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Global-referenced navigation grids for off-road vehicles and environments

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Abstract

The presence of automation and information technology in agricultural environments seems no longer questionable; smart spraying, variable rate fertilizing, or automatic guidance are becoming usual management tools in modern farms. Yet, such techniques are still in their nascence and offer a lively hotbed for innovation. In particular, significant research efforts are being directed toward vehicle navigation and awareness in off-road environments. However, the majority of solutions being developed are based on occupancy grids referenced with odometry and dead-reckoning, or alternatively based on GPS waypoint following, but never based on both. Yet, navigation in off-road environments highly benefits from both approaches: perception data effectively condensed in regular grids, and global references for every cell of the grid. This research proposes a framework to build globally referenced navigation grids by combining three-dimensional stereo vision with satellite-based global positioning. The construction process entails the in-field recording of perceptual information plus the geodetic coordinates of the vehicle at every image acquisition position, in addition to other basic data as velocity, heading, or GPS quality indices. The creation of local grids occurs in real time right after the stereo images have been captured by the vehicle in the field, but the final assembly of *universal grids* takes place after finishing the acquisition phase. Vehicle-fixed individual grids are then superposed onto the global grid, transferring original perception data to *universal* cells expressed in Local Tangent Plane coordinates. Global referencing allows the discontinuous appendage of data to succeed in the completion and updating of navigation grids along the time over multiple mapping sessions. This methodology was validated in a commercial vineyard, where several universal grids of the crops were generated. Vine rows were correctly reconstructed, although some difficulties appeared around the headland turns as a consequence of unreliable heading estimations. Navigation information conveyed through globally referenced regular grids turned out to be a powerful tool for upcoming practical implementations within agricultural robotics.

Keywords

Off-road vehicles; Autonomous navigation; Grid maps; Stereoscopic vision; Global positioning; Agricultural robotics

1.- Introduction

The application of robotics, information technology (IT), and automation to agricultural production is becoming a reality; its practical in-field massive implementation is a matter of time. According to Reid [1], the state of the art in robotics and automation technologies today can provide capable machine control and intelligence that apply to a broad cross-section of machines currently available in off-road equipment spaces, including agriculture, lawn and turf grass, and construction machinery. In fact, Blackmore and Apostolidi [2] concluded that significant savings can be achieved by adopting specific fleet-management algorithms and techniques for the centralized management of farm robots. Yet, many roboticists are still unaware of the great potential for robotics latent in the agro-industrial sector. Most of high accuracy GPS receivers currently in use for commercial purposes, for instance, are integrated in conventional off-road vehicles and often supplied by farm machinery manufacturers. The technology-inspired concept of precision agriculture (PA) has practically reached most production zones of the world, and although PA was initially developed for bulk crops, specialty crops are also demanding its solutions in the field. Pierce [3] estimated that labor constitutes 60 percent of the cost of producing sweet cherries in the Pacific Northwest, and consequently, economic forces will demand automation that replaces human labor in the specialty crop farm of the future, something that engineers are challenged to achieve. High-value crops, such as wine grapes and fresh-market fruits, are successfully introducing these technologies.

The practical embodiment of precision farming and field robotics is closely related to off-road equipment. Most of current and future applications necessitate self-propelled vehicles to gather key information from the environment and apply required production inputs. The concept of PA is based on the spatial variability inherent in farming environments, and consequently it relies on a vehicle’s capacity to locate itself and those features of interest in its vicinity. In general, positioning may be referenced to a global frame, or alternatively, to the moving vehicle. The former is typically achieved by satellite-based positioning systems such as GPS or GLONASS, and the latter is commonly used by optical and ultrasonic devices as digital cameras, laser rangefinders, or sonar. What makes global maps challenging is the need to fuse global and local positioning information, because perception typically occurs at a local scale whereas IT-based applications require data handled through global-referenced maps. Agrawal and Konolige [4] proposed visual (frame-to-frame) odometry to link a series of local-referenced maps generated from stereovision images. Although they mapped moderately-sized environments, visual odometry had to be backed up with a GPS receiver in conjunction with an inertial measurement unit, drift-compensated with a Kalman filter. The difficulties found in the transformation from local to global coordinates with odometry are aggravated in off-road environments where the phenomenon of slippage is habitual. For such situations, Rovira-Más [5] generated global maps by registering both global coordinates and pose of a stereo camera, and then transforming stereo-based point clouds to global coordinates east, north, and height.

