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SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Smart road infrastructure with high precision vehicle localisation

Laurea Magistrale in Mobility Engineering - Ingegneria della mobilità

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1. Introduction

The transition towards a more connected world leads to the need of adapting the already existing infrastructures and the newly built ones to cope with a growing demand for telecommunications.
In fact, the access to services for such a constantly growing number of people is one of the greatest challenges for the urban planners, for the political entities and for the whole scientific community.
To reach this goal, it is fundamental to transform our cities into Smart Cities and our companies into Smart Companies, where Information and Communications Technologies (ICTs) target to improve the sustainability, the workability and the liability.
One of the most interesting features of smart infrastructures is the capability to localise the players in motion [2]. Reliable and accurate localisation technologies enable such a breakthrough transformation, where the location information is updated with low latency. To this extent, the currently available localisation technologies are 5G and Ultra-Wide Band (UWB), which offer some differences in terms of diffusion, costs and performances. The work of thesis is carried out within a collaboration with Movyon, the technological branch of Autostrade per l'Italia. The main aim of the company is to identify the most suitable technology to precisely localize moving vehicles. As such, a first topic of this thesis to compare the technological options available on the market. Then, in a second phase, the thesis focuses on the development of a Matlab simulator for testing different mobility scenarios in which assessing the performance of localisation algorithms as well an optimization of sensors deployment (third phase).
This thesis, which focuses on vehicle localisation, can be considered as the first step of a much wider project whose objective is to carry out the shift of the highways towards smart infrastructures.

2. Phase 1 - Scouting of technologies

In the first phase of the project it is possible to distinguish two different activities: research of on-going or concluded trials and study of technological solutions used therein.
First of all, it is conducted a research over the projects which are already developed, or in a sufficient progress state, to see which are the localisation solutions used in the mobility sector.
Later on, it is carried out a more detailed study

over these solutions, with a special attention on 5G connectivity[3] and on the Ultra-Wide Band (UWB) one [4].
After the conclusion of this task, several different companies' proposals have been investigated, in order to select the most suitable alternative both in terms of costs and performances.
In figure 1 we can see the characteristics of the 5G solutions from different companies, while in figure 2 are reported the UWB ones.

Company	Bandwidth	Frequency range	Price	5G standard
Sivers Wireless	400 MHz	24 GHz - 29.5 GHz, 57 GHz - 71 GHz	200.000 €	3GPP Release 15 and 16
Rolling Wireless	100 MHz	6 GHz	5.000 €/module	3GPP Release 15
Sierra Wireless	400 MHz	6 GHz, 60 GHz (mmWave)	3.000 €/module	3GPP Release 15
USRP - Model B210	56 MHz	70 MHz - 6 GHz	2.000 €/module	3GPP Release 15
USRP - Model X310	120 MHz	70 MHz - 6 GHz	7.442 €/module	3GPP Release 15
USRP - Model 2955	80 MHz	10 MHz - 6 GHz	18.145 €/module	3GPP Release 15

Figure 1: 5G technologies features

Company	Bandwidth	Coverage	Position update	Kind of measurement
Decawave	500 MHz	290 m	10 Hz	Distance
Sewio Networks	500 MHz	150 m	10 Hz	Distance
Ubisense	800 MHz	60 m - 130 m	30 Hz	Distance + Angle
Zebra	500 MHz	100 m	1 Hz	Distance
Tracking for Fun	500 MHz	60 m	10 Hz	Distance
Pozyx	500 MHz	100 m	10 Hz	Distance

Figure 2: UWB technologies features

At the end, the choice has fallen on Ubisense UWB technology, since it is the only solution available in the market with a bandwidth up to 800 MHz, an updating frequency of 30 MHz and the joint use of distance and angular measurements. In addition, Ubisense system provides a via cable synchronization of its devices, making it even more accurate with respect to systems which use wireless or Global Navigation Satellite System (GNSS) synchronization [5].
Therefore, even if the original aim of this project was the 5G localisation, the only available technology with similar performances is the Ubisense UWB one, and this is the main reason for the choice.

