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THE HYBRID METRIC MAP: A SOLUTION FOR PRECISION FARMING

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Abstract— **This work presents a specific application of a novel map representation, the Hybrid Metric Map. This representation allows a consistent autonomous localization and simultaneously the synthesis of a detailed description of the environment where the robot or vehicle operates. There are many applications where an autonomous vehicle senses environment properties that are not necessarily used for the localization process. Precision agriculture is a special case of this. The proposed algorithm is able to fuse a large amount of information for the environment description and simultaneously estimate the vehicle position.**

Keywords— **SLAM, Autonomous Navigation, Precision Agriculture**

I. INTRODUCTION

Reliable autonomous navigation in highly unstructured outdoor environments presents remarkable problems in terms of sensing, perception and navigation algorithms. Several papers address this problem with different approaches (Fox *et al.*, 1999; Sukkarieh *et al.*, 1999; Guivant and Nebot, 2002; Leonard *et al.*, 2001; Castellanos *et al.*, 1999; Masson *et al.*, 2002; Wang and Thorpe, 2002; Neira *et al.*, 1999). Vehicle localization based on a known map of the environment and the synthesis of a map when the vehicle position is known are problems that can be considered solved. In fact there are many effective solutions in research and industrial applications (Durrant-Whyte, 1996). Outdoor environments present additional challenges due to the lack of sensors and perception algorithms that can work reliably in a wide diversity of environments. A much more complicated problem is when both, the map and the vehicle position, have to be simultaneously estimated. This problem is usually referred as Simultaneous Localization and Mapping (SLAM) (Guivant *et al.*, 2000). Although the implementation of SLAM can be made very efficient in terms of computational complexity and memory requirements there are still fundamental problems that need to be solved. Depending on the quality of the vehicle models and the internal and external sensors, that are used in the estimation process, the autonomous operation could be extended to large areas.

There are important issues involved in an SLAM application.

Map representation: A detailed representation of a dynamic environment is usually needed.

Consistency of the robot localization and map building process: Estimations of the map for large environments are usually prone to present large uncertainties in the estimates. In such case stochastic filters based on linearizations are not appropriate. In those situations the filter (usually an Extended Kalman Filter-EKF) could generate over-confident and non-consistent results.

Finally, in every estimation problem, the measurements need to be associated with the underlying states that are being observed. This is usually referred as the data association process and it is a critical problem in localization or SLAM applications. Incorrect data association involves a failure of the estimation process.

These three issues take special relevance in applications where the working environment is outdoor, unstructured, large and without *a priori* description. Precision Agriculture is one of these applications. Traditionally the field robotics solutions to precision agriculture were based on the almost exclusive use of GPS and dead reckoning sensors (Stafford, 1998). However it is known that this class of sensors can not guarantee reliability. The satellite availability introduces limitations on the GPS sensor operation. Then the accuracy of centimeters that is claimed in GPS RTK (Real Time Kinematics) systems is only possible temporarily. This is due to the satellite availability, occlusions and multipath effects. That situation is not acceptable for an autonomous vehicle that needs to operate without interruption.

In the following sections the precision agriculture technique is introduced. Additionally a discussion about the degree of its acceptance in Argentina as an agriculture tool is presented. A section is dedicated to present the Hybrid Metric Map as a new paradigm in map representation. The usefulness of this technique in agriculture is addressed. The paper includes experimental results and conclusions.

II. PRECISION AGRICULTURE

Precision Agriculture is an area of the agricultural technology developed to manage the soil, crop and environmental factors variability, usually found in fields exposed to agricultural exploitation. As a rule, the fields subject to agricultural exploitation are considered uniforms when agrochemicals and fertilizers are used. Then, uniform rates are applied to a system that is highly variable (soil properties, vegetation density). The use of this technology requires a navigation and guidance system to solve two aspects: 1) The environment description or map building (geographical correlation of the measured properties of interest); 2) The equipment necessary to apply variable rates of agrochemicals and fertilizers.

The mapping of soil properties, crop variability and environmental factors (humidity, temperature, etc.) requires reliable detection systems. The operation of variable rates techniques are usually based on a map that is used to calculate the control signals to the application system. The control law is a function of the position in the field. The requirements for the localization system that addresses these two problems are absolutely different in terms of position precision, reliability and dynamic behavior. The precision required, for example, it is in the order of ten meters for mapping crop and less than one meter when fertilizers are applied (Lark *et al.*, 1997).

The GPS is the most common position sensor in precision agriculture by the fact that allows an absolute reference and an acceptable accuracy for the majority of the particular applications. However, the lack of reliability in the accuracy has important consequences, for example in agrochemical application where incorrect dose application is not acceptable.

