Loosely Coupled GPS/INS Integration With Snap To Road For Low-Cost Land Vehicle Navigation

EKF-STR for low-cost applications

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***Abstract*— Nowadays, the availability of the vehicle position gets more and more important. The use of the Global Positioning System (GPS) receiver has solved this problem. Nevertheless, this system could suffer from availability of the minimum number of visible satellite, especially in harsh environment. Thus, complementary system, such us Inertial Navigation System (INS) comes to help the GPS in order to guarantee the availability of the position in these environments. Nevertheless, low cost Microelectromechanical System (MEMS) based INS integrated with the GPS has shown weak performances even in case of using Kalman filtering. To deal with this problem, this paper proposes a new approach based on loosely coupled GPS/INS integration using Extended Kalman Filter (EKF) and aided by a map matching technique. In the literature, researchers have widely investigated the EKF in order to improve the position accuracy. The developed approach overcomes the drawback of this method by adding the Snap To Road (STR) as a map matching technique. Experimental tests of EKF aided by STR system have shown better performances than standalone EKF even in harsh environment.**

Keywords*— *Global Positioning System (GPS); Inertial Navigation System (INS); Snap To Road (STR); Extended Kalman Filter (EKF); Loosely Coupled; Map Matching

I. Introduction

Nowadays, the use of navigation systems remains frequent in different fields such as marine and land navigation. The most useful systems are the Global Positioning System (GPS) [1] and the Inertial Navigation System (INS) [2], which are currently widely integrated in the new vehicles in order to communicate precise position and other parameters used by traffic managers to improve the traffic flow([3]and [4]) and monitoring the driver behavior [5].

Nevertheless, the availability of the GPS signal is constrained by the number of the visible satellite. In harsh environments such as urban canyons, tunnels, forested areas and bridges, the GPS signal is weak or unavailable. Therefore, other complementary system comes to aid the GPS receiver in order to have a permanent available position.

In the literature, many researchers have investigated the system composed by the GPS and INS to improve its performances in terms of accuracy. However, the precision is highly dependent on the cost of the used sensors. As the system is precise the price gets higher. To deal with such problem in mass market applications, MEMS based INS has been used while developing advanced GPS/INS integration algorithm. The method of GPS/INS integration differs from an application to another. In the literature, several GPS/INS integration algorithms has been presented based on the degree of the integration between GPS and INS systems, namely, Loosely Coupled [6], Tightly Coupled [7], Ultra-Tightly Coupled [8]. This paper focuses on the Loosely coupled GPS/INS integration based EKF, which is a low level of integration. The advantages of using Loosely coupled integration the low computation time and complexity. However, there are two main drawbacks of this integration method: 1. the precision of the position and 2. the high speed divergence of the navigation solution in case of GPS outages. To deal with these problems, researchers have adopted other types of Kalman filters such as Unscented Kalman Filter (UKF) aided by external fuzzy systems or simultaneous localization and mapping (SLAM) [9]. Nevertheless, the complexity of these solutions remains high, that’s why the use of Extended Kalman Filter (EKF) remains a good trade-off between these advantages and drawbacks for GPS/INS integration [10]. The EKF is an improved version of Kalman filter that cope with non-linear behavior (also called nonlinear Kalman Filter) which will be a better architecture to fit with our constraints.

To improve the performances of an EKF based loosely coupled GPS/INS integration, this paper proposes the use of map matching technique that is able to minimize the position error of the vehicle. The map matching technique is based on the theory of pattern recognition. It uses the positions of the vehicles and compared it to the existing map data. Based on the error between the vehicle path and the road trajectory, the map matching technique updates the vehicle’s positions. In this paper, the Snap To Road (STR) [11] is used as a map matching technique. Our approach is to combine the loosely coupled based Kalman filtering and the STR technique in order to obtain accurate navigation solution. Therefore, we can have the advantages of these two techniques, and deal with their drawbacks at the same time. Our strategy consists in dealing with two kinds of situations that depends on whether the GPS signal is available or not. In fact, a specific architecture is developed for each of these two scenarios.