3. Phase 2 - Simulation of mobility scenarios

The second phase of this thesis work is a simulation phase in which the focus is to create and define several use cases representative of real situations. The scenarios are simulated with MATLAB software.
The scenarios include an highway section, a motorway tollgate, a queue of trucks stuck on a lane, Indianapolis circuit and Castelletto di Branduzzo circuit, as detailed in the next section.

3.1. Scenarios definition

The following scenarios have been considered of interest and thus simulated:

- Section of a highway, useful case to simulate the behaviour of the localisation technology in presence of an accident/construction site along one of the lanes. The goal of this scenario is to verify if the technology is able to detect the number of vehicles which change lanes and the exact point on the road where the lane change occurs.
- Tollbooth scenario, to consider the presence of a really high number of vehicles interacting with each other, and the interference of the infrastructure with the GPS localisation.
  In fact, the proximity of tolling frequencies (5.8 GHz) and ITS band for Vehicle-To-Everything (V2X) communications (5.9 GHz), forces the vehicle to reduce the transmit power of a 5G signal, which might degrade cellular positioning.
- Trucks lane, representing the common situation of trucks stuck on a lane and the vehicle to localise which is moving in the adjacent one. The goal of this use case is to understand how the presence of trucks can interfere with the localisation of the vehicles moving on the other lane.
- Indianapolis Motor Speedway, indicating the 4.0 km-long oval track famous automobile racing circuit located in Indiana, USA. This is a geometrically simple scenario without any particular physical obstacle, but it is the most challenging setting for localisation due to very high speed.
- Castelletto di Branduzzo circuit, which refers to the modelling of a circuit in the province of Pavia.
  This motodrome is the choice for the development of the experimental phase of the localisation, since it presents very different stretches of road, both straights and curves, which can be considered a good proxy of different real behaviours of a vehicle in everyday situations. These characteristics can be appreciated in the top view image in figure 3.

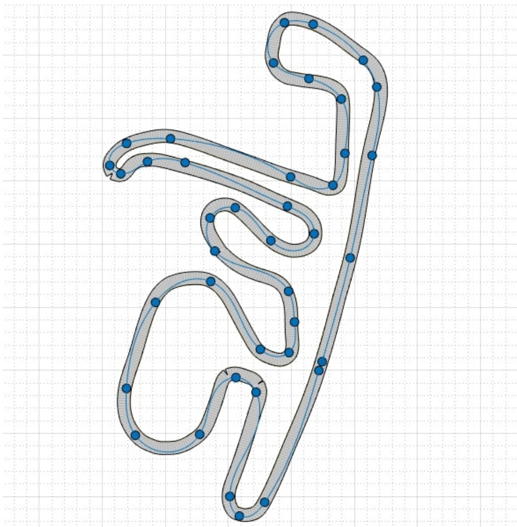

Figure 3: Castelletto di Branduzzo circuit in MATLAB

3.2. Scenario simulations in Matlab

After defining which are the interest scenarios, the next step is to create them on a software. This whole phase is based on the *waypointTrajectory* function. This command generates the trajectory of a vehicle imposing the crossing through specified points in space.
Multiple virtual scenarios have been generated in order to become familiar with this function and its criticalities, but the goal remains the creation of the previously defined scenarios into MATLAB.
The softwares 'Google earth PRO' and 'TCX converter' are used to import the real roads into MATLAB. The *waypointTrajectory* function requires as input even the instant of time at which the vehicle reaches each point, which is called $TimeOfArrival$.
The speed of the vehicles must be entered and to determine it, the $TimeOfArrival$ must be calculated. Two parameters are taken into account: the distance between the waypoints and the point on the route where it is located. If the waypoints are located along a curve, the speed will be significantly lower than in a straight line.
In figure 4 it is shown one of the results obtained by using this function. It corresponds to the "Castelletto di Branduzzo circuit" mentioned above.

