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Development of a planning and mission supervision system for a ground agricultural mobile robot

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ABSTRACT: *A series of algorithms was implemented to plan optimal routes and generate smooth trajectories, for optimal and safe navigation of an agricultural robot. For the generation of optimal routes, the algorithm called A* was implemented, while for the smoothing of the trajectory the algorithm called Bezier curves was utilized. The system is capable of generating smooth trajectories with a resolution of up to one centimeter, in less than a second, performing by teleoperation the monitoring and remote control of the robot with frequencies of 2 Hz, which makes it suitable for robots in agricultural tasks. The developed software permits demarcating, from an aerial image, the crop rows or other obstacles present, and once the optimal route is generated to visualize its smoothing and geo-referencing, to provide a sequence of geographic coordinates, through which the robot must navigate.*
KEYWORDS *agricultural robot, path planning, telemetry, teleoperation, Bezier curves.*

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I. INTRODUCTION

Robots are perceptive machines that can be programmed to perform specific tasks, make decisions, and act in real time. They are required in various fields that normally call for reductions in manpower and workload and are best suited for applications requiring repeatable accuracy and high yield under stable conditions [1]. Unmanned Ground Vehicle (UGV) or wheeled robot are widely used in field of industrial automation, warehouse management, planet exploring, disaster rescue, intelligent transportation and military operation [2, 3]. Nevertheless, and in spite of the tremendous number of robotic applications in the industry, very few robots are operation in agricultural production [4]. With the development and application of artificial intelligence and machine learning, more and more studies focus on unmanned vehicles and their applications [5]. The automation of agricultural robots is now considered essential for improving work efficiency and should include the potential for enhancing the quality of fresh produce, lowering production costs and reducing the drudgery of manual labour [6]. The main limiting factors lie in production inefficiencies and the lack of economic justification due to the very short period of potential utilization each year [7]. Unfortunately, unlike industrial applications which deal with relatively simple, repetitive, well-defined and predetermined tasks in stable and replicable environments, agricultural applications for automation and robotics require advanced technologies to deal with complex and highly variable environments and produce [8, 9]. Complexity increases when dealing with natural objects, such as fruits and leaves. This is due to the high variability of many of the parameters that affect robot behaviour, many of which cannot be determined a-priori. Development of a feasible agricultural robot must include the creation of sophisticated intelligent algorithms for sensing, planning and controlling to cope with the difficult, unstructured and dynamic agricultural environment [10], or integrate a human operator into the system.

One of the critical issues of a robot in agriculture is the path planification and its execution with the highest precision. The path planning a multi-modality constraint problem with three stages in terms of its basic ingredients which are route planning, trajectory planning and motion planning [5]. Among the first developments in this field was a path planning of an agricultural mobile robot employing neural network and genetic algorithm to create a suboptimal path [11]. Another proposal was a path planning method for transport units in agricultural operations involving in-field and inter-field transports incorporating the optimization criterions of time or traveled distance [12]. A randomized motion planner was presented which relies on splitting planning into two efficient phases to reduce its computational time, where the effectiveness of sampling-based planners is combined with the robustness of parametric vector valued splines [13]. In order to minimize skip/overlap areas between swaths, a path planning strategy based on side to side 3D coverage for agricultural robots method was explored [14]. Other approach of trajectory planning of an agricultural robot involved using sensor-based acquired data points of interest, with an approximation algorithm for data clustering in the form of non-convex and convex hulls and minimization of the travelled distance between the centers of gravity of the defined areas, via an evolutionary algorithm [15]. A collaborative control theory was utilized to construct an agricultural robotic system to monitor the condition of plants, which combines routing algorithm, adaptive search algorithm, and collaboration control framework, by which the protocol routes a robot to visit the sampled locations using a genetic algorithm [16]. For greenhouse spraying operation, a multi-objective algorithm was used to solve routes between the plants by means of a probabilistic roadmap path planner based on the designed virtual environment inside the greenhouse. In this approach, to determine the best routes for the mobile robot, a non-dominated sorting genetic algorithm using reference point based was applied to the system [17]. Also, a coverage path planning algorithm was proposed for discrete harvesting in cashew orchards using a Mahalanobis distance based partitioning approach for performing coverage. Optimization of the generated paths was achieved through a combination of local and global search techniques by combining a discrete invasive weed optimization technique with an improved 2-Opt operator [18]. Another proposal deals with an algorithm for planning paths within the drivable area to accurately and automatically plan spraying paths in peach orchards, using a colour-depth fusion segmentation method based on the leaf wall area of the colour-depth images [19]. In other path planning design, the autonomy of an agricultural mobile robot was enhanced in a structured environment as a greenhouse farm, to locate an optimum route such that the robot performs a selective and variable spray of pesticides to the plants using a non-dominated sorting genetic algorithm [20] .

