75m/s, with a structure robust enough to integrate the transplant mechanisms and mobile tray. In addition, the vehicle's 6063-T5 aluminum composite structure allows for easy assembly and reduced weight without compromising vehicle rigidity. The analyzes carried out allow us to verify that the structure will resist the load of the components since the maximum displacements in the Z axis were 0.554mm, which are within the permissible error range for the oversized weight. The modifications in the ergonomics and lengths of the transplant mechanism do not affect the operation and its trajectory, since a maximum vertical displacement of 19.4cm and a required torque of 0.2Nm were obtained to mobilize the mechanism, in addition it was obtained that the maximum deformation in the final effector is 0.67772mm, taking into account the pressure exerted by the cultivation land and the torque required to mobilize the mechanism. The mobile tray designed facilitates and optimizes the handling and transport of the raw material (mats of rice seedlings). On the other hand, the design of the traction type guarantees that the motors are not affected by the cultivated land, since they are located in the upper part of the chassis, and the kinematic model of the robot by achieving a nominal speed of 0.75m /s, equal to that of commercial 4-row transplanting machines, but with two rows, it is stated that its efficiency with respect to the manual process turns out to be at least double, and its equivalence with respect to human capital half of a commercial model of 4 rows, around 7 workers/hour. These results indicate that it is possible to ensure and provide an option to farmers in developing countries, with which they can increase their productivity without high economic risk. In addition, the possibility of integrating an autopilot and an SBC represents a huge potential for integration into future research, related to improvements in vehicle control precision, real-time data acquisition and analysis, which involves image recognition by means of artificial intelligence and development of interfaces with connectivity capacity to the cloud.

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