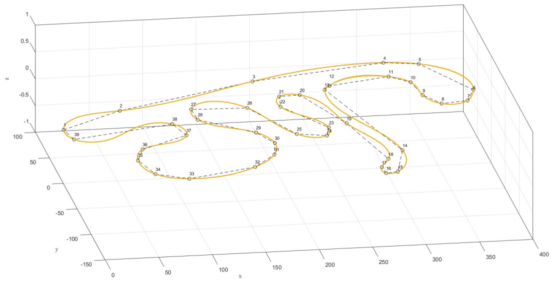

Figure 4: Trajectory function

After modelling all the scenarios, it was used an add-in app in MATLAB, which makes possible to build them in a much easier way: The "Driving Scenario Designer" app.
Using this app it is possible to overcome some of the passages explained in the previous section. In fact, the import of the maps into the Driving Scenario Designer is instantaneous as the insertion of the waypoints directly on the map, in order to describe the desired trajectory. The great advantage of using this application is the ability to better visualise scenarios and the comfort of having useful preset tools to be able to change their characteristics. Another useful function is the one that allows to generate the scenarios in 3D through a rendering, which is very useful during the presentation of the project to Movyon allowing a better understanding of how the simulations work.
Figure 5 shows the scenario for the trucks lane.

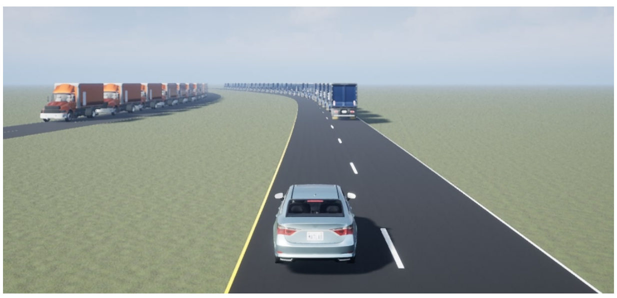

Figure 5: Double trucks lane using the Driving Scenario Designer - 3D

4. Phase 3 - Optimisation of deployment

The third part of the project consists in the creation of an optimiser for the geographical location where placing the UWB sensors in order to achieve a better accuracy in the vehicle's position estimate. A good geometry is achieved when the reference stations are arranged uniformly around the vehicle. For this reason, the system must be designed in such a way that the best geometric arrangement is obtained over the considered area. From the estimation theory, the Cramer Rao Bound (CRB) is used to calculate the best achievable localisation accuracy. It is calculated as:

$$CRB = \sigma_\rho^2(\mathbf{H}(\mathbf{u})^\mathbf{T}\mathbf{H}(\mathbf{u}))^{-\mathbf{1}} = \sigma_\rho^\mathbf{2}\mathbf{GDOP} \quad (1)$$

which shows how the accuracy of localisation depends on two terms. The first term σ_ρ^2 is characteristic of the measurement error, and in case of wireless localisation systems it is influenced by various effects, such as interference, thermal noise, reflections and weather. The second term is the Geometric Dilution Of Precision (GDOP), which represents the impact of the geometry of reference stations on localisation.
The focus of the optimizer is on this last term in order to obtain the optimal sensor layout. Matrix **H** calculation depends on the kind of method used to carry out the measurements and can be seen in table 1.

Method	$h_i(\boldsymbol{u})$	$[\mathbf{H}(\mathbf{u})]_{i-th\ rows} = \frac{\partial h_i(u)}{\partial \boldsymbol{u}}$
TOA	$d_i = \lvert s_i - \boldsymbol{u}\rvert$	$[-a_{ix} \ , -a_{iy}]$
TDOA	$\Delta d_{ij} = \lvert s_i - \boldsymbol{u}\rvert - \lvert s_j - \boldsymbol{u}\rvert$	$[a_{jx} - a_{ix}, a_{jx} - a_{iy}]$
AOA	$a_i \angle (s_i - \boldsymbol{u})$	$\left[\frac{a_{iy}}{d_i} \ , -\frac{a_{ix}}{d_i}\right]$

