Formula Student Racing Championship: Design and implementation of an automatic localization and trajectory tracking system

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Abstract. The aim of the IST Formula Student Project consists in designing and implementing a low budget car with limited resources, to compete with similar cars from other universities. The objective of the presented project is to design and implement an automatic location and trajectory tracking system to equip the car and understand the relation between the position of the car and the values acquired from the other sensors. The position obtained by the Global Positioning System (GPS) will be adjusted to the track and it will be represented in the pit-stop screen. The aim of the system is divided in two main targets: georeferencing the car's data that is: collected by several sensors, and tracking the car and represent its position in the circuit drawn in the pit-stop screen. Besides these two objectives, the system can be divided in two parts: one that consists in a GPS module connected to the communication system located at the car; and another one in the base station (at the pit-stops) where the data will be processed, analyzed and represented.

1 Introduction and Motivation

1.1 Context

The Formula Student Championship consists of a car competition very similar to Formula 1. The main difference is that this project is created and managed by student teams from many universities all over the Europe, with some strict restrictions like low budget and other limited resources [1].

The Formula Student Tecnico (FST) is one of the existing teams in Portugal, composed by students from several departments of Instituto Superior Tecnico (IST). The actual car, is the 4th vehicle built by the team and the first of an electrical era [5]. This car will be equipped with a full featured telemetry system, based in a mini-PC that collects data from several sensors such as: suspension displacement, engine RPM, tire pressure, battery level etc. This data is collected using a Controller Area Network (CAN) bus that interconnects the sensors and the car's station. Such data is then sent to a base station, installed at the pits, using the IEEE 802.11 (WiFi) protocol [10].

1.2 Motivation and Objectives

In order to enhance the existing telemetry system and to support the processing of the acquired data was decided to implement a georeference system that relates the information acquired by the car's sensors to the position, on the track, where that points were collected. Besides that, it was also required to implement an automatic tracking system that represents the actual and previous position of the car in the circuit map. This data will be represented at the team base station.

This system provides a significant added-value to the data gathered by the car sensors, by relating this data to the car's position. This will allow the team developers to detect the origin of failures, by relating the data values with the track position, or to detect where those failures have started, facilitating the introduction of consequent improvements in the car using this information. As an example, it will be possible to know that the right front suspension starts to fail after a certain hairpin turn.

As such, the main objectives of this project can be expressed as:

1. Create a real-time trajectory and tracking system, that provides the position of the car to the pit-stop team, with good accuracy.
2. Create a georeference system that relates the data from the car sensors with the place where the data were collected.
3. Integrate the information concerning to the position of the car in the base station screen, together with the existing widgets that represent the other sensors.
4. Integrate this solution with the existing telemetry and communication platforms, already existing in the car.

2 Related Work

2.1 Uncoupled GPS Road Constrained Positioning Based On Constrained Kalman Filtering

In order to reduce the GPS error and to determine the most probable position of the receiver on a given road, this algorithm makes use of a Kalman Filter (to reduce the noisy points) and of a previously generated map to constrain the points to a predefined track [11]. This algorithm is particularly addressed to low cost receivers and to platforms with reduced computational capabilities.

The Kalman Filter takes as input the noisy coordinates from the Global Positioning System (GPS). Then, it predicts the location based on past positions and corrects the estimated value based on the most recent location [8]. The resulting values have less noise and tend to be closer to the real location. Then, the constrain function takes that points and restricts them to the nearest point of a predefined map. The final step will project the obtained coordinates in the road map, thus reducing the initial error margin. The map is generated from a linear or quadratic regression, obtained from a set of very accurate and previously traced points [11].

2.2 Constrained Unscented Kalman Filter Based Fusion of GPS/INS/Digital Map for Vehicle Localization

This alternative proposal presents a solution to multipath and signal loss (e.g. in a tunnel) problems with GPS [9]. Besides using the data obtained from a Differential Global Position System (DGPS) device, it also uses the data from Inertial Navigation Systems (INS) and road geometry from Digital Map. To increase the accuracy and to combine these different sources of data, the solution makes use of a Constrained Unscended Kalman Filter, to constrain the estimates to a predefined road that can be obtained from a Digital Map Database.