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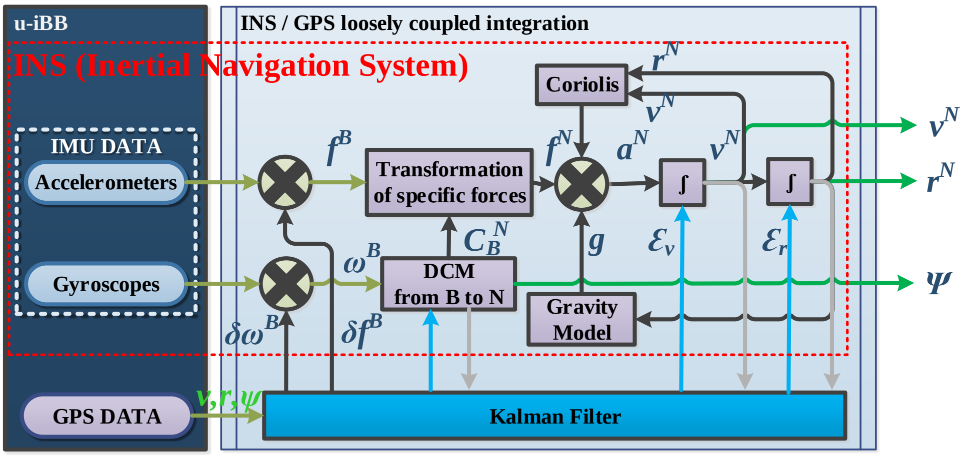

FIG. 1. GPS/INS EXTENDED KALMAN FILTER (EKF) CONSIDERED

In this paper, Section II presents the loosely coupled GPS/INS integration architecture and followed by Section III, which introduces the STR technique. Our proposed solution is presented in Section IV. Before drawing conclusions in Section VI, Section V summarizes our tests and results of the proposed new approach.

II. INTEGRATION SYSTEM

A. Global Positioning Systems (GPS)

The GPS is able to provide position and speed in three precise and continuous dimensions via its constellation of satellites. With GPS, precise positioning has become available for a variety of applications. Moreover, the decline in the cost of GPS receivers over the past few years has made this system increasingly attractive in all applications where cost is an important factor. GPS accuracy is affected by several types of deterministic and random errors [12]. Some of them are independent of the GPS receiver local environmental conditions such as orbital errors, and clock drifts. The other errors, such us masking signal, depend on the environment conditions.

B. Inertial Navigation System (INS)

This system is used to integrate the inertial measurements to obtain the position, speed and orientation of the vehicle. As shown in the Figure 1, an INS consists of two main elements, an Inertial Measurement Unit (IMU) [13] and a processing unit. The IMU consists of an assembly of accelerometers and gyroscopes used to measure respectively the acceleration (specific forces) and the angular velocity of a platform along three orthogonal axes. The processor processes the dynamic equations of the inertial system in order to compute the attitude, the speed and the position of the mobile.

1) Accelerometers

An accelerometer measures the specific force $\tilde{\boldsymbol{f}}^B$ as shown in the Figure 1. This force is composed by the real specific forces $\boldsymbol{f}^B$, the measurement error $\delta\boldsymbol{f}^B$, and a white Gaussian noise $\boldsymbol{\eta}_f$ with zero mean and variance $\sigma^2_{\eta_f}$. It is given by the following equation [14]:

$$\tilde{\boldsymbol{f}}^B = \boldsymbol{f}^B + \boldsymbol{\delta f}^B + \boldsymbol{\eta}_f \tag{1}$$

The gravitational, centripetal and Coriolis forces are subtracted from the specific force in order to obtain the acceleration of the mobile according to the navigation frame. Gravitational and Coriolis accelerations can be estimated using mathematical models, which is related to the vehicle position and speed. Then, the acceleration is integrated in order to obtain the speed of the mobile. The speed is integrated in order to obtain the position of the mobile. However, this precision will degrade more and more over time [15].

2) Gyroscopes

A gyroscope is used to measure the angular velocity $\tilde{\boldsymbol{\omega}}^B_{\text{IB}}$ of an object with respect to the earth inertial frame [16]. It is composed of the real angular velocity $\boldsymbol{\omega}^B_{\text{IB}}$, the measurement error $\delta\boldsymbol{\omega}^B$ and a white Gaussian noise vector $\boldsymbol{\eta}_\omega$ with zero mean and variance $\sigma^2_{\eta_\omega}$. It is given by the following equation:

$$\tilde{\boldsymbol{\omega}}^B_{IB} = \boldsymbol{\omega}^B_{IB} + \boldsymbol{\delta\omega}^B + \boldsymbol{\eta}_\omega \tag{2}$$

As shown in the Figure 1, the vector $\tilde{\boldsymbol{\omega}}^B_{IB}$ is then processed to update the attitude matrix $\boldsymbol{C}^N_B$ that characterizes the orientation of the mobile compared to the navigation frame. Then, the updated attitude is used to transform the accelerometer measurements from the body frame to the navigation frame.

