On the Usefulness of Accelerometric Data for Applications in the Transport Sector

A Renault 4L in the Moroccan Desert

François Saulgeot & Alban de Guillebon

Table of Contents

1 Introduction **2**

2 Presentation of the Measurements and Primary Analysis **2**

2.1 Presentation of the Measurements . . . 2

2.1.1 Measurement Equipment . . . 2

2.1.2 General Description of the Collected Data . . . 3

2.1.3 Methodology Employed . . . 3

2.2 Trajectory and Orientation . . . 3

2.2.1 Methods for Reconstructing the Vehicle's Trajectory . . . 3

2.2.2 Case study of one trajectory in particular . . . 4

2.2.3 Precision and relevance of accelerometric measurements applied to the calculation of the vehicle's trajectory . . . 5

2.2.4 Automatic evaluation of the road quality . . . 6

3 Complementary analysis of the behavior of the car **6**

3.1 Characterization of the damping of the vehicle . . . 6

3.1.1 Frequency analysis of the damping . . . 6

3.1.2 Application to diagnostics and quality control . . . 6

3.2 Application of accelerometric measurements to transportation . . . 6

3.2.1 Alternative solution for vehicle orientation and industrial scale deployment . . . 6

3.2.2 Automation of speed in response to terrain . . . 7

4 Conclusion **8**

1 Introduction

The humanitarian rally "4L Trophy", now well-known to lovers of old cars and solidarity-based races, provided, during its 2025 edition, an ideal opportunity for us to carry out a physical study of our car's behavior across different terrains. Aboard our Renault 4L GTL model, we traveled along roads, tracks, trails, and dunes through the countryside and desert of western Morocco, pushing this humble, unassuming car to its limits. Thanks to *Isitix*, one of our main sponsors, we were able to equip our vehicle with accelerometers, whose data were recorded along different segments.

This entire dataset is what we sought to analyze throughout this study, to understand, analyze, and interpret the car's various behaviors during driving situations.

Accelerometers provide a set of raw data which must first be sorted and classified by relevance. A first step is then to reconstruct, from the accelerometric data, the vehicle's trajectory, and thus its orientation over time. A more detailed study of the frequency spectrum of the vehicle's different accelerometric oscillations finally allowed us to analyze the behavior of the shock absorbers, their response depending on the terrain over which the car was moving, and the possible optimization solutions that can be considered.

A final task was carried out at the end of this study to catalog, in a non-exhaustive manner, the different possible applications of recording accelerometric data on vehicles and to discuss their feasibility in the industrial market.

2 Presentation of the Measurements and Primary Analysis

2.1 Presentation of the Measurements

2.1.1 Measurement Equipment

To collect as complete a set of measurements as possible, *Isitix* provided us with two similar accelerometers: one operating via Bluetooth connection to a phone, and the other recording data onto an SD card.

Figure 2: *9-axis Accelerometer WT901SDCL (MPU9250, Kalman)* – WIT MOTION

Specifications	Values
Available outputs	Acceleration, angular velocity, magnetic field, angles (roll/pitch/yaw), quaternions
Measurement ranges	Acc: ±16 g; Gyro: ±2000°/s; Mag: ±2 G
Angular accuracy	0.05° (static XY), 0.1° dynamic
Typical resolution	Acc: 0.0005 g/LSB; Gyro: 0.061°/s/LSB; Angles: 0.0055°/LSB
RMS noise	Acc: 1 mg; Gyro: 0.03°/s
Battery life	6 hours (200 mAh battery)
Operating temperature	–40 to +85°C
Dimensions	80×30 mm; weight: 50g

Table 1: Main specifications of the WT901SDCL accelerometer used for the measurements

We mounted these two accelerometers at the rear of the vehicle's trunk, as far from the metal walls as possible, almost vertically aligned with the rear suspension. However, as we will see later, it is possible that the vehicle's large metal frame, along with the close placement of the two measurement instruments, may have interfered with some of the gyroscopic data. In any case, the accelerometric data remain reliable, as they are not dependent on the magnetic field.

