Mobile Mapping for Autonomous Navigation in Urban Areas

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***Abstract*— Recent researches have proved that Intelligent Autonomous Vehicles (IAV) can perform autonomous navigation in urban environment by using natural features (used as landmarks) sensed by on-board sensors. For this purpose, the features have to be characterized in a learning stage called "mobile mapping" which consists in geo-referencing such information. This paper addresses this problem. We propose a strategy based on the use of GNSS (Global Navigation Satellite System) positioning and GIS (Geographical Information System). More precisely, we propose a strategy that consists in regrouping the features in local maps attached to the roads of a GIS layer in order to take benefice essentially of the very good connectivity of the road network structure. We illustrate our developments using visual landmarks made of key images and side walk impacts detected by a lidar (laser scanner). Real experiments are reported to illustrate the performance of this approach which is robust to GPS outages due to poor satellite visibility in urban areas.**

***Index Terms*—Localization, Global Positioning using GNSS, Geographical Information System.**

I. INTRODUCTION

INTELLIGENT Autonomous Vehicles (IAV) currently hold the attention of many researchers because they can provide solutions in many applications related to Intelligent Transportation. One example of such a system is the transport of passengers in urban environments using a CyCab [1].

There are many applications which need a high precision localization (ie around 10-20 cm). Real Time Kinematic (RTK) GPS is a very interesting candidate for this localization purposes since it can reach few centimeters accuracy in real-time by using phase corrections. Nevertheless, this technology is not adapted to vehicles that evolve in urban areas since the receiver needs to see at least 5 satellites with a good configuration (small DOP). Moreover, after the loss of the "fixed" mode, the system needs to solve the phase ambiguities problem which requires typically 30s processing. A solution relies on the use of additional sensors like video cameras and lidars. Indeed, they are well adapted to the sensing of natural landmarks, especially those of urban areas since they are very stable like, for instance, buildings or road features. The landmarks are characterized and localized in a learning stage during which the vehicle is driven manually. Afterwards, the vehicle is able to locate itself and control its movement near to the learned trajectory. Recent works [2] have proved the validity of such a concept.

If there are several identical vehicles that evolve in a common urban area for transportation purposes, an interesting idea is to build a "common features memory" by carrying out *mobile mapping*. The mobile mapmaker can be an IAV driven manually or a standard car equipped with the sensors used by the IAV (see Fig. 1). Once the mapping has been done it can be uploaded to all the IAV.

Fig. 1. Experimental car used as a mobile mapmaker.

In this paper, we present a methodology to achieve the goal of a unique mobile mapping that can that can be shared afterwards by all the IAV for autonomous navigation. The key idea is to use GNSS positioning and maps of the road network. Indeed, these maps are very usefully thanks to their very good connectivity, even if their accuracy and description of the environment are not good enough for autonomous navigation. Therefore, we suggest regrouping the natural features in local maps attached to the roads. Then, the main problem deals with the ability to precisely select the right road, both while mapping and while navigating.

II. MANAGEMENT OF LANDMARKS IN A GIS

A. Landmarks

There are different kinds of landmarks that can be classified in three categories:

1) *Active landmarks*. They are beacons that include active components in order to transmit a signal. They mainly rely on the use of radio-frequency signals (GPS pseudolites, transponders stored in the pavement, WIFI antennas, etc.). Such landmarks are usually distinguishable from each other.

2) *Passive landmarks*. They are artificial landmarks pertinently located in the environment for localisation purposes like magnets in the pavement or reflectors installed on post in curves.

3) *Natural landmarks*. Natural landmarks are features of the environment detected by aboard sensors like video cameras or lidars. They can correspond to characteristic points (edge of windows for example), road markings, roof of buildings, posts, curbs, sidewalks, etc. In cadastral maps, natural landmarks like road markings or curbs of the roads are sometimes charted by the cartographers.

In order to illustrate the concept of natural landmark, let consider visual landmarks with characteristic points 3D as used by Royer et al. [2] for the navigation of a Cycab using a mono-camera at video rate. These landmarks are characteristic points in images called Harris points [3] (cf. Fig. 2). Thanks to these points, one can rebuild the 3D pose of the vehicle using a sequence of images (called *key images*) in which each landmark has been detected at least in two images. Please see [2] for more details.