In this work, the aim was to develop a software for planning and supervision of missions and tele-operation for an omnidirectional agricultural robot allowing: 1) Planning a mission within a vineyard arranged on trellises. 2) Generate a smooth path that the robot can follow with constant speed. 3) Monitor the status of the mission by viewing the robot's UTM coordinates, electrical consumption, angular velocity and wheel orientation. 4) Tele-operate the robot by sending it a suitable digital frame that allows modifying the orientation and angular speed of the wheels. The second section of this paper shows three methods for monitoring systems of solar plants. The third section discusses communication and monitoring systems for wind turbines, and finally the conclusion is discussed in the fourth section.

II. METHODOLOGY

Robot description

The robot called BACO was designed to operate in trellised vineyards. These vineyards are characterized by restricting mobility, due to the reduced space for maneuvers and turns, which is why their architecture is omnidirectional, with four translation and four turning motors. A view of the robot structure is shown in the image of Fig 1, which moves on the row as depicted in the figure, determining the restrictions in the generation of the route to follow.

Fig. 1. Structure of the robot BACO and its position on the row.

Software development

In order to implement the planning and trajectory smoothing algorithms, a planning mission supervision and tele-operation software was developed for the BACO robot. The software was made up of two modules, one dedicated to mission planning and the other to supervision of the mission and remote operation of the robot. The software was developed on Microsoft's Visual Studio Community 2017 platform, in Visual C # language.

Definition of the working area

To locate and select the work area, the Google Earth program was used, from which an image of the work area was extracted. Once the image was obtained, the angle of the rows was determined with respect to true north. The procedure consists of drawing a line on one of the rows of the work area, using the Google Earth "rule" tool which determines the value of the "heading" parameter, which corresponds to the angle in the right-hand direction with respect to the true north of the rows. The user must select a point on the work area to use it as the origin of the coordinate system that will be mounted on it. This point must be located in the upper left corner of the work zone and its UTM coordinates must be known. Finally, the work area must be rotated until the rows are oriented vertically. Once the work area is defined, it is saved as an image file with the extension ".jpg" in a predefined directory from which it is read by the planning software.

The software test was carried out in an area located in the premises of the University of Concepción, Campus Chillán, Chile, in a vineyard arranged on trellises as shown in Figure 2. The image of the working area was divided into smaller parts that allow identifying and marking the occupied areas. The effect of applying the grid is an image divided into a matrix arrangement of "n" horizontal squares by "m" vertical squares, both numbered with respect to the reference point defined by the user. Once the grid was generated on the image, it was necessary to determine the areas not available for the robot to transit. Contrary to logic, the occupied zones are the streets and not the rows because the BACO robot moves on the row and not between rows. The selection of the occupied zones was made manually based on the following criteria: a grid will be considered unavailable for the robot's transit if it is partially or totally occupied by an obstacle. Both, rows and any object that remains static within the work area are considered as obstacles.