It is also important to remember that the behavior of the shock absorbers and the vehicle's movements are necessarily different between the front and rear. Here, we specifically analyze the rear of the vehicle, where the load was heaviest.

An interesting initiative could have been to place an accelerometer near the front suspension to compare measurements and behavioral differences between the front and rear. In our case, this seemed too complex to implement, so we limited ourselves to rear suspension data only.

2.1.2 General Description of the Collected Data

The accelerometers used in our onboard system measure a complete set of physical data essential to analyzing the vehicle's motion. Specifically, they record linear acceleration, angular velocity, angular position, and the magnetic field—each along the three spatial axes (X, Y, Z). Additionally, these sensors also provide quaternions[1], which, although not used in our current analyses, provide an interesting basis for future modeling of more complex spatial orientations.

All of this data is collected with a precision of at least one hundredth of the typical unit of variation of the measured quantities. This ensures sufficient sensitivity to detect even subtle variations in vehicle behavior—such as trajectory changes or jolts caused by terrain, especially on rough tracks. With a sampling rate of around 10,000 points per ten-minute journey (10 Hz), we obtain a data density that enables precise, continuous reconstruction of the vehicle's path. This level of detail not only allows for reliable interpretation of driving phases (acceleration, deceleration, turns, stability), but also strikes a good balance between precision and manageable data volume. This approach thus provides robust results while keeping computational costs reasonable—crucial for real-world integration or use in resource-constrained embedded systems.

2.1.3 Methodology Employed

Data was recorded in intervals averaging about ten minutes, covering representative travel segments across a wide variety of terrains: desert tracks, paved roads, dried riverbeds, etc. This diversity of surfaces allows us to evaluate the vehicle's dynamic behavior under contrasting conditions, each involving different mechanical responses.

The data acquisition frequency, adjustable via the mobile app interface paired with the accelerometer, was set to 10 Hz for all recordings. This frequency — midway between precision and efficiency — proved optimal for accurately capturing the characteristic chassis oscillations and broader vehicle movements, while effectively filtering out parasitic vibrations caused by tire contact with the ground, often considered background noise not relevant to the macroscopic analysis of road behavior. At this frequency, each second of driving yields ten complete samples, which ensures sufficient temporal resolution to monitor dynamic transitions (acceleration, braking, shocks, inclines) without unnecessarily overloading the dataset.

This configuration thus allows for fine yet rational tracking of the vehicle's kinematics in line with our analysis goals and the constraints of embedded processing or storage systems.

2.2 Trajectory and Orientation

2.2.1 Methods for Reconstructing the Vehicle's Trajectory

Several methods were explored to reconstruct the vehicle's trajectory from raw inertial sensor data. Two main approaches were tested:

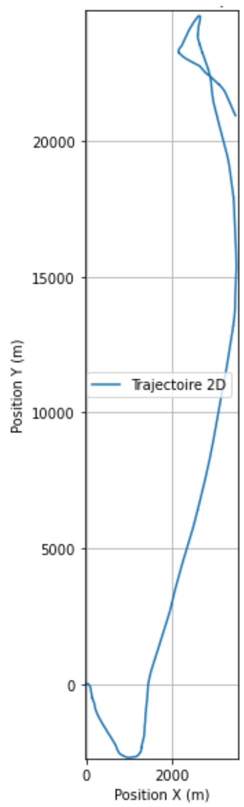
- **Accelerometric:** The first approach involves double integration of the acceleration data to directly estimate the position in space over time. This method, although demanding in terms of input data quality, has the advantage of working directly from the most fundamental acceleration data.
- **Gyroscopic:** The second, more hybrid, approach consists of performing a single integration of acceleration to obtain instantaneous velocity, then combining this with gyroscopic data. The latter provides orientation change information, allowing dynamic reorientation of the velocity vector and thus progressive reconstruction of the trajectory by adjusting the travel direction based on the vehicle's rotations.