Fig. 2. Example of detected visual features: Harris points

Visual features can be also SIFT *Scale Invariant Feature Transform* features [8]. These features are invariant to image scale, rotation and partially robust to changing viewpoints, and to the change in illumination. The SIFT are mainly used in 3D SLAM and can give very interesting results.

Natural features can be also detected by a lidar installed vertically in a way to detect for instance lateral sidewalk edges [6] (Fig. 3). The horizontal and inclined setting proposed in [12] dedicated to road-boundary detection can be an alternative.

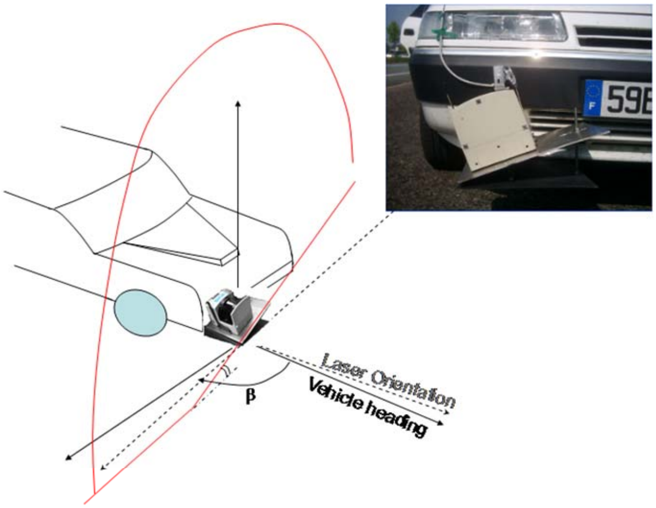


Fig. 3. Example of a vertical lidar installed at the right front of an experimental vehicle.

Laser features can also be road-markings: by taking profit of the reflectivity property of the laser beam, it is possible to differentiate the target surface [9] and thus to detect the lines on the road. Other urban characteristics that can also be used for localisation as signposts [11] or buildings fronts and walls [10]. Alternative lidar features consist in building high dense feature maps [4]: the drawback of these features is their need for high memory constraints and their relatively complex management, nevertheless, at the acquisition phase, they require no segmentation processing since they are raw laser data, projected in an absolute reference.

B. Geographical Information Layers

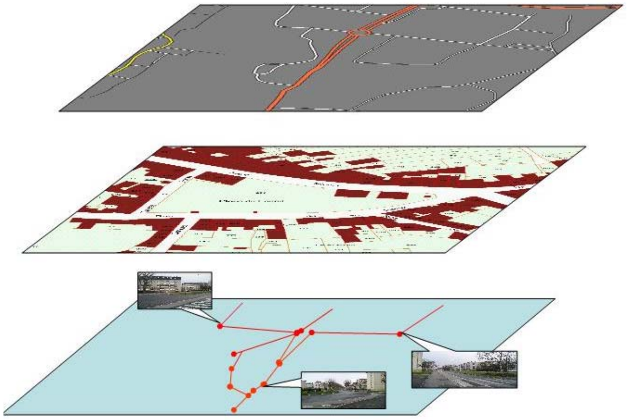


Fig. 4. Geographical Information layers: road-map layer, enhanced geometry layer, landmark layer

A GIS is very useful to manage landmark information in dedicated geographical information layers added to the road-map since a GIS provides a set of tools and methods that manage and handle vectorized or raster geographical information that can be enhanced geometry like cadastral information or landmarks (actives or passive landmarks provided by a third entity, natural landmarks sensed and characterized by the embedded localisation system) (see Fig. 4).

A GIS is also interesting to retrieve the landmark information for the localisation each time the vehicle navigates in a known area.

C. *Local Maps*

A difficulty of using local landmarks is the management and the structuring of a large amount of data for on-line navigation. Indeed, how to organize the landmark information for a vehicle that evolves in a large area including many roads? The usual answer to this question is to regroup landmarks in local maps, a local map being a set of landmarks put together because of i) memory constraints arising from the use of embedded systems, ii) the need to download or update a limited amount of data from a distant server and iii) the connections that exist between the landmarks, essential to compute a location.