The mapping of terrain with regular grids for assisting robot navigation roots in the pioneering concept of occupancy (or certainty) grids, enunciated by Moravec and applied to sonar [6] and stereovision [7]. Condensing the richness of information in the vicinity of a vehicle into a two-dimensional (2D) grid has been effective for real time applications. The Cye personal robot, for example, can navigate handling dynamic obstacles with wheel encoders as the only sensors on board and dead-reckoning as the primary navigation mode [8]. This simplification is favored by the efficiency of handling data in 2D grids and the fact that Cye operates in indoor environments. Moving outdoors, however, complicates navigation significantly, what has induced a progressive sophistication of navigation grids. In this line, the DARPA LAGR Program enabled a robotic vehicle to travel through complex terrain by processing two simultaneous world models generated from dual stereo cameras [9]. This double gridding was possible setting a different resolution for each stereo pair; both 2D arrays consisted of 200 x 200 cells, but the differential size of cells allowed for close ranges up to 40 m and long distances reaching 120 m. Although several perception sensors ([6],[9]) have been proposed as main generators of navigation maps, binocular stereoscopic vision holds a preeminent position due to the richness of information contained in every stereo pair of images. The advantages of 3D perception are a key for outdoor navigation where, in addition to unpredictability, vehicles usually must cope with unstructured environments. The problem of mapping while navigating has been traditionally related to the concept of SLAM (Simultaneous Localization And Mapping), frequently solved representing 3D information in regular grids. However, according to Marks et al. [10], simple binary occupancy grids are not sufficient for off-road navigation, particularly in vegetated terrain, and as a result, a grid containing the variance of heights instead of occupancy probability was proposed as a means to determine traversability. As a matter of fact, the information contained in the cells of the grid leads to a particular type of grid. The terrain maps developed by Rovira-Más et al. [11], for example, associate each cell to the 3D density (defined as stereo-correlated points per unit volume) calculated from stereo vision point clouds. Another way of modifying certainty grids in order to increase fault tolerance of navigation sensors is by implementing redundant coverage and multi-sensor scanning [12]. This procedure showed better performance than the classic Bayesian approach for a small prototype vehicle dealing with 10-cm square cells and 0.8 m ranges. However, enhanced fault tolerance required triple coverage, and when a grid cell was updated by subsequent measurements, the order of updates affected the results. A practical alternative to occupancy grid maps has been feature-based SLAM. While the former has been widely used for unstructured environments, the latter is appropriate when predefined landmarks are readily available; yet, it is possible to implement both for mixed environments combining open spaces (with few landmarks) with dense indoor structures [13]. This distinction is interesting for agricultural environments which are outdoors and semi-structured, that is, there exist certain structures of known characteristics such as crop rows, tree lines, and cut-grass swaths. An interesting attempt to make 2D navigation grids more versatile is by implementing variable meshing in such a way that the size of grid cells increases as distance from the mapping vehicle grows, as only the vicinity of the vehicle needs to be searched carefully [14]. This approach is useful when dynamic objects are considered, and the primary reason for its execution is run-time improvements when heuristic planners such as the A* or D* algorithms are incorporated. The bigger implementation challenge, though, was handling the boundaries between resolutions.

All the approaches discussed above demonstrate that storing perception information for navigation in a regular grid format presents so many advantages that it has gained universal acceptance in robotics, becoming in practice the standard procedure for path planners and obstacle avoidance algorithms. But in spite of this, as evidenced in [10], while the SLAM maps provide excellent relative position information, they are not absolutely aligned with the Earth. This fact, which can be obviated for many robotic applications —mainly small vehicles and indoor environments—, is of capital importance in agricultural robotics, where global references are essential for management techniques that often need to account for spatial variability and may require multiple actuations discontinued in time. As a result, the most effective way of reconstructing the environment in which off-road intelligent vehicles operate would be by combining 2D regular grids with global-based references. The stereovision-based path planner GESTALT, implemented in NASA Mars exploration rovers, uses a uniform grid as the basis of its world model, where each cell carries a goodness value indicating terrain traversability [15]. As global references in Mars cannot be obtained from GPS receivers, odometry was the only possibility to merge consecutive local grids. Solutions based on odometry, however, suffer from important limitations in terrains where the vehicle wheels may slip significantly, and consequently cause the estimated rover position to be erroneous. In conclusion, agricultural intelligent vehicles greatly benefit from both global references and grid-based information, but on the other hand, they are usually subject to wheel slip and typically traverse the same terrain various times per season, allowing the multi-stage generation of navigation maps. With these premises in mind, the objective of this research is the development of a framework to construct globally-referenced obstacle grids by combining GPS localization with 3D stereoscopic perception as a navigation tool for off-road farm-oriented applications. Its final goal is to provide permanent and stable positioning for every cell of the newly-developed universal grids covering off-road equipment operation sites.