Deployment of the A*algorithm

To generate the optimal route, the graph search algorithm A* was chosen, widely used to solve mission planning problems [21]. To implement the algorithm the parameters to be optimized must first be set. In this work, the distance traveled by the robot was optimized. The robot will be allowed to advance through the grids both in a straight line and diagonally, with the user being able to select one or the other by means of a button. The result of running the A* algorithm on the image is a series of points that the robot must follow in order to complete the mission. Indeed, the coordinates of these points correspond to the centers of the grids that the robot must cross to complete the mission. The points generated have the format P (i; j), a point that identifies the center of the grid located in the j-th row and the i-th column with respect to the reference point. For example, point R (3; 5) refers to the center of the grid located in row 3 and column 5 with respect to the origin. It should be noted that these points do not have a geographical reference, an exception that is resolved below.

Fig. 2. Robot working field . Source, Google Earth.

Georeferencing of control points

To assign a geographical reference, latitude and longitude, to the points generated by the A* algorithm, it is necessary to rotate them in the opposite direction to which the image was rotated in the manual selection stage of the work area. Then, it is necessary to georeference them with respect to the point that the user chose as a reference. The equation for rotating ordered pairs is shown below:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (1)$$

where θ is the rotation angle with respect to origin (rad) , x any are the coordinates of the point we need to rotate, and x', y' the coordinates of the rotated point.

La ecuación para geo-referenciar los puntos ya rotados es:

$$T = (LON + l*(j-0.5) ; LAT - l*(i-0.5)) \quad (2)$$

were LAT is the latitude of the point selected as reference (UTM), LON is the longitude of point selected as reference (UTM), l is the dimension of the grid (m), I is the row of the grid (i=1…n) and j is the column of the grid (j=1…m).

Smoothing with Bezier curves

The optimal path generated by algorithm A*, is composed of a series of disconnected points that do not provide a smooth path for the robot to follow. Therefore, these points were joined by a smooth curve, created by Bezier curves [22], thus generating a path that the robot can follow. Bezier curves are an algorithm that allows joining points by means of smooth curves of degree 3 . Although there are other algorithms for generating curves from a series of points, such as cubic splines, Bezier was used since it demands less computational resources, which that allows its calculation dynamically. It should be noted that, although Bezier offers a smooth curve, it must be segmented so that, from the straight segments created, the orientation of the wheels can be determined, as well as the distance they must travel.

Communication of the optimal path to the robot

The optimal path, already smoothed, is communicated to the robot wirelessly, as a series of ordered data packed into an array, which the robot must read and interpret as movement in a given direction and speed. The information included in the arrangement is: latitude and longitude of the target point, angular velocity of wheel 1, 2, 3 and 4, orientation of wheel 1, 2, 3 and 4. Since the robot can operate in manual or automatic mode, this information must also be communicated. The array format is shown in the following equation:

$$R = ID01,A,LAT,LON,Wi,\ldots,ORi,\ldots\backslash n \quad (3)$$

where ID01 is the Identifier of the optimal path arrangement, A is the automatic operation mode, LAT is the latitude (UTM), LON is the longitude (UTM), Wi is the angular speed of wheels in RPM (i=1…4) and ORi is the wheel orientation in radians (i=1…4). Each information packet sent to the robot must end with the characters "\ n" which are interpreted as the end of the array. For the transmission of information to and from the robot, the XBEE PRO radio equipment was used, with a transmitter located on the robot and another connected to the computer that will host the software. The baud rate was set to 115200 bps and the serial port in the 8N1 format: 8 data bits, no parity bit and a stop bit.