The GIS is very useful for the management of landmarks in local maps by benefiting from the roads description stored in the road-map database. Indeed, the management of landmarks for an IAV can be performed with respect to the roads described by linear lines which correspond to the central axis of the road (Fig. 5). In such a case, the absolute accuracy of a GNSS-based positioning is not crucial since the road-map as a meter-level precision. Therefore, a single frequency GPS receiver fused with dead-reckoned sensors and a map in order to handle satellites outages is sufficient.

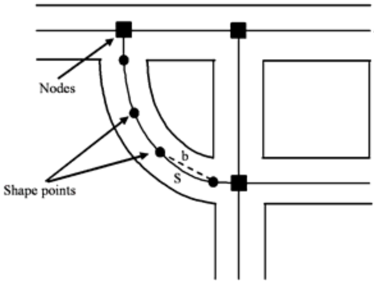


Fig. 5. Description of the roads in a usual map by nodes and shape points.

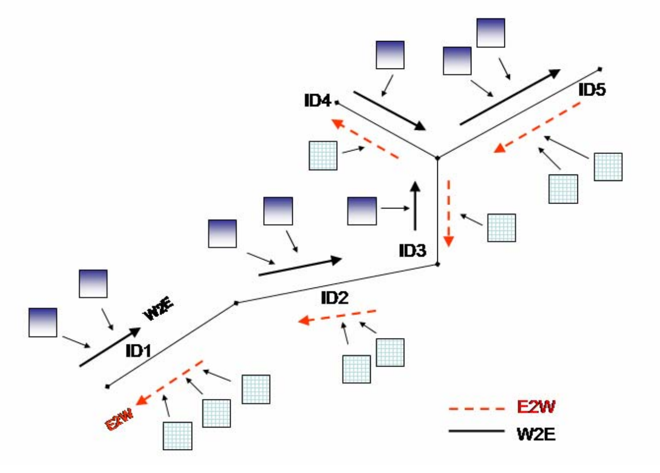


Fig. 6. Associating Images to Road Segments.

As we proposed to regroup the images in local maps to facilitate their management, the use of ID (Identification Number) of the roads is well adapted; two different roads have necessarily different IDs. Indeed, a road is a set of same ID segments with eventually a junction at its beginning or/and at its end.

Moreover, each road can be one-way or double direction (this information is contained in the road attributes). For one-way roads, a unique local map is built. It contains all the features matched to it. For double direction roads, two maps are built, one for each direction: E2W (East To West) or W2E (West To East). Figure 6 shows double direction roads with features associated to each direction.

III. GLOBAL AND MAP-MATCHED LOCALIZATION

In order to create the mapping or to retrieve feature previously stored in the GIS, two localization processes are needed: one is global (in the GPS reference frame for instance) and one consists in map-matching.

A. *Fusion of GPS and dead-reckoning sensors*

Because of poor satellite visibility in urban areas, let consider the fusion of a GPS receiver, an odometer and a gyro. If the satellites signal is blocked by buildings, for example, the evolution model provides a dead-reckoned (DR) estimate, the drift of which can be corrected afterwards using the map information.

The mobile frame is chosen with its origin M attached to the centre of the rear axle. The vehicle position is represented by (x_k, y_k), the Cartesian coordinates of M in the projection frame of the map. The bearing angle is denoted θ_k.

If the road is perfectly planar and horizontal, the evolution model can be expressed by the usual odometric model:

$$\begin{cases} x_{k+1} = x_k + \Delta_k \cdot cos(\theta_k + \omega_k/2) \\ y_{k+1} = y_k + \Delta_k \cdot sin(\theta_k + \omega_k/2) \\ \theta_{k+1} = \theta_k + \omega_k \end{cases} \quad (1)$$

The pose at instant k is (x_k, y_k, θ_k) and the measured inputs are Δ_k and ω_k being respectively the elementary distance covered by the rear wheels and the elementary rotation of the mobile frame. The values of Δ_k and ω_k are computed using the odometer measurements and a gyrometer.

The fusion of GPS and odometry is done by Kalman Filtering (Extended KF here but it could be Uncented KF [7]) which uses the prediction/update mechanism. In the prediction step, the car evolves using (1) and the covariance of the error is estimated. When a GPS fix is available, a correction of the predicted pose is performed (for more details on the filter equations see [6]).