C. Extended Kalman Filter (EKF)

Figure 1 shows the proposed loosely coupled GPS/INS integration (EKF). It represents a closed loop architecture that allows to correct parameters errors [15]. The main advantage of loosely-coupled integration is the low computational time and complexity [6]. In fact, it uses only the speed, position and orientation given from the GPS and it does not compute them from the GPS's internal parameters such as the ephemerids and the satellite position, which requires more heavy computation [17].

The Kalman filter has two steps. The first one is the state estimation, where the GPS data is not available (GPS outage) and the second step is the update, which is designed to update the state parameters. The state vector $\boldsymbol{\delta x}$ is composed by three attitude error $\boldsymbol{\psi}^N$, three speed error $\boldsymbol{\delta v}^N$, three position error $\boldsymbol{\delta r}^N$, three accelerometer bias $\boldsymbol{b}_f$ and three gyroscope bias $\boldsymbol{b}_\omega$. It is given by the following expression:

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$$\boldsymbol{\delta x} = \begin{bmatrix} \boldsymbol{\delta r}^N & \boldsymbol{\delta v}^N & \boldsymbol{\psi}^N & \boldsymbol{b}_f & \boldsymbol{b}_\omega \end{bmatrix}^{\mathrm{T}} \tag{3}$$

In the estimation step, the EKF computes the state parameters based on the INS data. The propagation model used in the loosely coupled GPS/INS integration is based on the error propagation model summarized in the evolution equation represented in continuous time. It is composed of the transition matrix of the state vector $\boldsymbol{F}$, the continuous system noise distribution matrix $\boldsymbol{G}$ and noise vector of the system $\boldsymbol{\eta_p}$. It given by:

$$\boldsymbol{\delta \dot{x}} = \boldsymbol{F} \cdot \boldsymbol{\delta x} + \boldsymbol{G} \cdot \boldsymbol{\eta_p} \tag{4}$$

Once the GPS data is available, the update step starts. The measurements vector $\boldsymbol{\delta z}$ computed from the GPS receiver data, is composed of three position error, three speed error, and three attitude error. The measurements vector $\boldsymbol{\delta z}$ is composed by the state vector $\boldsymbol{\delta x}$, noise vector of measurements $\boldsymbol{\eta_m}$and the measurement matrix $\boldsymbol{H}$ and given by the following equation:

$$\boldsymbol{\delta z} = \boldsymbol{H} \cdot \boldsymbol{\delta x} + \boldsymbol{\eta_m} \tag{5}$$

The covariance matrix associated with the state error vector is given by equation (6) and composed of the variance of the noise of the accelerometers $\sigma^2_{\eta_f}$ and noise variance of the gyroscopes $\sigma^2_{\eta_\omega}$, which can be determined by a statistical analysis of the raw measurements from inertial sensors.

$$\boldsymbol{Q_c} = \begin{bmatrix} \sigma^2_{\eta_f} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{\eta_f} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{\eta_f} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{\eta_\omega} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{\eta_\omega} & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_{\eta_\omega} \end{bmatrix} \tag{6}$$

The covariance matrix R is associated with the measurement noise and composed of the variance on the position measurement provided by the GPS receiver σ^2_r, variance on the speed measurement provided by the GPS receiver σ^2_v and variance on the measurement of $\boldsymbol{\psi}$ provided by the GPS receiver σ^2_ψ that were computed in stationary conditions.

$$\boldsymbol{R} = \begin{bmatrix} \sigma^2_r & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_r & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_r & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_v & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_v & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_v & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \sigma^2_\psi \end{bmatrix} \tag{7}$$

III. Snap to Road

The Snap To Road (STR) is used as a map matching technique. It consists in determining the nearest vehicle's GPS coordinates to the Google's map road. It is offered as a service from Google Maps Roads API. This API is a web based application available to the public through a HTTPS interface and offers different services: Snap to roads, nearest roads and speed limits. The maximum allowed amount of data in each request is 100 points. The distance between two consecutive points should not exceed 300 meters in order to obtain accurate response. The response of the API is composed by the Snapped Points, which is an array of captured points that each includes the following fields: location (latitude and longitude), Original Index of the point in the request and the place Id, which is a unique identifier for a place. All location IDs returned by the API correspond to road segments that can be used with other Google APIs. The most important drawback of the use o f STR is the limited times of use per day. In fact, it is allowed to send a maximum of 100 000 requests per day, 2500 query for free and 0.5 USD for each 1000 additional requests. Another problem comes when the sent data are not accurate. In that case, the STR could refer to the wrong road that is parallel to the right one as shown in the Figure 2. In fact, the application of the STR technique to the GPS point (represented in grey color) provides the estimated trajectory represented by the purple color instead of the real trajectory that is represented by the green color in the Figure 2. In this case, the estimated and the real trajectories are too close and parallel.