Supervision module

This module allows us to monitor the behavior of the robot by showing variables of interest to the robot on the screen during the development of the mission. The monitored variables are angular velocity of each wheel, orientation of each wheel, current and voltage of the motors that drive the driving wheels and position of the robot in UTM coordinates. On board the robot, a microcontroller is responsible for packaging the information in an arrangement with a predefined format. The transmission of the arrangement is by wireless communication from the XBEE PRO module on board the robot to the XBEE PRO connected to the computer where the mission planning software is housed. As the optimal path is communicated to the robot, the monitoring information is packaged in an array with a unique identifier that the XBEE PRO transmitter connected to the computer recognition. The following equation shows the format of the array:

$$S = ID02,Wi,\ldots,ORi,\ldots,CMAi,\ldots,CMGi,\ldots,Vi,\ldots,LAT,LON\backslash n \quad (4)$$

where ID02 is the identifier of the monitoring array, Wi is the angular speed of wheels (i = 1…4), Ori is the orientation of the wheels (i = 1...4), CMAi is electrical current in Amperes of the translating motors (i = 1...4), CMGi is the electrical current in Amperes of the rotary motors (i = 1...4), LAT is the geographic latitude of the robot (UTM) and LON is the geographical longitude of the robot (UTM).

Teleoperation module

The software incorporates a teleoperation module that allows taking control of the robot, going from autonomous mode to manual control mode, in order to carry out tasks such as storing, unloading or positioning the robot within the orchard if necessary. Manual control is done by tele-operating the robot wheels. To guide the movement of the platform, the angular velocity and orientation of each wheel is indicated. The following equation describes the arrangement with the information necessary for teleoperation:

$$T = ID03, Wi,\ldots, ORi,\ldots, LAT, LON \backslash n \quad (5)$$

Where ID03 is the identifier of the teleoperation array, Wi is the angular speed of the wheels (i = 1… 4), LAT is the geographic latitude of the robot (UTM) and LON is the geographic longitude of the robot (UTM). The transmission of the teleoperation arrangement is done in the same way as described for the optimal path arrangement except for the unique identifier that will indicate to the robot that is a teleoperation frame. An onboard microcontroller interprets and implements the information communicated in the array.

III. RESULTS AND DISCUSSION

Path planner module

The mission planning module was divided into two sections, one dedicated to setting mission planning parameters and the other to visualizing the mission scenario. The settings section, shown in Figure 3, is made up of four panels: grid creation panel (A), stage creation panel (B), smoothing panel (C) and coordinate display panel (D). Panel A, "Crear grilla" permits to define the number of rows, columns and the size relative to the image of the working area of the grid. By entering the actual height of the image, the actual size of each grid is calculated. Panel B, "Crear escenario", allows to define the mission route components, where the "row" and "column" parameters allow to select the location of the mission start point. The option "Diseñar escenario" is to change the state of any grid position, free or occupied by clicking with the mouse pointer on them, registering a busy position with yellow color. The option "Buscar ruta óptima" allows to search for the optimal route, being able to change the Euclidean distance by checking the option "Permitir diagonales". The optimal route in real time is achieved by placing the mouse pointer over the box that the user defines as the destination of the mission. When clicking, a report is generated in panel D with the coordinates of the control points relative to the grid. Once the mission is created, panel C, "Suavizar", provides options to determine the smooth trajectory, either relative to grid coordinates or geographic coordinates. The option “Segmentos entre puntos de control” defines the number of intermediate points that will connect consecutive control points. Optimal path smoothing can be applied relative to the grid or in geographic coordinates. In geographic coordinates, it is necessary to enter the angle of the rows with respect to true north and the UTM coordinates of the point chosen as the anchor. A table in panel D allows to view the list of UTM coordinates of the smoothed path.