However, due to the experimental setup of the accelerometers—positioned at the rear of the vehicle—they were located too close to the metal elements of the tailgate structure, such as steel reinforcements. This proximity, difficult to avoid

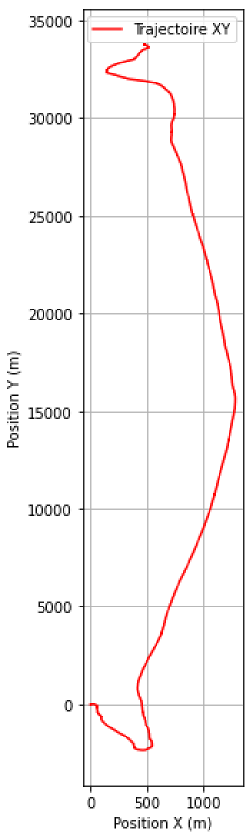
[1] In computer graphics applications, quaternions are used to represent rotations in three dimensions. They offer key advantages over the traditional method of defining rotational transformations using Euler angles. [2]

in an old car like the Renault 4L — where spaces more than 20 cm away from any metal component are rare — unfortunately introduced significant interference in the magnetic field measurements. These electromagnetic interferences compromised the quality of the magnetometer data, which in turn impacted the accuracy of derived gyroscopic measurements, especially those used to reconstruct the vehicle's angular orientation dynamically, as shown in Figure 3a.

When compared with the path generated by double integration in Figure 3b, we see that the hybrid method's reconstructed trajectory features an intersection—which we did not actually make in real life. Furthermore, a slight drift can be observed: the trajectory stretches slightly more in the X-direction and slightly less in the Y-direction, likely due to compass drift caused by proximity to metallic components.



(a) Trajectory reconstructed using the hybrid method (velocity + angles)



(b) Trajectory reconstructed using the double integration method

Figure 3: Two distinct methods for retracing the overall track-road-track path

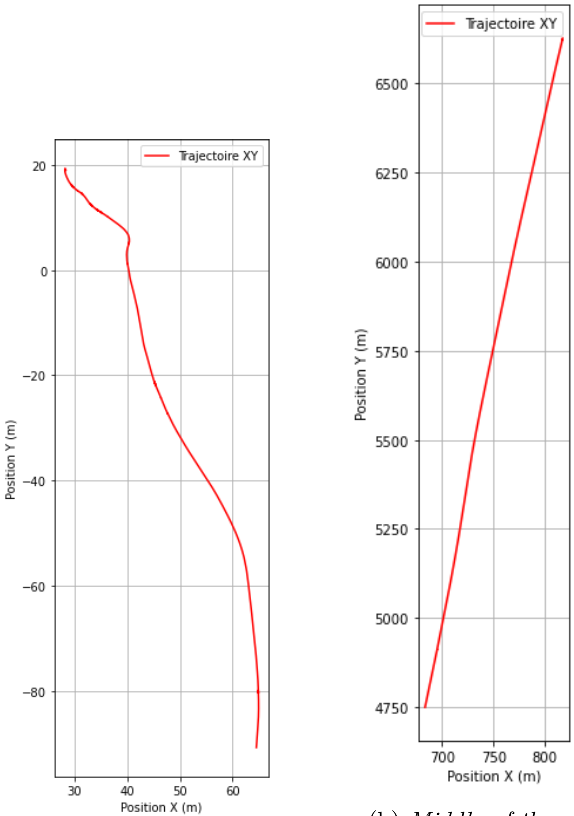
This alteration of the inertial sensor data has made it difficult to exploit the hybrid method described in section 2.2.1, which relies on a combination of the speed coming from the integration of the accelerations and of the gyroscopic data to correctly orient the trajectory. In theory, this method presents a potential superior to the double integration of the acceleration alone, insofar as it would allow one to free oneself from the errors accumulated during the second integration, particularly sensitive to the drift and to the noise of measurement. It would also allow for better modeling of the turns and changes of heading, frequent on the winding and varied routes of the 4L Trophy, like the dune crossings, the sharp turns on track, or the improvised detours in wadis.

Despite these advantages, the real experimental conditions, imposed by the configuration of the vehicle, have led us to discard this approach in favor of the method by double integration of the acceleration, more stable in our specific context. It is nevertheless appropriate to emphasize that, in a better controlled framework — for example with an optimized installation away from the sources of magnetic disturbance — the method based on the joint exploitation of the speeds and of the gyroscopic data could not only become usable, but also surpass in precision the results obtained in this study.