A new concept named *plant scale husbandry* has emerged in precision agriculture. In contrast with crop mapping or variable rate fertilizers, plant scale method requires a dynamic position estimation with accuracy in order of few centimeters. The method is based on sensing properties in small areas and acting in real time according to the measured properties. The mapping of this information is not an objective of the system. This technique allows an individual treatment of each plant and prevents the waste of agrochemicals. However this type of method is in general slow to be applied with vehicles with human operators. It must be developed based on an autonomous vehicle, without human supervision (Tillett *et al.*, 1998).

This concept appears in a first view as an autonomous system that only need a reactive guidance without localization capabilities. However, the needs of traceability and the integration of information from different sources, some of these with position references and with different acquisition times, impose a solution with a complete navigation capability.

Two reasons make the application of agrochemicals in a uniform way not an acceptable solution. First: the environmental impact of the misuse of agrochemicals. Second: the farmers need to maximize profits. The technologies currently being developed in autonomous navigation allow the application of herbicides, for example, with high precision. The weeds appear in the field in reasonable static places. A saving of 50% in two or three applications implies important savings that economically justify these techniques. The reduction of the impact on the environment is also remarkable.

A. Precision Agriculture in Argentina

In Argentina the adoption of precision agriculture techniques begins in 1995 (Bragachini *et al.*, 2002) and was introduced as in other countries as yield monitors and parallel swathing systems based in GPS. These two technologies give benefits quickly and for this reason are a good entry point.

The extensive exploitation of fields in Argentina grows each year. Then, the efficiency grow in the use of workforce, as grow the acquisition of new technologies in genetics or in plagues or weeds control, in the use of better techniques of storage and commercialization, etc. These are favorable conditions to the adoption of precision farming solutions.

The INTA (National Institute of Farm Technologies) is a national institution that has projects to solve several problems in farming; for example the cultivation of only one type of product or the adoption of better tilling methods. In particular, the Precision Agriculture Project is an interdisciplinary work in conjunction with private farmers, suppliers of equipment and other institutions. The aim of the project is to design better analysis methods, data mining and diagnoses.

In Argentina around 600 yield monitors exist, 420 with GPS, and is incipient the variable rate application of agrochemicals. This indicates an acceptance by the farmers of the technology as an element to improve the production.

It can be concluded that the precision agriculture in Argentina has a great potential of application.

III. THE HYBRID METRIC MAP (HYMM)

This novel representation allows the propagation of the corrections from a features map to a detailed (and dense) metric map, making them consistent. It allows to combine feature map with other metric information to obtain a dense representation of the robot's surroundings (Guivant *et al.*, 2004; Nieto *et al.*, 2004).

A. HYMMs Overview

When working with feature based maps, a set of features can be used to partition the region covered by the map. One example of these partitions is shown in Fig. 1. In this case, triangular regions are used which will

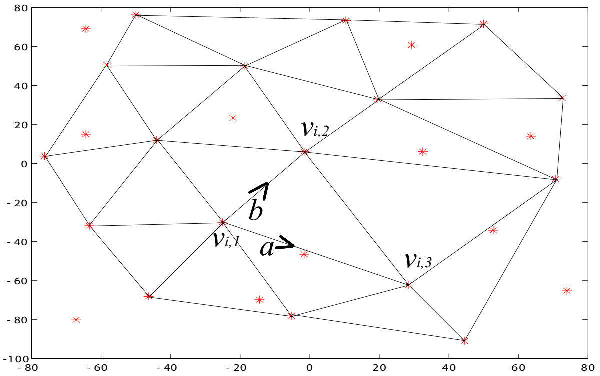

Figure 1: Landmarks map (‘*’) and a particular partition of triangular subregions (LTRs). As shown, not all the landmarks are needed as vertex points in the LTRs definition.

be referred as *local triangular regions* (LTRs). Each LTR is defined by the position of three landmarks called vertex points, as is also shown in Fig. 1. Any point that belongs to a LTR can be characterized by a convex linear combination of the three vertex points associated with this sub-region. In Fig. 1 a LTR Ω_i is defined by the vertex points $\{\mathbf{v}_{i,1}, \mathbf{v}_{i,2}, \mathbf{v}_{i,3}\}$. A local coordinate frame is defined based on the three vertex points and any point that belongs to Ω_i can be expressed as:

$$\mathbf{x} = \mathbf{v}_{i,1} + \alpha \overrightarrow{a}_i + \beta \overrightarrow{b}_i \qquad (1)$$

where $\overrightarrow{a}_i$ and $\overrightarrow{b}_i$ are the vectors that define the triangle i and α and β are factors that define the point in local coordinates, greater than zero and $\alpha + \beta \leq 1$. Furthermore any function of the global position $\mathbf{x}$ can be locally defined as a function of the local representation of $\mathbf{x}$,

$$\mathbf{z} = f(\mathbf{x}) = f\left(\mathbf{v}_{i,1} + \alpha \overrightarrow{a}_i + \beta \overrightarrow{b}_i\right) = g(\alpha, \beta) \qquad (2)$$