2.- Conceptual definition of global-referenced universal grids

The building blocks of a globally referenced 2D navigation grid, henceforth *universal grid*, are vehicle-fixed local grids; therefore, obtaining adequate local grids is a necessary, but not sufficient, condition to succeed in the construction of universal grids. In this research, local grids were generated from the perceptual information acquired with a binocular stereoscopic camera, transferring the 3D data carried by the point cloud of the scene to the cells of the local grid after applying the concept of *three-dimensional (3D) density* [11]. Fig. 1 illustrates the fundamental stages of this process for a typical agricultural scene: real scene of a vineyard (a), true-color 3D point cloud taken with 8 mm lenses (b), and its corresponding vehicle-fixed local grid (c). Before constructing a local grid, several key parameters must be determined for it to be useful, especially the *resolution* of the grid and the *cell size*. The cell size is directly influenced by the dimensions of the objects to be detected, and in general, the smaller the cell size is, the more accuracy will the map have. The resolution of the local grid is a pair of numbers (n_x, n_y)

representing the number of cells in the horizontal axis X and the number of cells in the vertical axis Y, being the total number of cells given by the product $n_x \cdot n_y$. The resolution of the local grid is the straight quantization of the space reliably perceived by the mapping sensor. In this project, the stereo camera was set to cover a rectangle of 15 m in the traveling direction (Y) and about 6-10 m in the perpendicular direction (X). This configuration of the local axes X-Y is shown in Fig. 2. The onboard stereo camera was capable of sensing beyond 15 m from its position, but ranges were limited to this distance in order to avoid inaccurate pixel-matching for distant objects. Although these local grids are setup in two dimensions, rectangular-shaped, and composed of square cells, the environment they are representing is actually three-dimensional. In fact, stereo cameras provide 3D point clouds which are simplified by projecting the points into the ground plane previously quantized by regular cells. This procedure requires the selection of the thickness of the slice parallel to the ground (X-Y plane) inside which the points of the cloud considered in the local grid are contained. Heights over the vertical dimension of the targeted objects will certainly result in outliers adhering to the grid. As a result, each application must determine the optimal settings for the slice of 3D space ($\Delta Z = Z_{max} - Z_{min}$) considered in the generation of local grids.

Fig. 1. Generation of local grids: (a) real scene taken with 8 mm lenses; (b) 3D point cloud of 19602 points; and (c) associated local grid of resolution 300 x 200.

The move from a set of independent local grids to a unique universal grid is, in reality, the superposition of all the local grids onto the global-based universal grid. The information contained in each local grid (Fig. 1c) is directly transferred to the universal grid, and from that point on, uniquely referenced to general axes east (E) and north (N), and to a common origin (O_E, O_N). While the orientation of the global axes (E, N) is well determined, the orientation of local axes (X, Y) will always be defined by the heading direction (forward direction) of the vehicle. Fig. 2 illustrates the generating process of a universal grid of resolution 16 x 15 from the superposition of two local grids created by a vehicle moving along trajectory Γ. Notice that in Fig. 2 local (grid) cells are smaller than universal (grid) cells, which is an effective means to make navigation maps more operative, although both global and local cells may be equally sized. However, it does not make sense to define universal cells smaller than local cells because the primary source of information is always local, and therefore accuracy cannot be artificially augmented over the transformation process ($L_U \geq L_L$). The transfer of data from local to global grid cells is an important operation in the construction of universal grids. In theory there are many ways to deposit information from the overlaying grid to the one laid under; however, not all of them result useful for awareness and navigation. The superimposition of two flat, rectangular gratings with identical, regular square grids produces unique interference patterns known as Moiré fringes [16]. If, in addition, we consider different cell sizes and any possible relative orientation between grids, the download of perception information from local grids to the underlaid universal grid may be challenging to carry out without losing key data. For that reason, the information stored in each local cell is assigned to the local coordinates (x_i, y_j) of its geometrical center, which are then transformed to global coordinates east-north with Eq. 3. The global coordinates (E_i, N_j) of the cell corresponding to (x_i, y_j) can only be enclosed by a unique cell of the universal grid, which from that point on adopts the 3D density value of the local cell represented by (x_i, y_j). If the newly-filled universal cell already has a 3D density value, old and new 3D densities are then averaged to yield the definite value represented in the obstacle map. The block diagram of Fig. 5 provides the detailed step-by-step chain of operations devised to create universal grids. Both Fig. 2 and Eq. 3 highlight the determinant role of vehicle heading ϕ whose accuracy is crucial to obtain correct maps. Section 3 deepens in the definition of heading and the local-to-global transformation.