Fig. 2. Example of STR error

For more information about the use of the STR, readers can refer to [18].

IV. Proposed Solution: EKF-STR

A. Overview of the proposed solution

As described earlier in this paper, the use of the standalone EKF could not deal perfectly with some situations such as long GPS outage period. In this section, the EKF aided STR is detailed. The proposed architecture deals with two different situations that depend on whether the GPS signal is available or not. When the GPS signal is available, the use of the STR will improve the position accuracy. In case of GPS outage, the EKF estimates the vehicle state and the STR is used to correct the vehicle position and to have a robust navigation solution.

As shown in the Figure 3, the proposed architecture is composed by three main blocks. The first one is the IMU which provide the inertial measurement composed by the gyroscope and the accelerometer data. These data are processed to compute the position (r), the speed (v) and the attitude (ψ). The second block, represented by the red frame in the Figure 3, is the GPS/STR data selection. This block contains a switch that chooses the right process according to the situation (GPS

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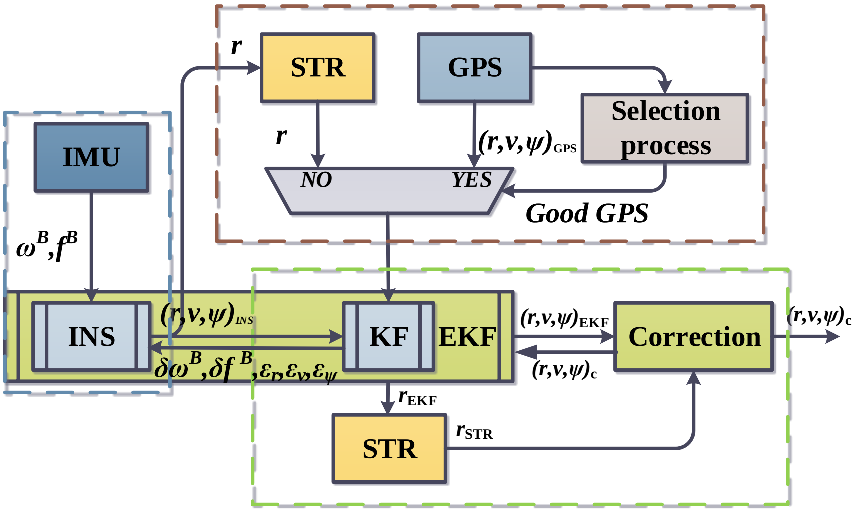

FIG. 3. OVERVIEW OF THE PROPOSED EKF-STR INTEGRATION SYSTEM

available or not available). The third block is the processing unit and is framed in green color in the Figure 3. This latter contains the Kalman filter that is estimating and updating the vehicle state at each time step and whether the GPS signal is available or not. The vehicle position is updated another time using the STR technique in order to have more precision.

B. Operating principle

As mentioned above, there is two different situations that depends on GPS signal availability.

1) GPS Signal is available

When the GPS signal is available, the STR is used to improve the correction of the obtained position from the update step in the EKF as shown in the Figure 4.

2) GPS signal is not available

In the case of GPS outage, the INS estimates the vehicle position at the estimation step of the EKF. Once achieved, the

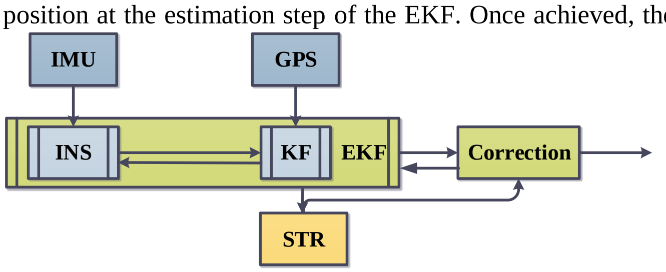

FIG.4. PROPOSED ALGORITHM WHEN THE GPS SIGNAL IS AVAILABLE

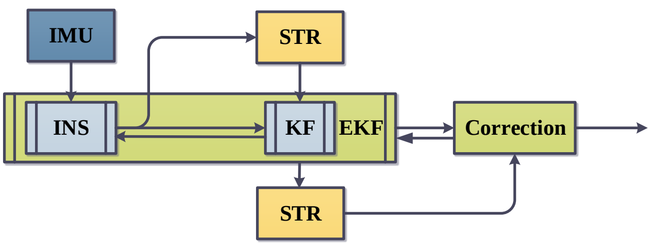

FIG.5. PROPOSED ALGORITHM WHEN THE IN CASE OF GPS OUTAGE

update step is used to correct the estimated position using the output data from the STR. These latter are computed from the estimated positions.