In some applications a function can be defined locally by an observer that has its position well defined with respect to the vertices of the related LTR. This means that the position uncertainty of the observer will be low since it is expressed with respect to a local frame. Then any information gathered from this location and associated with position can be accurately represented in the local frame, and will be independent of the global uncertainty. Due to the structure of the map, the vertex points and any interior point of the LTR are highly correlated. High uncertainty in the vertex points will not affect the quality of any property defined as a function of the observer position (local). This is true if the observer measures certain property p of points that are inside the LTR and it is well localised with respect to the vertex points of this LTR. Any improvement in the estimation of the position of the vertex points will imply an improvement of z expressed in a global coordinate frame.

A relevant application of this concept is when a robot is concurrently doing SLAM and measuring a property p. The property p does not necessarily have to be used for the robot localisation process. Assume a vehicle simultaneously doing SLAM and measuring three properties: soil salinity, humidity and terrain occupancy. These properties can be locally represented in each LTR by using grid maps for example[1]. In addition, some of the properties (e.g. terrain occupancy) could be used to assist the data association stage of the SLAM process or to do path planning for example.

Another useful representation can be obtained based on $2D$ LTRs and defining the vertex points in a $3D$ space. The LTRs can have different inclinations and are not necessarily horizontal or contained in the same flat surface. This representation allows, for example, the use of a piece-wise linear frame for terrain surfaces based on features. Over the defined LTRs a more detailed local description can be obtained as a function of the local coordinate variables (α, β). For example a function representing the level of the terrain surface respect to the triangular flat LTR (perpendicular to it) can give useful information about the terrain traversability of certain area.

A.1. Fundamental principle of the HYMMs

The HYMM framework represents the position of each property inside the LTRs, through a deterministic relation of the feature vertex position 2. The framework does not maintain the correlations among different properties represented inside the LTRs. This correlation will be zero when there is full correlation between the local property, expressed in global coordinates, and the feature vertices (assuming same uncertainty magnitude). Although it can be proved that in a SLAM process the feature map become fully correlated in the limit, in practice only “high correlation” is achieved. However, it can be demonstrated that the assumptions made by the HYMM framework are, in practice, very good approximations for SLAM problems. The next paragraphs explain two well known properties of SLAM that justify the approximations made in the HYMMs:

1. *Geographically close objects have high correlation*: If a set of observed objects are geographically close from the vehicle viewpoint, then the error due to the vehicle pose uncertainty will be a common component of these estimated landmark positions. This is a typical situation in SLAM where the vehicle accumulates uncertainty in its estimated position and incorporates observations that are used to synthesize a map. Due to this fact, the estimates of landmarks that are geographically close will present similar uncertainties and high cross-correlations. Any update in

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[1] It is important to notice that any method could be used to represent the local maps, the technique is not restricted to any particular representation.

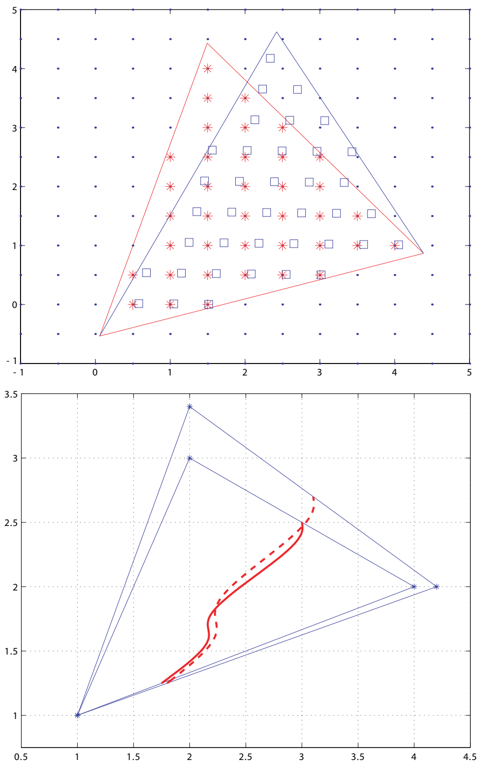

Figure 2: Effects of changing the position of the base landmarks in a LTR. In (a) the concept is illustrated in a grid, and in (b) in a curve. It is evident that there are small changes in the points close to the static landmarks, and large changes in the points close to the landmarks that moved.

a particular landmark will imply a similar update on any landmark sufficiently close to the first one.