In urban areas, GPS suffers from multi-tracks and bad satellite constellation that degrades the precision. So, when a GPS position is available, it is necessary to verify its coherence. For that, a Normalized Innovation Squared (NIS) with a chi-square distribution is used: a distance d_m is computed between the GPS observation and the state vector.

Let Y_v be the observation vector, μ_v the innovation vector.

$$Y_v = \begin{bmatrix} x_{GPS} \\ y_{GPS} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} . X_v + \beta_{GPS} \quad (2)$$

$$\mu_v = \begin{bmatrix} x_{GPS} - x \\ y_{GPS} - y \end{bmatrix} \quad (3)$$

$$d_m = \mu_v \,.\, (P_\mu)^{-1} .\, \mu_v^{T} \quad (4)$$

Where (x, y) is the predicted position and P_μ is the covariance of the innovation.

If the computed distance d_m is smaller than a threshold then the GPS measurement is assumed to be correct and a correction is performed. Otherwise, the dead-reckoned pose is kept. Please, note that the GPS noise is not stationary. The GPS measurement error can be estimated in real time by using the *NMEA GST* sentence.

B. *Map-Matching*

In order to simplify the matching process, one can assume that the vehicle follows the pre-computed itinerary. Figure 7 gives an example of a pre-computed itinerary obtained thanks to a usual route calculation functionality of a GIS. The map-matched localization is done by a pose tracking method based on Kalman filtering.

Figure 7: Overview of the road map around the experimental field, with the itinerary plotted in bold.

In map-matching a kea issue is the segment selection problem which consists in extracting from the GIS map the most likelihood segment using the predicted state vector. Thanks to the pre-computed itinerary this stage becomes simple and map-matching is more reliable.

Let $(x_{pred}, y_{pred}, \theta_{pred})$ be the predicted pose. The distance between (x_{pred}, y_{pred}) and segments of the itinerary that are near to the last fused pose are computed. The segment that has the smallest distance to the predicted pose and whose driving direction corresponds to the heading of the vehicle is considered as the good one. We have observed experimentally that this simple matching strategy gives good results. Then, the matched point is obtained by projecting the estimated position onto the selected segment.

The matched point can be used as a map observation (denoted Y_{vm}) in order to correct the drift the DR estimate if the GPS is unavailable:

$$Y_{vm} = \begin{bmatrix} x_{MAP} \\ y_{MAP} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} . X_v + \beta_{MAP} = \mathrm{C}_v \,.\, X_v + \beta_{MAP} \quad (5)$$

A NIS coherence test is used to verify the map observation coherence before fusing it thanks to a Kalman filter correction stage.

IV. CASE STUDY: MANAGEMENT OF VISUAL LANDMARKS

Let consider the use of natural features detected by a camera.

A. *Mapping stage*

During the mapping stage, the images are time stamped and geo-reference in local maps. In order to have a reliable map-matching in urban areas with poor GPS visibility, a destination point is chosen and an itinerary is computed using the GIS route planning functionality. The vehicle has to follow strictly this pre-computed itinerary.

Afterwards, visual features are detected by post-processing and stored with their associated key images in the GIS in the local maps characterized previously. In order to manage the landmarks for navigation, several attributes have to be saved. They are the GIS ID, the direction and, for each landmark, its map-matched position, its covariance (considered to be equal to the one of the nearest map-matched pose) and its date of acquisition (see Table 1).

Local map of index "j"
★ GIS ID ★ Direction (E2W or W2E) ★ Set of *I* landmarks made up of - Key Images - Projection Matrices associated with each key image - Characteristic 3D Points localized in the frame of the map with arcs specifying the images where these points are found - Matched position Xmap$_{j,I}$ - Covariance of this position Pmap$_{j,I}$ - Date of the acquisition

Table 1. Landmarks with extended attributes for their management in a GIS.

The main objective of the visual landmarks characterization consists in finding enough landmarks for precise localization. It depends mainly on the curvature of the trajectory. In a straight line, key images can be characterized every 5 meters while it can be necessary to store them every meter, if the vehicle does a rotation.