Since the INS solution could diverge in such situation, then the vehicle positions provided to the STR block is not accurate. In that case, the STR takes part of the last corrected data and another part from the estimated position from the INS.

V. RESULTS AND PERFORMANCE

A. Experiemental test set-up

To test our proposed approach, two systems are used as shown in Figure 6. The first one is the IMU-CPT [19], which is integrated with the Novatel ProPak6™ Triple-Frequency GNSS Receiver [20]. It is composed of Fiber Optic Gyros (FOG) [21] and Micro Electromechanical Systems (MEMS) accelerometers [22]. FOG offers high precise data and stable

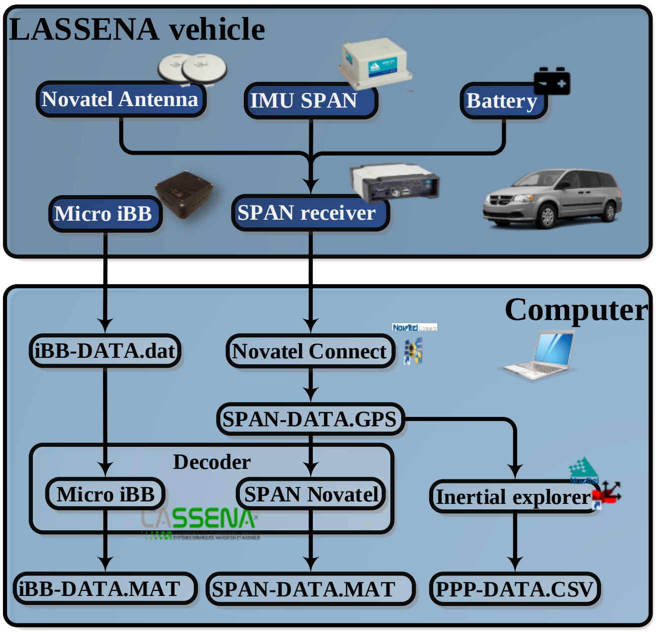

FIG. 6. DATA COLLECTION EQUIPMENT

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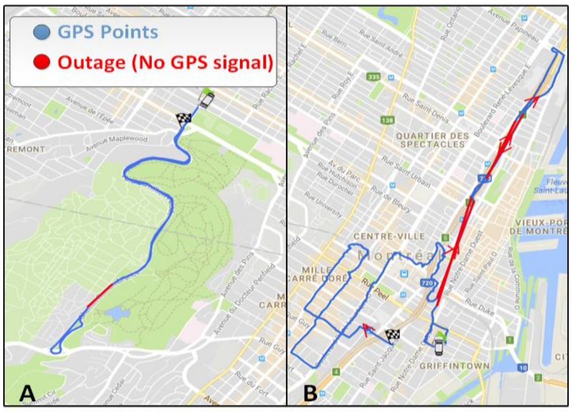

FIG. 7. (A) TRAJECTORY 1, (B) TRAJECTORY 2

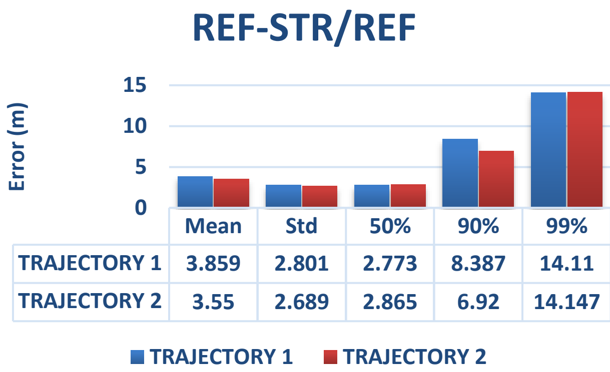

FIG. 8. COMPARISON DIAGRAM BETWEEN REF AND REF-STR

performances compared with other similar gyro technologies. The data from the Novatel system are used in the inertial explorer interface to generate a tightly coupled GPS/INS navigation solution, which is considered as a reference to compare the performances and the effectiveness of the proposed approach when applied to low-cost MEMS based sensors. The second system, namely micro-iBB [23], is in lab designed using low-cost systems such the gyroscope L3GD20 MEMS and the magnetometer and accelerometer LSM303DLHC.