2. *The relative representation stores close landmarks in local coordinate frames and then permits to reduce correlation to the rest of the map (Guivant and Nebot, 2002).*

The local representation defined by Eq. 1 takes advantages of the fact that geographically close objects have high correlation (Property 1). This means that if a relative estimated point $\mathbf{x}$ is close to $\mathbf{v}_{i,1}$ and the estimation process generates changes in the base landmarks $\mathbf{v}_{i,2}, \mathbf{v}_{i,3}$ but no change is introduced in $\mathbf{v}_{i,1}$ then a very small change will be made over the estimate of $\mathbf{x}$. This can be seen by analysing the variation of an internal point $\mathbf{x}$ when there is a change in the LTR landmarks position. Figure 2 shows the effects of changing the position of the base landmarks in a LTR. In Fig. 2(a) the concept is illustrated in a grid, while in Fig. 2(b) in a curve. It is evident that there are small changes in the points close to the static landmarks, and large changes in the points close to the landmarks that moved.

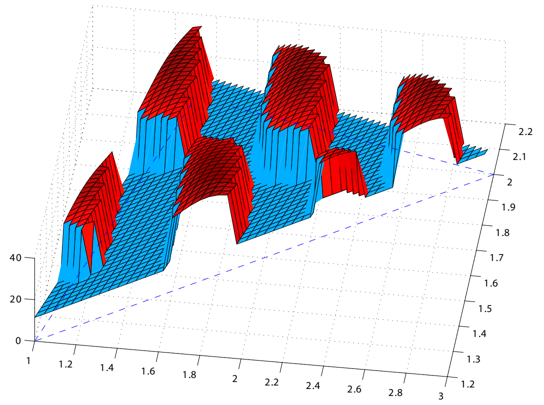

Figure 3: Occupation property inside a triangle. As it can be seen in the figure input or output doors can be defined to each triangle as a function of the free space.

Due to the nature of the representation a high accurate map can be obtained inside a LTR independently of its absolute location. If a set of properties, useful for navigation and path planning purposes, are locally described in each LTR then the set of LTRs that define the whole map will have all the necessary information required to deploy a global path planning strategy. The properties describing the occupancy in each LTR is essential for path planning purposes. An example of a list of properties can be occupancy, probability of presence of humans, animals or other moving objects that can be function of the time/date or weather and terrain surface type (concrete, soil, sand, water) or shape. Each LTR defines a private set of doors that communicate the LTR with its exterior. The doors are on the borders of each LTR, as is shown in Fig. 3. A function describing the cost of moving from one door to another can be defined based on local properties, that is defined by a matrix where each element $\mathcal{C}_k(i,j)$ represents the minimum cost to go from one door to another.

A global path planner can perform an optimization problem based on the set of cost matrices considering the connectivity between LTRs. The connectivity matrix indicates if a LTR shares a border with another LTR. The basic objective of the global path planner will be to obtain the sequence of doors that allows the vehicle to move from one point to another with the lowest overall cost. This is a discrete optimization problem and the cost matrix of a LTR will remain constant if the local properties, shape and size of the LTR do not change.

At this point, the consequences of an HYMM representation are clear. Specially in the type of applications considered in this paper: precision agriculture.

B. The HYMM in precision agriculture

The first thing that is clear is the possibility to develop an autonomous mobile that can safely navigate and control its trajectory and at the same time the

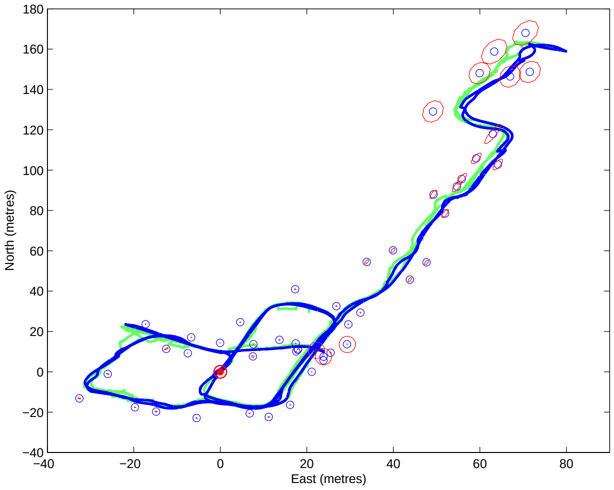

Figure 4: SLAM result in the experience done. The lighter line is the position reported by the GPS and the darker line is the estimated by the SLAM. Also the estimated landmarks position are shown with the 3σ contour of the landmarks covariance. These are the feature map of the HYMM.