The INS contains an Inertial Measurement Unit (IMU), which is composed by a gyroscope and an accelerometer. It provides the values of the yaw rate and forward acceleration, which will be used to create the Dynamic INS equations. These equations will be the state equations of the Unconstrained Unscented Kalman Filter (UUKF) algorithm, when the coordinate estimations from DGPS will be part of the measurement equations. The result of the algorithm, applied to this loosely coupled DGPS/INS system estimates, will be finally projected into the state constraints provided by a Digital Map database [9].

2.3 RaceLogic VBox

The VBOX GPS data logging system, is placed in the car and can acquire data at 100Hz and send it, in real-time, to a USB or bluetooth device (like a PC) or even send it through the CAN bus, just like other car sensors. It can also be combined with an IMU that can provide better measurements in poor visibility conditions, and with a Real Time Kinematics (RTK) station to provide more accuracy.

The IMU consists in three accelerometers and three gyroscopes, that can measure accelerations and rotations in the x,y,z axis. The objective is to provide better measurements in conditions with low or no visibility to the satellites (like in a tunnel or under a bridge), using a real-time Kalman Filter. The RTK unit is a station composed by a second GPS receiver with a very known location. This auxiliary station gets its GPS coordinate, compares with its real location and corrects the position acquired by the car's GPS module increasing the accuracy of the car position to 2cm [6].

2.4 Anti-Carjacking System/ Fleet Management

This system provides the location at distance, i.e. it is possible to be at home, or in the fleet management office, and watch in the computer map where a particular car is at any time. It is also possible to track where the car had been before, relate with its speed, engine sensors and other information.

The technology behind this system is a GPS module, that locates the car in the globe, and a communications unit based on a GPRS module (or similar technology), located in the same device, that sends the GPS coordinates and other data related to car components to a data center. The user can then receive and see the data through the internet or the mobile phone (via SMS), either in the form of GPS coordinates, or through a computer map/satellite image, where it is represented the car location and other related information, such as the car sensors. History data can also be remotely obtained [4].

2.5 MoTeC Software

MoTeC is a leading company concerning to telemetry, the most relevant MoTeC product's are: the i2 and i2 Pro data analysis tool, the MoTeC telemetry system, the GPS modules and specially the components of these systems that provide the car location service, relation between the car's sensor information and the cars position.

The i2 application is divided in two levels, the i2 free software and the i2 Pro version. The i2 Standard is a software tool freely available to the customers with data logged from the MoTeC Data Logger product or a Electronic Control Unit (ECU) from the same manufacturer. The i2 Pro is a more advanced software tool that provides mathematics, multiple overlays and a paid license that allows the software to analyze data from other types of source and file formats.

The Telemetry Monitor system is a similar software tool that presents to the user located in the pit stop (or other fixed location) real time information about the vehicle through a set of widgets. The data is collected and logged by the data acquisition system located in the car and connected by a CAN bus to an Advanced Central Logger (ACL) module, that sends the data to a remote computer through a Ethernet connection. This allows the data engineer to monitor the engine and chassis data in real time, while the vehicle is still on track [7].

3 Supporting Platforms and Algorithms

In this chapter will be presented the platforms and algorithms integrated in this work, in order to archive the proposed objectives.

This work is integrated with an already existing telemetry system, this telemetry system is composed by a Mobile Station corresponding to a mini-computer installed at the car which will gather all the CAN-Bus information and will send to the Base Station located at the pitbox through the existing communication platform[10]. The Communication platform consists in a framework which enables the transfer of information between the developed station using the WiFi protocol [10]. The base station corresponds to the user computer and the application installed, which enables the user to observe the acquired sensors values through widgets, to log the gathered information and to analyze this information later.