Fig. 2. Assembly of universal grids.

Before a universal grid can be constructed, all the configuration parameters that make possible its deployment must be determined, which in practice means setting boundaries, axes, and dimensions. The word “universal” is used here as an indicator of global referencing, and it does not imply that the extension of the map covers the entire globe. As a matter of fact, the coordinates used for mapping the 3D point cloud are expressed in the Local Tangent Plane (LTP) system of coordinates, which neglects the sphericity of the Earth, and therefore cannot span over vast areas. Section 3 elaborates further on the transformation from local-based and heading-affected (x, y) coordinates to Cartesian LTP east-north coordinates. A universal grid, due to its universal character, must enclose every single grid cell formerly registered with a local grid. This implies that the size of the universal grid has to be such that it accommodates the entire set of local grids. One of the advantages of the LTP system is the possibility to set the origin at the most convenient location. This flexibility implies that east and north coordinates can be either positive or negative; however, grid cells are commonly indexed by natural numbers. Fig. 3 illustrates the coexistence of a user-defined arbitrary origin for east-north coordinates and the origin of the universal grid. It is essential to understand that in spite of having different origins as a result of a simple translation, the direction and orientation of the North-East axes are exactly the same, as expected from a universal positioning setting. As previously defined for the local grids, the resolution of a universal grid also comprises a pair of positive integers (n_H, n_V) specifying, respectively, the number of cells in the east (horizontal) direction and in the north (vertical) direction. Given that any point perceived with the stereo camera is, *a priori*, a member of the universal grid, the dimension of a universal grid must account for the extreme values of coordinates east and north. In addition, the maximum range reachable by the stereo camera in the traveling direction, y_{max}, needs to be considered as well to assure that not only the camera but the totality of the 3D point cloud is enclosed in the universal grid. Eq. 1 provides the mathematical expression that permits the calculation of the grid resolution, where L_U is the size of universal cells measured as the side of the square cell, E_{max} and N_{max} are the top values for the east and north coordinates, E_{min} and N_{min} are the farthest west and south coordinates respectively, and y_{max} is the maximum range set by the user in the stereo camera. Fig. 3 shows the main constituents of a universal grid: LTP origin, E-N axes, grid origin, and grid numbering.

$$\left.\begin{aligned} n_H &= \frac{E_{max} - E_{min} + 2\, y_{max}}{L_U} \\ n_V &= \frac{N_{max} - N_{min} + 2\, y_{max}}{L_U} \end{aligned}\right\} \tag{1}$$

Fig. 3. Configuration parameters of universal grids.

3.- Mapping methodology

The conceptual schematic of Fig. 2 depicts the initial elements (departure point) of the algorithm —2D local grids whose cells store 8-bit normalized (0-255) values of 3D density— along with the universal grid composed of new cells holding the perception information just transferred from the local grids. But, as justified in Section 2, going from local cells to global cells requires the intermediate transformation of cell centers from vehicle-fixed coordinates (X, Y) to global-based (E, N). This transformation relies on the real-time knowledge of two fundamental states of the vehicle: *heading angle* ϕ and *global coordinates* (E_0, N_0) for the *origin* of local coordinates. In reality, GPS receivers supply geodetic coordinates latitude, longitude, and altitude; therefore the onboard computer needs to transform them to LTP coordinates. This transformation, although essential to the process outlined here, falls outside the scope of this paper, and will not be explained further (a step-by-step procedure is available in [17]). Given the inherent sensitivity of this method to outliers, provisions must be made to cope with erroneous GPS messages. Stereo point clouds usually contain massive amounts of data, and just one miscorrelated 3D point leading to an impossible location is enough to adulterate the proper configuration of a universal grid. This situation is not rare in open fields where multipath reflections, poor satellite distributions above the receiver, or electronic noise may induce the acquisition of wrong positioning data. Rovira-Más and Banerjee [18] investigated these particular cases and proposed filtering mechanisms to enhance reliability in agricultural operations, most of which were successfully implemented in the mapping vehicle used for this research.