same algorithm represents a complete tool for precision farming in any type of applied technique. It is also possible to relate geographically dependent information with previous one in a data fusion process. This could be seen from the following figures that show experimental results.

An experimental test was done in a place near the ACFR building. In the experiment, a standard utility vehicle was fitted with dead reckoning and laser range sensors. GPS information is also available but not all the time due to the nature of the environment (buildings, trees, etc). Figure 4 shows the trajectory and landmark positions estimated with the SLAM algorithm and also the GPS information which has been used only as a reference. The vehicle starts to navigate at $(0, 0)$ coordinate. The largest uncertainty in the estimation it can be observed at the top part of the trajectory. The vehicle has an error of approximately five meters respect to the GPS information. Figure 5 shows an Occupancy Grid map obtained with the algorithm. This is a feature needed for navigation, but it has been said, this can be only one property acquired.

Figure 6 shows an example of a layered map. This map is similar to Fig. 5 and it can be constructed at the same time that the SLAM is performed. Each layer represents a different property. For example, layer A represents terrain shape, layer B humidity and C salinity. But also, each layer can represent the same property in different exploration times. For example, a soil nutrient that is measured in a first expedition shows a great variability and insufficient level (as layer C). A second and third expedition incorporating nutrients, regularize the level of it to the desired level (layer B and A).

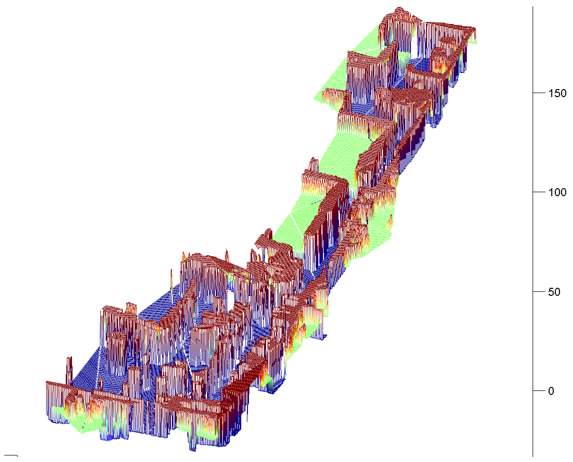

Figure 5: Occupancy Grid plot of the HYMM.

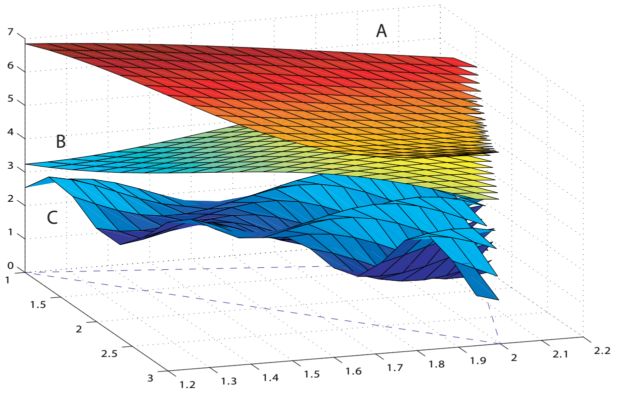

Figure 6: A set of properties can be defined as a function of the local coordinate variables. Each one could be different properties or the same in different expedition of the mobil.

IV. CONCLUSIONS

The HYMM is a map representation that has a great impact not only in the autonomous localization and guidance problems, but also in concrete applications as could be seen in the present paper. This approach allows the robot to synthesize and maintain a rich representation of the environment, localize the robot and perform an efficient path planning based on the information and uncertainty of the map estimation. The map structure also allows for the description of additional environmental properties that are not necessarily used for navigation purposes. The focus of this paper was on the precision agriculture application, a relevant problem in Argentina as wall as other countries where the agriculture plays an important role in the economy. Other industrial contexts as mining industry or cargo handling in ports are good examples of applications that can take advantage of this technique.

The experimental results in an outdoor environment demonstrated the robustness of the algorithm, particularly when it is compared with an standard GPS approach.

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