In order to acquire the location information it is integrated in the system one GPS module (GlobalSat ND-100 GPS USB Dongle [2]), which provided information will be acquired by using the GPSd tool [3]. This tool communicates with the GPS and returns one data structure to one socket, where the Mobile Station application will read and process in order to send to the Base station.

To accomplish the objective of providing accurate information about positioning, the existing work "Uncoupled GPS Road Constrained Positioning Based On Constrained Kalman Filtering" [11], will be integrated in the base station as-is, by using the MATLAB C Compiler (MCC) tool. This work consists in mathematical algorithms, which process the acquired coordinates by using one Kalman Filter, and then constrain these filtered coordinates to an generated digital map.

4 Solution Design and Implementation

The developed system is composed by two subsystems: the mobile station, which is installed at the car; and the base station, which is installed at the pit-box.

The figure 1 represents this system integrated with the already existing telemetry platform. The GPS receiver will acquire and calculate the positioning of the car, and sent that information to the car application installed in the vehicle. The acquired data will be sent through the communication protocol to the base station located at the pitbox. After receiving this information, the base station will process this information and represent it to the user in a map widget.

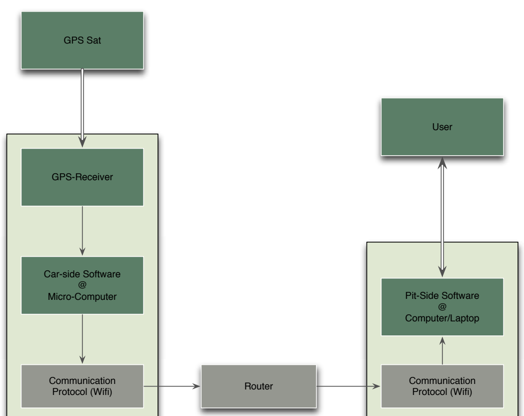

Fig. 1. Simplified block diagram of the proposed architecture: Mobile, Base Station and Communication infrastructure.

4.1 Mobile Station

The mobile station architecture, represented in fig. 2, consists in: the GPS device which acquires location data from the satellites; the GPSd software tool, which communicates with the GPS module and returns one data structure containing location, time and speed information; and the GPS Acquisition application which receives the data from GPSd, converts, timestamps (according to the CAN-Bus gathering application) it and sends to the Pit Box station.

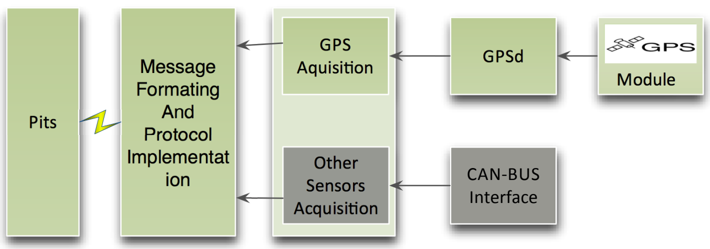

Fig. 2. Mobile Station Architecture.

4.2 Base Station

In figure 3 is presented the final architecture of the Mobile Station location and tracking application, a brief description of each module is present in the following paragraphs:

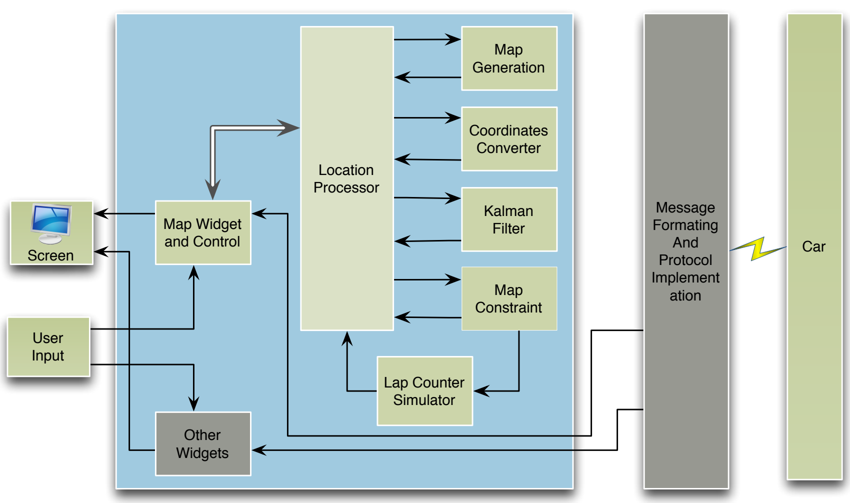

Fig. 3. Base Station Architecture.