As important as dealing with vehicle robust positioning (E_0, N_0), is the acquisition of stable estimations of the vehicle's heading angle. These angles can be measured by external devices, such as inertial sensors or fluxgate compasses, but can, alternatively, be deduced from the vehicle positioning data [19]. In either case, as inferable from Fig. 2, it is essential to identify inaccurate headings as early as possible to discard their associated local maps from the universal grid. Being the heading angle such an important parameter in the transformation from local to global grids, it is critical to use a consistent and unambiguous definition of heading. Unfortunately, there is no generally accepted definition of heading, and ad-hoc formulas typically meet theoretical needs. However, for the case of practical, field-oriented, general solutions, calculations must remain sound in all situations, some of them unexpected. The LTP coordinate system allows the use of Euclidean geometry, which offers many advantages to spherical geometry; yet, the calculation of headings involves the use of the inverse trigonometric function arctangent that is defined between -90º and +90º. This range of operation reduces the actual E-N plane in half, and forces a redefinition of heading angle to cover the entire plane in the interval [-180º, 180º]. Such a general reformulation, formally enunciated in [19], requires the specific treatment of every quadrant. Fig. 4 graphically represents the definition of heading for each quadrant, and Eq. 2 specifies their transformation expressions, where ϕ is the heading angle of the vehicle and φ is a supplementary angle for quadrants 3 and 4. Interestingly, despite the fact that each quadrant requires its own expression for calculating headings, all of them are equivalent, and the full simplification of the eight expressions given in Eq. 2 leads to the unique general expression of Eq. 3, where (E, N) are the global coordinates of the transformed point, (x, y) are the local coordinates of the transformed point, (E_0, N_0) is the global position of the vehicle-fixed origin of coordinates, and ϕ is the heading angle defined for the range [-180º, 180º] according to Fig. 4.

$$
\begin{aligned}
&Q_1:\ \emptyset \in [0, 90] \ \rightarrow \ \begin{cases} E = E_0 + x \cdot \cos\emptyset + y \cdot \sin\emptyset \\ N = N_0 - x \cdot \sin\emptyset + y \cdot \cos\emptyset \end{cases} \\
&Q_2:\ \emptyset \in [-90, 0] \ \rightarrow \ \begin{cases} E = E_0 + x \cdot \cos\emptyset + y \cdot \sin\emptyset \\ N = N_0 - x \cdot \sin\emptyset + y \cdot \cos\emptyset \end{cases} \\
&Q_3:\ \emptyset \in [-180, -90] \ \rightarrow \ \begin{cases} E = E_0 - x \cdot \cos\varphi - y \cdot \sin\varphi = E_0 - x \cdot \cos(180 + \emptyset) - y \cdot \sin(180 + \emptyset) \\ N = N_0 - y \cdot \cos\varphi + x \cdot \sin\varphi = N_0 - y \cdot \cos(180 + \emptyset) + x \cdot \sin(180 + \emptyset) \end{cases} \\
&Q_4:\ \emptyset \in [90, 180] \ \rightarrow \ \begin{cases} E = E_0 - x \cdot \cos\varphi + y \cdot \sin\varphi = E_0 - x \cdot \cos(180 - \emptyset) + y \cdot \sin(180 - \emptyset) \\ N = N_0 - y \cdot \cos\varphi - x \cdot \sin\varphi = N_0 - y \cdot \cos(180 - \emptyset) - x \cdot \sin(180 - \emptyset) \end{cases}
\end{aligned}
\tag{2}
$$

$$
\begin{bmatrix} E \\ N \end{bmatrix} = \begin{bmatrix} E_0 \\ N_0 \end{bmatrix} + \begin{bmatrix} \cos\emptyset & \sin\emptyset \\ -\sin\emptyset & \cos\emptyset \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} \tag{3}
$$

Fig. 4. General definition of vehicle heading.