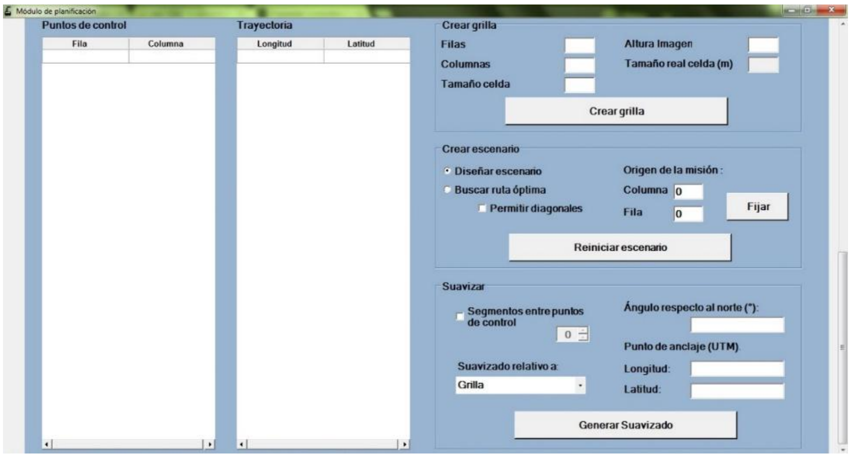

Fig. 3. Path planning module: (A) path creation, (B) path display,
(C) path smoothing (D) optimal path coordinates display.

The visualization area of the planning module is shown in Figure 4, The module allows loading the image of the work area, displaying the free and occupied areas of the mission, the optimal route and the smoothing of the trajectory of the mission through the working path. The Figure 4 indicates, in yellow, the cells selected as obstacles for a mission along the work area. The cells pertaining to the optimal path, marked in blue, starts up in a cell marked in red, pointed with the blue arrow.

Fig. 4. Robot path and obstacles.

Figure 5 shows in red color the trajectory determined by the planning software for the optimal route. This stage is crucial for the development of the mission since it is finally this trajectory that will lead the robot through the working zone. The figure also shows a detail of how the Bézier curves smooth the changes of direction allowing the robot to carry out the mission with constant speed. The smooth trajectory generated depends on the selected obstacles, then the size of the grid must be such that it allows, to establish adjacent zones as occupied zones. The smaller the cell size, the better the ability to demarcate obstacles and safety zones. However, this considerably increases the marking time.

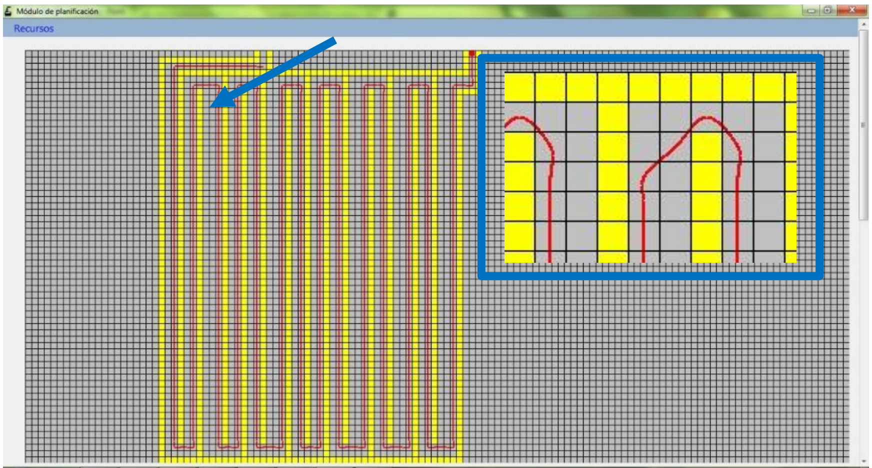

Fig. 5. Image of the red smoothed path, with Bezier curves, for control points determined with A*.

Supervision and teleoperation module

The appearance of this operation module is depicted in Figure 6. The module is composed of four tools. The supervision panel (A) controls the eight motors of the robot, panel (B) deploys the image of the operation zone showing the position of the robot, the teleoperation panel (C) provides a manual control of the robot displacement, and the communication panel (D) was implemented to configurate the communication parameters with the robot.