To collect real data, the Dodge car 2012 vehicle is used. Two road trajectory tests were carried out, as shown in Figure 7. Both of the test trajectories are conducted in the city of Montreal in Canada. This choice is made since they partly contain urban roadway, highway, urban canyon, tunnel, bridge and mountain. In such areas, the GPS signal is weak or unavailable. In this paper, trajectory #1 lasts 7 minutes and includes an outage of 20 seconds. Trajectory 2 lasts 27 minutes and has three outages, each one being longer than 1 minute.

In the rest of the paper, the following parameters refer to:

- EKF: Loosely coupled GPS/INS integration (Figure 1)
- GPS: GPS data
- REF: Reference data (tightly coupled GPS/INS integration)
- EKF-STR: Loosely coupled GPS/INS integration with Snap to Road technique (Figure 3)
- REF-STR: Snap to Road applied to the Reference data
- GPS-STR: Snap to Road applied to GPS data

B. Results and discussion

Figure 8 presents the errors generated from the application of the STR on the reference data that are obtained from the application of the high precise post-processed tightly coupled GPS/INS integration using the 'Inertial explorer' software from NOVATEL. We note that the REF and REF-STR refers to the reference data and the STR applied to the reference data, respectively. It is intended that the STR will not have an impact of the reference data since they are already very high precise. However, as shown in the Figure 8, the statistical analysis of the two test trajectories has revealed that there is a mean error of 3.859 m in the first trajectory and 3.55 m in the second trajectory. These errors come from the bad calibration of the Google's road map. Therefore, these errors will appear in every STR use. In the rest of the paper, the algorithm performances will be compared to REF-STR and REF data.

Figure 9 compares data from the EKF-STR, GPS, GPS-STR to the reference data REF and STR applied to the reference data (REF-STR) and also the EKF data to the REF-STR. The comparison is made in terms of absolute error and cumulative error. Figures 10 and 11 summarize and detail the obtained results for the first test trajectory.

Figure 10 presents the statistical analysis of the absolute errors of the first trajectory using the reference data REF. It presents the error of the EKF-STR compared to the reference data, which is the main contribution of this paper. The error based on the GPS data are computed when the GPS signal is available (no GPS outage). Once the STR technique is applied, this latter interpolates between the last and the first available GPS positions considering the Google's road map.

As shown in the Figure 10, the mean error and the standard deviation generated from the application of EKF-STR relative to the REF ($\bar{\varepsilon}_{EKF-STR/REF} = 3.7$ m, $\sigma_{EKF-STR/REF} = 2.64$ m) are less than the mean error generated from the application of the

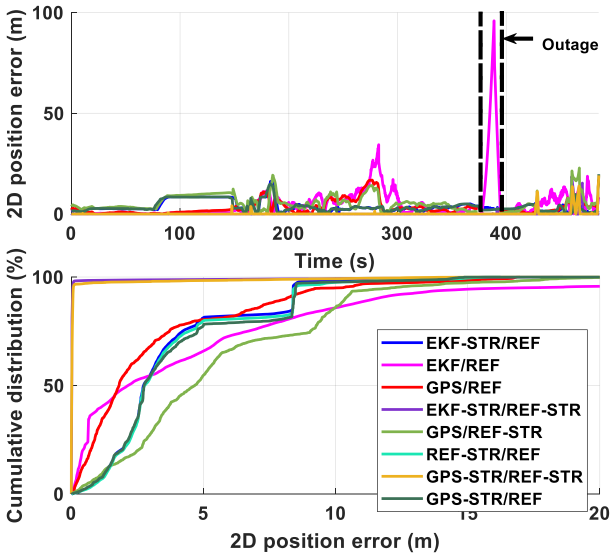

FIG. 9. TRAJECTORY 1 ERROR ANALYSIS: POSITION ERROR(TOP) AND CUMULATIVE DISTRIBUTION (BOTTOM)