2.2.2 Case study of one trajectory in particular

Let us now focus on the results obtained from our method of analysis, applied to a representative trajectory recorded in real conditions. This specific trip presents the interest of covering different types of terrain — beginning and ending on desert track, intermediate segment on road — which makes it a good example to evaluate the performances of the vehicle in varied driving contexts. It indeed allows us to observe the dynamic behavior of the car at different speeds, on surfaces with contrasted mechanical properties (grip, roughness, stability), and according to trajectory profiles ranging from regular straight to winding and uneven routes.

The curve presented in Figure 3b illustrates the trajectory reconstructed from the double integration of the acceleration data. One can clearly distinguish there the different phases of the trip: the portions on track are characterized by an oscillating trajectory, with marked irregularities due to the unevenness of the terrain, whereas the central portion on road results in a much more fluid and regular path. These observations are detailed in Figures 4a and 4b, which respectively zoom on the track and road segments.



(a) *Start of the trajectory (driving on track)*

(b) *Middle of the trajectory (driving on road)*

Figure 4: Trajectories compared in driving on track and on road

In complement, Figure 5 presents the evolution of the global speed of the vehicle throughout the route, calculated as:

$$v = \sqrt{v_X^2 + v_Y^2}$$

This graph highlights a clear difference between the regimes of speed observed according to the type of terrain. On track, the speeds remain relatively low and fluctuating, with an average of around 4 $m.s^{-1}$, reflecting a careful driving adapted to the irregularities of the ground. On the other hand, on road, the speeds reach peaks going up to 26 $m.s^{-1}$, sign of a more stable and fast driving, made possible by a better quality of surface and a more rectilinear trajectory.

2.2.3 Precision and relevance of accelerometric measurements applied to the calculation of the vehicle's trajectory

A first limit identified in our study concerns the sampling frequency chosen. Although a recording at 10 Hz allows to effectively capture the global movements of the vehicle, including the jolts induced by the irregularities of the terrain (bumps, track deformations, avoidance maneuvers), **this frequency remains insufficient to grasp the very brief transient events, like localized shocks or high-frequency vibrations caused by the rolling of the tires on rough surfaces (corrugated iron for example)**.

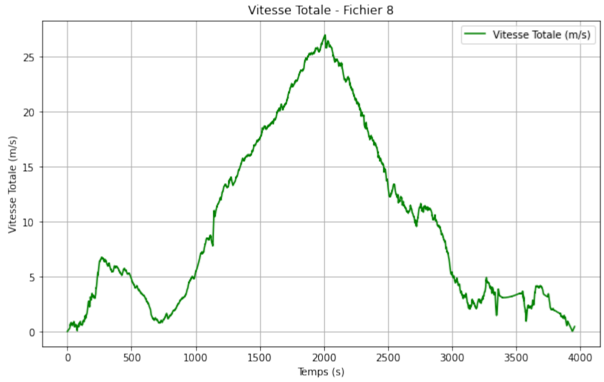


Figure 5: Global speed

This lack of temporal resolution can lead to an overestimation of certain high-frequency dynamic phenomena: indeed, a rapid variation of the acceleration — for example during a brief shock where the acceleration vector changes sign almost instantaneously — risks being recorded with the same weight as a more lasting acceleration, and not changing sign — for example during a turn — thus introducing a potential bias in the integration calculations.

The second limit lies in the method used for the reconstruction of the trajectory. Lacking usable gyroscopic data — disturbed by the magnetic interferences linked to the surrounding metallic structure — we were forced to resort to a method based only on the double integration of the acceleration data. Now, this approach, although simple in principle, is known for being particularly sensitive to measurement noise, and thus subject to important cumulative drifts, especially on long series containing several thousands of points. The greater the observation duration, the more these errors propagate, potentially leading to a significant deviation compared to the real trajectory.

If one envisages, in a perspective of improvement, an increase in the sampling frequency — and thus an increase in the number of points — it will then become relevant to favor a hybrid method combining the acceleration measurements with a reliable estimation of the orientation of the vehicle (from gyroscopic data or from quaternions). This type of method, by integrating both the linear and angular dynamics, allows to limit the integration errors and to improve consequently the fidelity of the reconstructed trajectory in a significant way.