B. *Landmark Extraction during Navigation*

Let consider now a vehicle that navigates in an environment learned in a previous stage. As did in the learning stage, a destination point is chosen and an itinerary is computed using the GIS. The vehicle follows this pre-computed itinerary.

In the navigation phase, the system needs high precision for localization. A few centimeters precision can be obtained when the vehicle can use the pertinent learned landmarks regarding the observed landmarks during navigation.

The topic of this paragraph concerns extraction and selection in the additional layer of GIS of pertinent features at each time sampling of the navigation stage. The landmarks management for navigation consists in two parallel tasks: local map extraction and visual landmarks selection.

1) Find the right local map: map-matching fused poses

The goal of this task is to obtain a vehicle pose with a metric precision and then to find the appropriate local landmarks map stored in the GIS built landmark layer. The localization algorithm is the same one used in the learning stage.

The selected road ID and the heading permit to select the adequate local map. If the selected local map is a new one, the visual landmarks are then loaded in the dynamic system memory.

This supervisory task is repeated during the navigation process. It guaranties correct transitions between two local maps.

2) Visual landmarks extraction

The previous task provides a local map map_j composed by a set of geo-referenced visual landmarks as previously described. To obtain a precise localization in order, for instance, to control the vehicle, the navigation process needs to use the landmark I having the nearest matched position $X_{mapj,I}$. Two approaches are then possible.

A method is based on the matching of features points (i.e. Harris coin detector) between the current image and all key-images of the local map. The matching of feature points consists in finding corresponding pairs. One example of matching algorithm is standard RANSAC-based method [2]. The selection of the pertinent landmarks depends on matching results. This method is well adapted for tracking process when previous correct localization has been done.

We propose to develop a hybrid method which consists in using when it is possible the current pose of the vehicle in order to select landmarks from the local map. The matched pose of the vehicle (on the GIS and with the driving direction) is compared with the pose of visual landmarks in the GIS. This comparison can be implemented, by using the landmarks I of the local map "map$_j$" which has been selected previously and then to compute Mahalanobis distances tacking into account the inaccuracy of positions: the most likely image is the one with the smallest distance:

$$D_{Mh} = (X_{v,k} - X_{map_j,I})^T.(P_k + P_{map_j,I})^{-1}.(X_{v,k} - X_{map_j,I}) \quad (6)$$

Where,

- $X_{v,k} = [x_{v,k}, y_{v,k}]^T$ is the vehicle position at the time k.
- $X_{mapj,I} = [x_{mapj,I}, y_{mapj,I}]^T$ is the absolute position of the landmark I of map$_j$.
- P_k is the covariance matrix of the vehicle position.
- $P_{mapj,I}$ is the covariance matrix of the landmark I.

The selection of pertinent landmarks can be obtained by applying a threshold. If several landmarks are selected, the RANSAC method has to be used to solve the ambiguity.

C. Experimental Results

Real experiments have been carried out with our experimental car (see Fig. 1) in the downtown area of Compiègne (see Fig. 7) using a KVH fibre optic gyro sampled at 100Hz, an odometer input and a Trimble AgGPS 132. The GPS has been tuned in a 3-D only-mode to deliver reliable positions, by setting the threshold of DOP to a low value and the threshold of the SNR to a high value. Such a tuning induces a reliable but intermittent positioning in urban areas.

Figure 8 shows the vehicle localization result (in bold) on the map (thin) in the urban environment. This localization results had been used to map-match the natural features. The zoomed view shows key-images positions associated to road segments.