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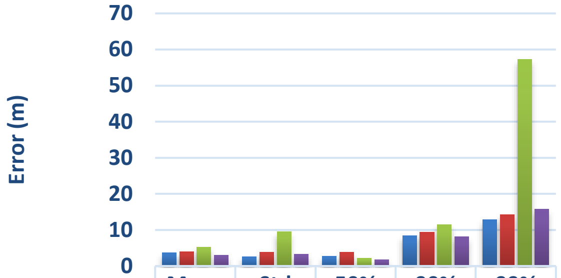


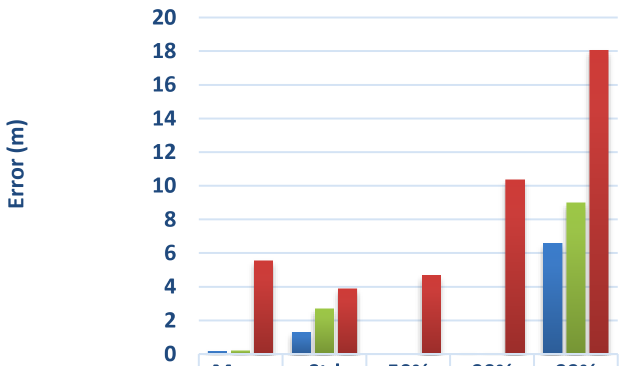
	Mean	Std	50%	90%	99%
EKF-STR/REF	3.712	2.645	2.73	8.386	12.859
GPS-STR/REF	3.932	3.885	3.812	9.41	14.25
EKF/REF	5.296	9.493	2.144	11.509	57.231
GPS/REF	3.074	3.345	1.808	8.134	15.719

EKF-STR/REF GPS-STR/REF EKF/REF GPS/REF

FIG. 10. TRAJECTORY 1: STATISTICAL ANALYSIS OF THE ERROR ACCORDING TO THE REF

EKF alone ($\bar{\varepsilon}_{EKF/REF} = 5.29$ m, $\sigma_{EKF/REF} = 9.49$ m). Regarding the cumulative distribution error, 99 % of the obtained errors during the mission is less than 12.85 m, which is also the lowest obtained value compared to those obtained when using the GPS data and the STR applied to the GPS data. This shows that the STR together with the EKF has improved the performance of the navigation solution in terms of position when it is compared to the errors obtained without the consideration of the GPS outages (GPS/REF).

Figure 11 presents the statistical analysis of the absolute errors when using the STR technique applied to the reference data (REF-STR). From this Figure, it can be seen that the EKF-STR is more accurate than using only the GPS data (GPS) and using the STR applied to the GPS data when the GPS signal is available (GPS-STR). In fact, 99 % of the obtained errors is less than 6.57 m compared to 8.97 m and 18.06 m in case of GPS-STR and GPS respectively.



	Mean	Std	50%	90%	99%
EKF-STR/REF-STR	0.156	1.292	0.009	0.037	6.576
GPS-STR/REF-STR	0.21	2.691	0.016	0.06	8.978
GPS/REF-STR	5.545	3.895	4.673	10.363	18.06

EKF-STR/REF-STR GPS-STR/REF-STR GPS/REF-STR

FIG. 11. TRAJECTORY 1: STATISTICAL ANALYSIS OF THE ERROR ACCORDING TO THE REF -STR

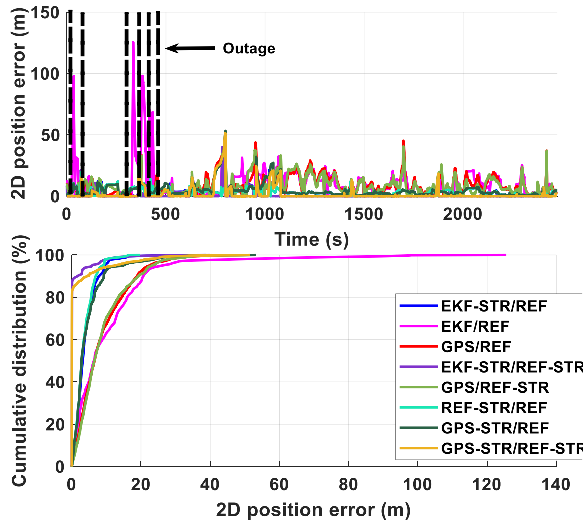
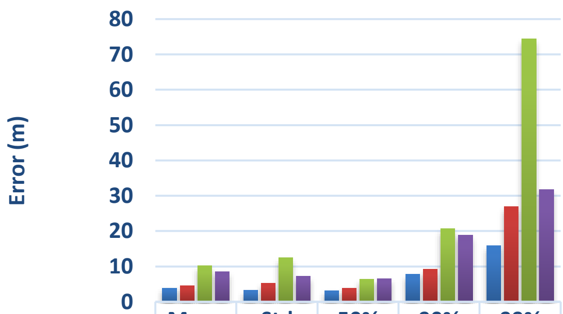