Once the principal configuration parameters of the universal grid have been established, and the transformation equation obtained (Eq. 3), what remains to finish up the construction of the global navigation grid is the iterative routine that transfers all the information, cell by cell, from the set of local grids to the absolute universal map. Fig. 5 outlines this process with a flow chart. The first step of the construction process is the establishment of the universal map, according to the configuration parameters involved in Eq. 1. As stated above, the resolution of the universal grid is determined by the 3D coordinates of the extreme points perceived with the camera and the user-selected size of global cells. Notice that users may change the size of the cell according to their needs, but the boundaries of the map depend on the scenario sensed by the binocular camera, remaining fixed after the acquisition stage. Yet, the resolution of the universal grid will change with the cell size despite the invariance of the boundaries. After providing the general structure for the recipient of perception data, local grids are added iteratively, one by one. From each local grid, the algorithm requires the LTP coordinates of the origin, the grid's resolution and outlay (symmetry in the X direction), its heading direction, and the original cell size used during acquisition. Once the local grid in progress has been characterized, data transfer occurs cell by cell for the entire grid. The LTP coordinates of each local cell center are then calculated and situated on the universal map, falling into a specific universal cell that automatically adopts the 3D density value of the current local cell being transferred. If that universal cell is not empty and already has a 3D density value, the final label for that cell is estimated by averaging old and updated 3D densities. This recurrent process continues until the last cell of the local grid has been "globalized", and likewise until the last local grid available has been remapped. After the last local grid has been appended to the universal navigation map, the assembly algorithm ends with the graphical representation of the map. The size of universal cells, along with other basic configuration parameters, is necessary for the instantaneous conversion between LTP and universal grid coordinates. Inside each labeled cell, for those with valid information, an 8-bit number —or its corresponding color/intensity code— indicates the 3D density, being 0 the code for empty space and 255 the maximum 3D density inherited from primitive vehicle-fixed local grids. It is important to keep in mind that the concept of 3D density, as enunciated in [11], has nothing to do with the physical density of objects, as the 3D density is related to the concentration of points in the stereo cloud that shape an object rather than to the mass of the object.

Fig. 5. Block diagram of the algorithm for constructing universal grids.

4.- Vehicle architecture and validation tests

The standard tractor of Fig. 6 was setup as the mapping platform for validating the methodology proposed to create global referenced navigation grids. Global-based satellite positioning was available from a differential GPS (Deere & Co, Moline, IL, USA), set to deliver SF1 signals with a static accuracy of 75 cm and a pass to pass accuracy of ±33 cm. Three-dimensional perception was assured by a binocular stereoscopic camera (Videre Design LLC, Menlo Park, CA, USA), also featured in Fig. 6, mounted on the tractor’s cabin at 2.8 m above the ground, looking ahead, and tilted down a slight angle between 12º and 20º. Although the stereo camera allowed a variable baseline and interchangeable lenses, the baseline was fixed at approximately 20 cm, and only 8 mm and 12 mm lenses were actually used in the experiments. Both camera and GPS receiver were connected to the onboard computer (AOpen, San Jose, CA, USA), which served as the host of a customized C++ program designed to gather the input data for the algorithm shown in Fig. 5. The off-road scenario used as environment to be mapped (Fig. 6) was the vineyard of a commercial winery located in Requena (Spain). Navigation options were basically limited to the 3-m wide empty lanes bounded by Cabernet-Sauvignon vines, guided by plane trellises, and with plants reaching an approximate height of 1.5 m to 1.7 m (July-August, 2010).

Fig. 6. Mapping vehicle and off-road environment used in the experimental phase.

5.- Results & Discussion

The first verification pursued in the field was on coherence along a single testing row. The complexity of the entire system working as a whole made it vulnerable at multiple points and stages: GPS outliers, stereo mismatches, hardware glitches, code bugs, power failures, environmental difficulties such as complicated lighting or blocking branches, and many other hindrances susceptible of deterring the construction of global grids. In order to reconstruct a vineyard row, 17 stereo images were first taken along the east-west trajectory plotted in Fig. 7a, and then real-time converted to vehicle-fixed local grids. The actual inter-row lane driven was quite straight, and so was expected for its corresponding universal grid. Vehicle heading was practically constant, as indicated by the plot of Fig. 7b which represents the heading angle estimated from GPS position and time following the algorithms proposed in [18] and [19]. One of the key steps of the algorithm outlined in Fig. 5 is the *local to global transformation* of Eq. 3, which is very sensitive to the reliability of heading (ϕ) estimations. In fact, straight rows as the one studied here will never appear straight unless the vehicle heading has been properly determined. Fig. 8 shows two versions of the universal map assembled from 17 local maps whose origins of coordinates coincide with some of the points traced in Fig. 7a. The difference between Figs. 8a and 8b rests on the application of Eq. 3. The former grid of Fig. 8a applies the instantaneous heading estimated during the run for each local map from GPS data [19], graphically represented in Fig. 7b. The grid of Fig. 8b, on the contrary, considers a constant heading of -100º for the entire row, which is the average heading angle directly calculated from the trajectory plotted in Fig. 7a. GPS-based heading estimations tend to degrade over the headland turns, especially when maneuvers involve moving in reverse. However, Fig. 7a shows no turn at all, and a close inspection of both grids barely reveals slight differences between them. This result implies that whenever correct headings are available, as those in Fig. 7b, this mapping method reconstructs reality quite consistently. The legend bars on the right side of the universal grids of Fig. 8, as well as on all of the rest, represents the 3D density (stereo-based points shaping objects and counted for each cell) normalized to a 0-255 scale, where bright cells represent low 3D density indicating traversable space, and dark cells (over 100 in the current implementation, based upon field results) point to potential obstacles perceived by the camera, here originated by the canopies of vines. As these universal cells are squares of size 50 mm, distances and shapes can be immediately retrieved from the global grid.