Despite these limitations, the results obtained within the framework of this first experimental approach remain quite encouraging. They demonstrate the feasibility of an inertial trajectory tracking from a minimalist onboard instrumentation, even in a constrained context like that of an old vehicle. They thus open promising perspectives for more precise analyses, provided that the sensor installation is optimized (by distancing it from the disturbing metallic structures) and that the methodological choices are re-evaluated according to the future experimental conditions.

2.2.4 Automatic evaluation of the road quality

The results obtained previously clearly show that the data from the embedded accelerometers can be exploited not only to reconstruct the trajectory of the vehicle, but also to identify in an automatic way the type of surface taken as well as the state of the road. Indeed, the differences of dynamic behavior between driving on track and on road — notably in terms of regularity of the trajectory, amplitude of oscillations and regime of speed — are sufficiently marked to allow a reliable classification from simple physical criteria. The improvement of the sampling frequency, in particular, would allow to capture with more finesse the micro-variations characteristic of certain surfaces (potholes, gravel, undulations), thus opening the way to a finer detection of the state of the pavement.

3 Complementary analysis of the behavior of the car

3.1 Characterization of the damping of the vehicle

3.1.1 Frequency analysis of the damping

By applying a Fourier transform to the collected acceleration data (Figure 6), it becomes possible to identify certain characteristic frequencies of the dynamic behavior of the vehicle.

These frequency components correspond to recurrent vibratory modes, which reflect the way in which the structure of the vehicle reacts to the mechanical solicitations induced by the terrain. In the case of our Renault 4L, the spectral analysis — although affected by significant noise, largely due to the non-periodic nature of the signal — has nevertheless revealed a visible peak around 1.2 Hz. This resonance frequency corresponds to a proper oscillation mode of the chassis, linked to the flexibility of the suspension of the vehicle.

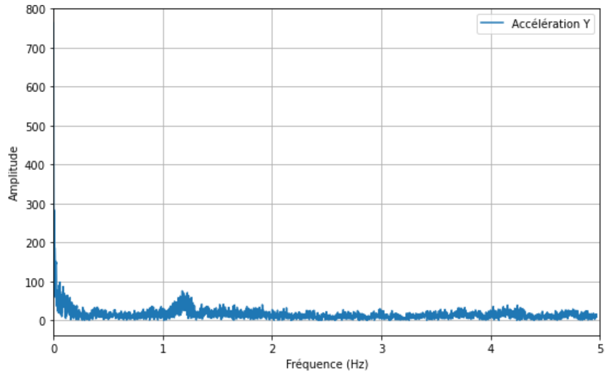


Figure 6: *Fourier analysis of the car's acceleration*

Such a study of the car proves particularly interesting from the point of view of the optimization of driving conditions, notably in the adjustment of the response of the shock absorbers according to the typical oscillation frequencies of the road surface. Driving on a road whose oscillation frequency is close to the resonance frequency of the car's shock absorbers will favor large amplitude movements. *Conversely*, adapting the resonance frequency of the vehicle's shock absorbers to ensure that it does not couple with that of the road will optimize the reduction of vertical movement of the car.

3.1.2 Application to diagnostics and quality control

This phenomenon, although little perceptible in modern vehicles — whose suspension systems are more rigid, damped, and technologically advanced — remains typical of older cars. On this type of vehicle, the slightest irregularity of the terrain causes a relatively slow and regular oscillation of the chassis, easily identifiable by spectral analysis. This result not only confirms the sensitivity of the sensor and the quality of the recorded measurements but also suggests that frequency analysis could be used as a diagnostic tool or for fine characterization of the dynamic properties of a vehicle, particularly in a perspective of comparison between models or evaluation of the wear state of suspension components.