- **Coordinates Conversion Module:** This module converts the gathered global Latitude, Longitude and Altitude (LLA) coordinates to a local coordinates representation using meters East, North and Up (ENU). Since the coordinates are in meters, this will allow the introduction of some features like a speedometer and a odometer, based on this GPS information.

- **Map Constrain Module:** The aim of this module is to improve the accuracy of the representation, by constraining the car position to the already defined circuit map. If the current location of the car is in a place with a bad GPS reception (in the middle of buildings or mountains), the constraining of the coordinates to a previous defined map can reduce the error margin that occurs in these situations.
- **Kalman Filter Module:** This filter is used to reduce the noise of the GPS samples, in order to provide better estimates. In this application, the filter is especially useful to design a smoother map of the track using the car GPS sensors, by removing some irregularities.

  Then, this module projects the estimated points into the track that was modeled by the Map Generation Module.
- **Map Generation Module:** This module is responsible to model the map of the circuit where the car will run by using a set of arithmetic functions.
- **Map Widget and Control Module:** This is the interface module between the application and the user. This module draws and manages the user interface, receives input from the user and generates the Portable Document Format (PDF) report.

  To support these functionalities, this module makes use of several widgets to represent the circuit map, the speed, the traveled distance and the current position. For the offline analysis mode of the application, this module also represents the sensors values for each coordinate, allowing a correlation between position and car behavior.

  The Control part of this module provides the data management support, by receiving the coordinates data from the communication platform and dispatching it to the other modules responsible for the coordinate processing. It is also this module which is responsible for the conversion between the ENU coordinates and the screen coordinates, the managing of the window events and the user input, and also for updating and reading values from the database.
- **Location Processor Module:** This is one of the main processing modules. It is this module that contains the functions to transform raw coordinates into local filtered coordinates and maps.

  These functions are made available to the representation module by a set of interfaces. To implement those functionalities, this module uses and manages the converter module, the Kalman filter, the map generation and the constrain module.

  Depending on the user input gathered by the representation module, the Location Processor Module chooses the corresponding data flow between the modules: generate map, tracking car's position, etc.
- **Lap Detector Module:**

  The aim of this module is to analyze the collected positioning information and to determine when the vehicle has completed a Lap. This information will allow to organize the gathered information into distinct Laps, leading to a more user friendly analysis.

The implementation of the Map Generation, Coordinates Converter, Kalman Filter and Map Constrain Modules was made by integrate the work presented in 2.1 as a Matlab C library in this application. The Location Processor, Lap Counter Simulator were implemented in C/C++, where the Map Widget and control was implemented in Qt, C/C++ and fully integrated with the already existing telemetry application.

5 Experimental Results

In order to fully test this prototype, all components from the telemetry system were used: the mobile station was installed in a private car, while the router and the base station were installed near the track.

The figure 4 represents the offline session mode of the application. In this figure can be observed the map, which was generated from the data gathered by the vehicle, the positions and the speed information acquired during the second lap. By mapping the color of the position with the color bar, is possible to determine that the car moved faster in the straights (20km/h and the 30km/h, and more slowly in the curves with the values (10km/h and 20km/h). This indicates that the geo-positioning of the speed sensors are in accordance to what was expected by the team. It can be also observed in this screenshot that the car traveled the distance of 1515.5 meters during the test, and the 2nd coordinate acquired has 114 as timestamp value, and at this moment the car was parked since the speed value was 0 km/h.