Fig. 7. Trajectory coursed (a) and heading angle (b) for a mapping vehicle reconstructing a vineyard row.

Fig. 8. Global referenced navigation grid assembled using real-time GPS-based heading (a) and a constant heading value of -100º (b).

Unlike local grids whose cell size is determined at recording time in the field, universal cells may vary in size anytime, and therefore global referenced grids admit multiple versions according to the resolution needed for each application. The flowchart of Fig. 5 points out where in the grid-construction algorithm is the cell size introduced. Obviously, the smaller the size the greater resolution of the universal grid, and consequently the higher computational resources will need to be allocated. The minimum size of universal cells is just the size of the cells of generating local grids; lowering that value will not increase accuracy. The grids of Fig. 8 have been built at the highest possible resolution of 50 mm cell size because the local grids originally recorded in the field were set likewise. But while 25 cm^2 squares provide an excellent resolution for local grids of dimensions 6.65 m x 14 m —i. e., an equivalent resolution of 131 x 280—, such degree of detail may not be necessary for the complete universal map reconstructing a vineyard row of about 200 m length. As a matter of fact, when the universal grid of Fig. 8 was rebuilt with a fivefold cell size of 250 mm (Fig. 9), in addition to preserve the structure of the row, the presence of vegetation was enhanced, easing the use of the map.

Fig. 9. Enhancement of the grid represented in Fig. 8 by increasing the cell size fivefold.

The conventional frequency stipulated for GPS receivers is 5 Hz, and stereo cameras can easily multiply that value several times. If a local map is registered every time the positioning receiver sends a message, overlapping will very likely be unavoidable, depending on the traveling speed, typically kept under 15 km/h for agricultural equipment. In practice, this rationale leads to obtain local grids only at selected points of the vehicle’s course, opening a discussion on which is the optimum sampling rate to attain the best coverage. Fig. 10a plots the trajectory of the mapping vehicle (Fig. 6) traversing four adjacent rows at velocities in the range 5 km/h to 8 km/h. The specific location points at which stereo images were taken, setting therefore the origin of their associated local grids, have been highlighted in the course traced in Fig. 10a with bold dots. The instantaneous heading angle of the vehicle estimated at each registered point is graphed in Fig. 10b. Apart from the expected big changes over the headlands and caused by a few isolated jumps, headings were stabilized at either 80º or -100º depending on the traveling direction (east for the former and west for the latter). Fig. 11 is a close-up of the central part of the global grid generated from the data of Fig. 10, using a cell size of 25 cm. As shown in the figure (11), rows are parallel and plants remain in the sides. Given that the stereo camera could not penetrate the thick canopies of vines, only the outermost vegetation perceived from the vehicle was integrated in the grid. The rest of the cells corresponding to the vines’ interior remained blank. However, the blank cells within the rows and between two consecutive local grids (stereo images) were caused by the lack of overlap. This absence of information can be easily amended by increasing the sampling rate, enlarging the span of local grids, enhancing the reliability of GPS positioning, and by appending additional grids captured in posterior mapping missions. Those cells representing unreachable locations for the camera, mostly at the canopy center, would demand complementary passes with the camera mounted on alternative locations in the vehicle. Intra-row gaps were often caused by the lack of reliable positioning information detected with GPS quality indices. Fortunately, universal grid maps offer the necessary permanency to be completed along successive mapping missions, which may be performed simultaneously to other farming tasks such as cultivating, fertilizing, or spraying; the most important precaution is to always keep the same local origin of the LTP coordinate system. The top row represented in the universal grid of Fig. 11, between east cells 330 and 350, reveals the detrimental effect of appending a local grid with the wrong orientation. This error was caused by one of the isolated jumps in heading noticeable in Fig 10b. In light of this result, heading jumps may actuate as an indicator to discard local grids with high chances of corrupting the map.