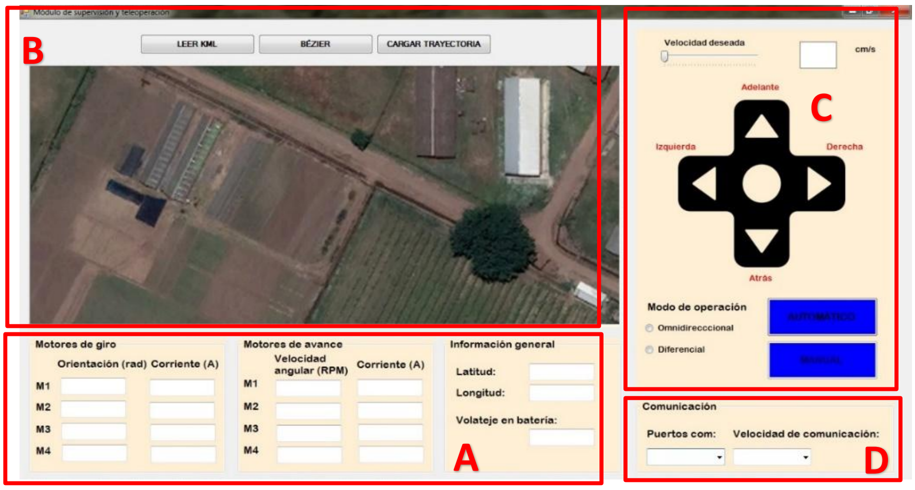

Fig. 6. Supervision and teleoperation module, (A) supervision of motors, (B) robot location, (C) teleoperation (D) communication.

Supervision panel

The panel A of Figure 6 it allows to remotely acquire information on the status of the robot while the mission is being carried out. The voltage of the set of batteries that power the advance and orientation system is displayed. For the advance motors, those that provide traction, reporting of angular velocity in rad/s and current consumption in amperes is monitored. For swing motors, those that orient the wheels, their orientation in radians and current consumption in amperes are reported. The window B of Figure 6 indicates the real-time location of the robot in the work area as well as the smoothed path through the rows . To simplify the demarcation of the route to follow, the software had the chance to import routes created in Google Earth, which although they are not optimal, are easy to create. The button "LEER KML" it allows to load a file with kml extension, containing the collection of control points. On the other hand, the "BÉZIER" button takes the information from the kml file, automatically extracts the coordinates of the points of the route and smoothes the points, generating a smooth trajectory. In this interface, the number of intermediate segments is fixed and equal to 5, since with third order Bézier curves, 20 cm segments are generated, sufficient for the most critical case, which is a closed curve at the end of a single row. Finally, the button "CARGAR TRAYECTORIA" displays the smoothed trajectory on the visualization window.

Teleoperation panel

The panel C of Figure 6 is responsible for manually and remotely controlling the robot's actions. It has two buttons to select between automatic and manual operation mode, being mutually exclusive, that is, pressing one relieves the other and vice versa. A virtual joystick allows the robot to give direction by clicking with the mouse on the orientation needed to communicate to the robot. When the manual operation option is selected, the robot speed is set to 0.2 m s-1, in order to avoid accidents due to speeding. In automatic mode, it is the user who defines the speed over the path, depending on the task to be carried out and the kinetics of the robot.

Communication panel

Transversal to the supervision and tele-operation module is the communication panel shown in Figure 6 panel C. In this panel, the frames defined for the communication of the optimal path to the robot, the telemetry and the teleoperation were implemented. Furthermore, this module allows selecting the communication port that will be used to transmit and receive information from the robot. In addition, it permits selecting the information transmission speed, which can be adjusted to values between 9600 bps, 19200 bps and 115200 bps.

IV. CONCLUSION

The implemented algorithms allowed us to generate optimal routes in structured environments, while providing smooth paths, useful for mobile agricultural robots. The algorithms provide an optimal route if there is one, and a smooth trajectory while remotely acquire information on the state of the robot in terms of speed and orientation of the wheels, energy consumption, voltage in the batteries and UTM coordinates of the position, which allows to monitor its status. The software also provides the visualization of the position through embedded Google Maps and remote control of the robot's actions manually and safely through a handling simulator.

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