FIG. 12. TRAJECTORY 2 ERROR ANALYSIS: POSITION ERROR(TOP) AND CUMULATIVE DISTRIBUTION (BOTTOM)

The second trajectory represents a complex configuration compared to the first one in terms of GPS outage and the quality of the GPS signal, which is weaker in this case.

Figure 12 shows the position error (top plot) and the cumulative distribution of position error (bottom plot) for trajectory #2. As shown in this Figure, there are three GPS outages in this trajectory and the errors are more important than those obtained in the first trajectory. Detailed results displayed in this Figure can be shown in the Figures 13 and 14.

Figure 13 summarizes the statistical analysis of the absolute errors of the second trajectory using the reference data REF. It can be seen that the error obtained from the proposed method EKF-STR ($\bar{\varepsilon}_{EKF-STR/REF} = 3.91$ m) is lower than the other errors obtained with the GPS-STR, EKF alone and the GPS data ($\bar{\varepsilon}_{GPS-STR/REF} = 4.53$ m, $\bar{\varepsilon}_{EKF/REF} = 10.24$ m, $\bar{\varepsilon}_{GPS/REF} = 8.59$ m).



	Mean	Std	50%	90%	99%
EKF-STR/REF	3.912	3.246	3.155	7.826	15.918
GPS-STR/REF	4.534	5.289	3.896	9.22	26.882
EKF/REF	10.246	12.484	6.391	20.664	74.428
GPS/REF	8.595	7.292	6.58	18.871	31.72

EKF-STR/REF GPS-STR/REF EKF/REF GPS/REF

FIG. 13. TRAJECTORY 2: STATISTICAL ANALYSIS OF THE ERROR ACCORDING TO THE REF

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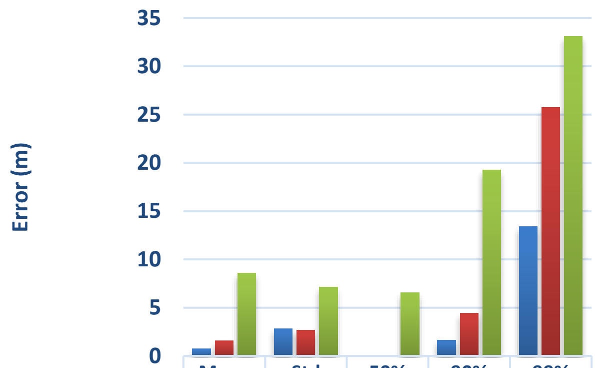

	Mean	Std	50%	90%	99%
EKF-STR/REF-STR	0.754	2.854	0.006	1.625	13.382
GPS-STR/REF-STR	1.585	2.691	0.013	4.428	25.721
GPS/REF-STR	8.565	7.158	6.538	19.261	33.097

FIG. 14. TRAJECTORY 2: STATISTICAL ANALYSIS OF THE ERROR ACCORDING TO THE REF- STR

In addition, this Figure shows that the maximum error decreases to 15.91 m when using the EKF-STR compared to the other methods (GPS-STR, EKF, GPS).

Figure 14 details the statistical analysis of the results obtain in the Figure 12. The same performances are obtained when using the REF-STR as a reference to compute the absolute error. In fact, 90 % these errors are less than 1.6 m when using our proposed approach EKF-STR, while it reaches 4.42 m and 19.26 m when applying the STR to the GPS data and using the GPS data respectively. This approves that the proposed method EKF-STR is more performant than the other ones.

VI. CONCLUSION AND FUTURE WORK

This paper has proposed a new method for loosely coupled GPS/INS integration. It uses the STR technique in order to improve the navigation solution in terms of position, especially in case of GPS outages. Two different real test trajectory are performed to validate the proposed method. The obtained results have shown the robustness and the efficiency in harsh environment that is characterises by GPS weak signal and outage. 90 % of obtained errors were less than 8.3 m and 7.82 m in the first and second trajectories respectively.

Our future work consists in improving the navigation solution in terms of errors and investigating the drawbacks of the STR technique by calibrating the Google's road map.

VII. ACKNOWLEDGMENT

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