Table 1: **H**-matrix generation according to the method used

In table 1 subscript j refers to the closest receiver to the vehicle and a_{x1} is equal to:

$$a_{x1} = \frac{s_{1x} - u_x}{|\mathbf{s_1} - \mathbf{u}|} \quad (2)$$

where s_{ix} is the x coordinate of the i-th receiver and $|\mathbf{s_1} - \mathbf{u}|$ is the distance between the receiver and the vehicle [1].
In the project it is used an hybrid system of 2D localisation, as the purchased Ubisense system which can use both the Time-Difference of Arrival (TDoA) and the Angle of Arrival (AoA) methodologies.
The optimiser that defines where these sensors should be placed is created with MATLAB: it randomly places the various receivers on a map and determines the best settings, through a consistent number of iterations which lead to an optimal result. The sensors have to be placed respecting two fundamental limits:

- Placement limit, since they can obviously be placed on the sides of the road, but not on the top of it,
- Range of the receiver limit, since placing a sensor too far away from the points it is supposed to locate would be useless because it would not be able to receive the signal.

An example of the candidate positions of sensors is reported in figure 6 with green dots.

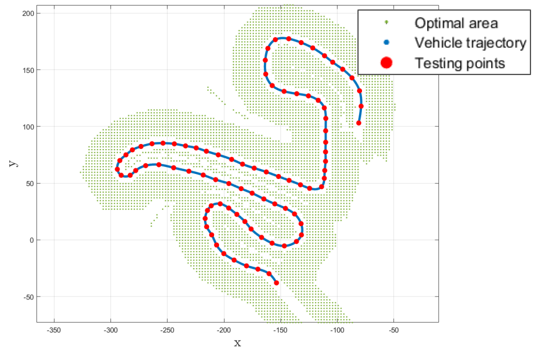

Figure 6: Optimal area definition

Considering the aforementioned area, the MATLAB code randomly positions the sensors within it. Then, it checks that it is guaranteed a minimum distance between sensors and that each point on the road can be detected by at least two receivers. Otherwise, it randomises again the possible positions of all the receivers.
If these two conditions are met, the software proceeds with the GDOP calculation along all the points on the road. Finally, the sensor layout with the lowest Circular Error Probable (CEP) of the GDOPs for all the points is saved.
The result obtained in the section of the motodrome related to figure 6 is shown in figure 7.

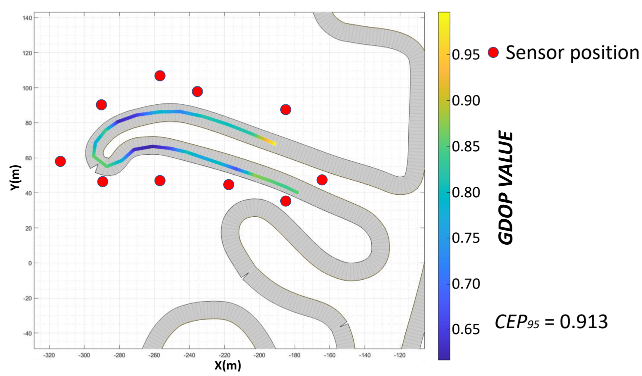

Figure 7: Output example

5. Conclusions

Starting from the existing state-of-art in the field of outdoor vehicle localization, this research first identifies a suitable technology which can be installed on the desired scenarios: Ubisense RTLS Dimension 4 sensors.
Once the technology has been selected, the focus moved into creating simulations of the chosen use cases in MATLAB, in order to represent real-life situations: the section of a highway, a tollbooth, a street with stuck trucks on a lane, Indianapolis Motor Speedway and Castelletto di Branduzzo circuit.
The last phase represents one of the most important tools that can be used in the experimental part with devices. The results obtained are the outcome of the best possible location of the devices, thereby increasing the efficiency of the localisation system and decreasing its planning time.

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