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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.

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% 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

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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, which 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 × 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 biggest 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