Fig. 10. Trajectory traveled (a) and heading angle (b) for a vehicle reconstructing four parallel and adjacent vineyard rows.

Fig. 11. Detail of three rows belonging to the universal grid of a vineyard.

The value of universal grids highly increases with reliability and completeness of grids, therefore the greater amount of correct data incorporated to the map the better. The advantages of global referencing significantly contribute to enrich grids by accumulating data over different mapping sessions. Working outdoors and with actual fields in production implies coping with technical difficulties of varied nature, from illumination challenges to positioning signal blackouts. The widest region mapped during validation tests in the vineyard involved the area corresponding to ten parallel rows of approximately 140 m in length. Fig. 12 plots the six inter-row trajectories and seven turns executed by the tractor without stopping. As in previous course plots, highlighted points indicate the origin of coordinates for the local grids generated in the field when the binocular camera carried 12 mm lenses.

Fig. 12. Tractor path along six lanes for generating a universal grid covering an area of 30 m x 140 m

The most evident feature that cannot be absent in any version of this universal grid is parallelism between rows of plants with a consistent inter-row lane spacing. The crop status by the end of August, when this grid was elaborated, was exuberant (Fig. 6, right image), being lanes often invaded by vine shoots. This meant that the original row spacing of 3 m was frequently reduced to 2.5 m or even less, which is equivalent to ten cells of 25 cm, the cell size fixed for this occasion. This tight row spacing in combination with the size and weight of the vehicle poses serious challenges to vehicle automation, where reliability is probably the highest need. Fig. 13 provides the central section of the universal grid, showing that parallelism among rows is correct. This fact allows the deduction of driving lanes even for the areas not yet completed, just by connecting discontinuous canopy lines properly aligned. But while straight portions were properly reconstructed, headland turns and row initiation led to certain misalignments, as illustrated in Fig. 14. The algorithm to estimate headings [19] considers calculation matrices of variable number of points, where point sequences must have a logic cadence. When turning maneuvers involved reversing forward motion, normal point sequencing was drastically altered, and the immediate consequence was the degradation of heading estimates. Inaccurate headings, thus, resulted in obstacles placed at the wrong location in this universal grid.

Fig. 13. Central section of universal map outlined in Fig. 12.

Fig. 14. Headland turns and heading inconsistencies for the universal map of Fig. 13.

6.- Conclusions

Navigation maps for outdoor robotic applications are either vehicle-fixed, odometry-based, and grid-oriented or, alternatively, GPS-based and waypoint-oriented; but not a hybrid of both. This research introduces a framework to combine the advantages of permanent global referencing with the capacity of synthesis proved for two-dimensional navigation grids. Perceptual 3D data is ideal due to its informative richness, but on the other hand, it is difficult to handle in the form of massive point clouds; regular grids offer a practical alternative that fits the real time needs of intelligent vehicles. The rough nature of off-road environments makes dead-reckoning techniques to be inconvenient. The automation of agricultural vehicles, which typically roam outdoor fields of moderate dimensions, highly benefits from mesh-based navigation maps, but conventional vehicle-fixed reference systems have been proved to be inadequate; global referencing while keeping a grid-oriented approach seems to bring the best solution. The method developed constructs global referenced navigation grids by combining 3D stereo vision with satellite-based real-time positioning. Field results demonstrated that local navigation grids, obtained from onboard perception sensors, can effectively get transformed to universal grids where every cell is undoubtedly associated to global coordinates east and north, giving navigation maps permanency over time. This transformation, however, was not always exempt of difficulties, and real implementations revealed certain sensitivity to GPS errors, very especially to the accurate estimation of vehicle heading. Nevertheless, global reference navigation grids were effectively assembled and showed a great potential for future implementations of agricultural robotics. Next moves to transform this potential into practical solutions should evaluate accuracy, reliability, and permanency of universal grids in depth, as well as the optimal relationship between application needs and grid parameters. The assurance of reliable real time estimates of vehicle headings is also vital for the future dissemination of this methodology.

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