By observing the positioning of the vehicle according to the map, it is possible to determine that around 98% of the coordinates where constrained to the map, meaning that some tuning should be made in order to increase this value. The live mode consists in a similar interface, where is present the following components: Filter mode options, circuit map and current positioning and the values corresponding to the actual and maximum speed and distance traveled.

6 Conclusions and Future Work

6.1 Conclusions

The objective of having a real-time trajectory and tracking system is accomplished with this application which is able to receive the positioning information and present it to the final user in real-time. During this process some filtering steps are applied in order to improve the GPS accuracy, by restricting the position of the car to the circuit map.

The offline mode loads a previous session, and presents to the user the acquired coordinates in the screen. In this mode is possible to observe the map,

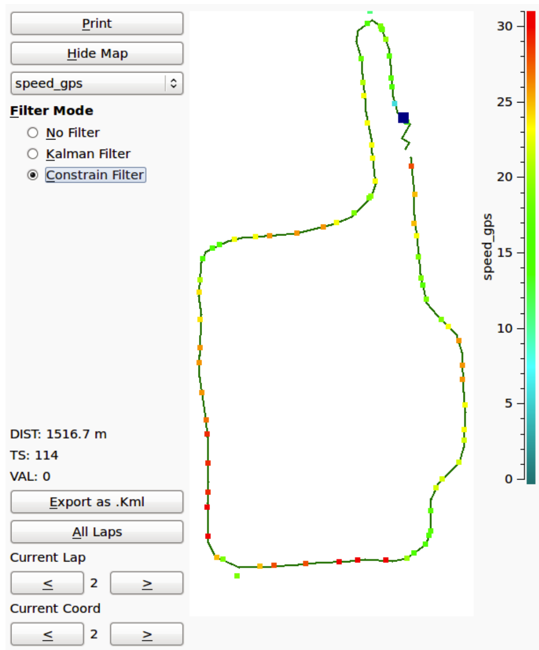

Fig. 4. Acquired coordinates using the constrain filter.

the acquired coordinates and select one sensor to analyze its information. After choosing one sensor, the map will be colored according to the values gathered from that sensor. This information can be both presented in the screen and exported to Google Earth.

The transfer of information between GPS acquisitioning application present in the mobile station, and the GPS processing and representation module installed in the base station is made by the already existing communication platform. The widgets corresponding to this work are also integrated in the already existing telemetry user interface.

6.2 Future Work

In order to improve this telemetry system, some solutions are proposed in the following paragraphs:

- Integrate gyroscopes an accelerometers in the vehicle with higher frequencies than GPS in order to improve the location information, with the data collected by these sensors is possible to calculate the intermediate positions between the GPS coordinates.
- Implement a DGPS like system, which requires an additional GPS receiver and placing it in a known position. With the information of the position the fixed GPS could calculate the error of the position calculation and correct the

mobile GPS with this information. This solution will improve the precision, but will not solve the low frequency problem.
– In the user interface some improvements concerning the organization of the widgets can be made. An example of one improvement can be: design a solution, which allows the user to save the definitions (like size and position of the widgets) into user profiles. These profiles should be loaded in the beginning of the application, allowing the user to set up his dashboard as he wants once, and using it multiple times.

In the Offline session, the usability and the data analysis can be also improved by:

– Augmenting the number of widgets available and the interoperability with them. With a set of widgets available, these widgets could be synchronized to show a snapshot of a moment selected by the user. For instance: having a plot representing the relation between speed and time, where the user could use a bar to navigate in the plot along the time. When he is navigating the steering wheel, the accelerator bar and the map could synchronously move and present the state of each sensor like in live session.
– Adding a formula editor, where the user can perform operations with and between the sensors. It should be possible to create graphs with the difference between the values of two sensors for instance. This editor could accept basic operations (+, -, / , *) with constants, available sensors and allow the user to choose how the result could be presents: in a bar, table, plot, etc.

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