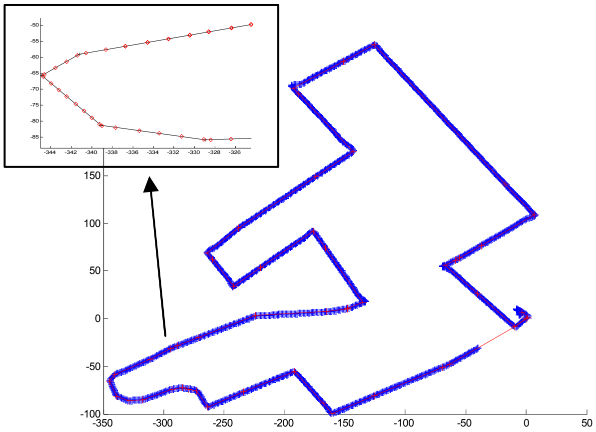
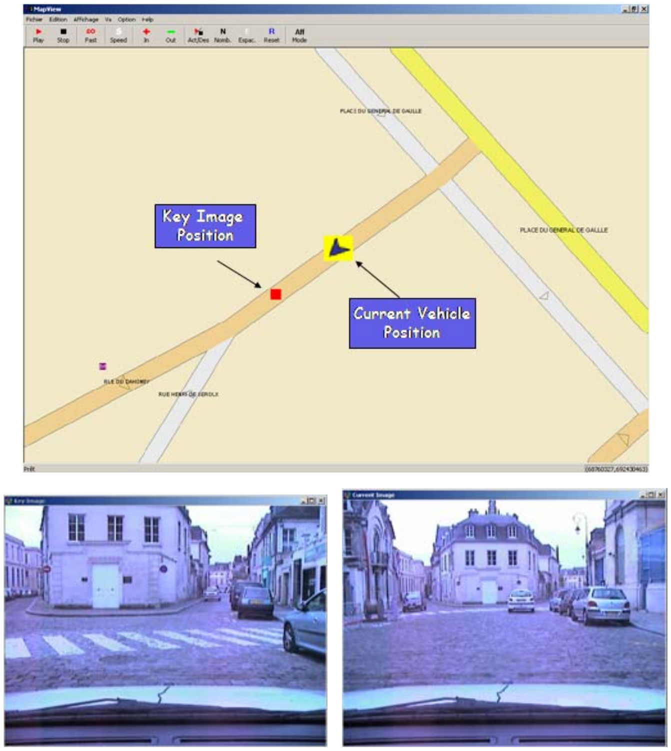


Fig. 8: Map Matched results in learning stage (scale in meters).

Two weeks later, we carried out navigation experiments to test the key images retrieval performance. The accuracy of the precise localisation hasn't been tested, since, because of the urban canyons, it was impossible to fix PPK (Post-Processed Kinematics) dual frequency GPS solutions for ground truth purpose. In these experimentations, a human driver controlled the vehicle along a defined itinerary.

To illustrate the visual landmarks management, we have extracted at each time (in fact at each new image) the best landmarks for localization using the strategy explained before.

A graphical interface allows to follows the way of the vehicle during the navigation process. The interface displays the map and adds two positions icons: the current matched position of the vehicle is drawn with a blue/yellow arrow and the reference of the key-image selected by the algorithm is drawn with a red point. Two additional windows display the current image and the selected key-image. At each position, the interface refreshes the current position, i.e. the current image and the key-image, if it changes. Figure 9 displays this interface.



Key-image current image

Fig. 9: Real time graphical interface.

The time stamped data was saved in order to analyze the results in post-processing and verify the extracted landmarks regarding to the current image. The route was 1.8 km long during 6 mn. At each key image selection, the overlapping between key image and current image has been verified manually. We have considered that the retrieval is correct if the overlapping between the current view and the key image is over 50%. The results gave 98% overlapping when local map is available, which is very good. The main errors came from the vehicle rotations at junctions.

V. CONCLUSION

This article has proposed a method to manage a huge amount of landmarks data in GIS for autonomous navigation in urban areas. Thanks to a mobile mapping stage carried out with a dedicated vehicle, natural features are recorded and stored in a GIS layer. This landmark memory can be shared and loaded afterwards in the memory of several IAVs that can perform with it autonomous navigation.

The example of visual landmarks with 3D points and connectivity links has been considered and the method has been illustrated with real experiments carried out in the downtown area of the city of Compiegne.

Our proposition is to regroup the landmarks in local maps defined by a map-matching process: a local map is a set of segments which have the same ID in the GIS database. In order to make the map-matching process more reliable, we use the route calculation of a GIS software to characterize an itinerary which has to be strictly followed by the vehicles.

The weakness of this strategy appears when the curvature of the itinerary is significant, especially when changing one local map to another one having an orthogonal geometry (like the top junction of Fig. 9). In such a case, the sampling distance of the key images must be decreased.

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