3.2 Application of accelerometric measurements to transportation

3.2.1 Alternative solution for vehicle orientation and industrial scale deployment

Subject to an improvement of the immediate environment of the sensor — notably by distancing it from any metallic structure likely to disturb the measurements — the inertial measurement system tested in this study could be considered for large-scale deployment. It constitutes an alternative, even complementary, solution to conventional geolocation systems, particularly in environments where the GPS signal is degraded or absent, such as tunnels, underground parking lots, or certain dense urban areas subject to the canyon effect. In some cases, it could even fully replace GPS, notably for applications where miniaturization, discretion, and low power consumption are essential: autonomous vehicles, drones, ground robots, or embedded devices in military or industrial systems (this is typically the kind of system that operates the orientation of the French army's Leclerc tank, the American aircraft carrier Nimitz, or the F-35 Lightning II).

This approach is particularly interesting in lightweight embedded systems, where weight and volume constraints limit energy capacity. The use of low-energy inertial sensors, such as accelerometers and gyroscopes, would reduce dependence on GPS modules, which are often more energy-consuming. Moreover, in sensitive contexts such as defense, autonomous inertial navigation offers the advantage of not relying on external communications, thus meeting requirements of security, confidentiality, and operational resilience. The encouraging results obtained, although from a modest experimental setup, thus suggest that well-calibrated inertial integration methods can form the basis of robust, compact navigation solutions adapted to a wide range of environments and operational constraints.

3.2.2 Automation of speed in response to terrain

As highlighted in section 2.2.4, measurements from accelerometers allow automatic detection of the type of road taken, or even assessment of its overall condition. These automatic detection features have concrete interest in several application areas.

On the one hand, they can be integrated into driver assistance or autonomous or semi-autonomous driving systems. For example, an intelligent cruise controller could adapt its strategy depending on the detected surface type: preventive speed reduction on rough terrain, or optimization of driving comfort by dynamically adjusting suspension parameters. On the other hand, information extracted from measurements can feed quality monitoring systems, both for road infrastructure and the vehicle itself. In this sense, automated mapping of highly degraded zones could be envisaged, facilitating preventive maintenance of the road network.

Furthermore, by cross-analyzing long-term driving data, it becomes possible to detect certain weak signals announcing mechanical failures: abnormal vibrations, asymmetric chassis behavior, or unusual dynamic responses can reveal premature wear of suspension elements or structural imbalances. This approach thus opens the way to predictive maintenance based on real usage data of the vehicle, contributing to improving both safety, performance, and durability of the entire rolling system.

4 Conclusion

This study, conducted within the framework of the 4L Trophy aboard a Renault 4L equipped with inertial sensors, has demonstrated the concrete interest of accelerometric data for the analysis of the dynamic behavior of a vehicle in varied environments. Despite the constraints inherent to a rudimentary experimental installation — notably the magnetic disturbance due to the vehicle's metallic structure and the limited sampling frequency — the results obtained proved promising on several levels.

On the one hand, the reconstruction of trajectories from acceleration data alone highlighted the capability of these sensors to track the global evolution of the vehicle depending on the terrain, with sufficient precision to distinguish different types of surfaces (road, track, etc.). On the other hand, frequency analysis allowed detection of characteristics specific to the vehicle structure, opening the way to applications in mechanical diagnostics.

Beyond these experimental observations, this study highlights interesting industrial and technological perspectives. Inertial sensors could, in the future, constitute a complementary — even alternative — solution to GPS systems, notably in environments where connectivity is limited or energy consumption must be controlled. They also present potential for intelligent automation of driving behaviors, or even predictive maintenance of vehicles.

Finally, let us recall that the data generated by such inertial systems are reasonable (only a few gigabytes over a whole year of measurement), so a commercial application at the scale of private vehicles appears quite feasible.

Thus, although this first approach is perfectible, it confirms the relevance of embedded inertial instrumentation for practical uses in the transport sector. Future improvements, notably in sensor accuracy, hybrid integration algorithms, and hardware installation optimization, could allow a new step towards autonomous, efficient, and robust navigation and control systems.

Bibliography

[1] Reference: 9-axis accelerometer WT901SDCL (MPU9250, Kalman) - WIT MOTION

[2] J.B. Kuipers. *Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace and Virtual Reality.* Princeton Univ. Press, 1999

[3] Thomas, E. W. (1972), *Space Vehicle Gyroscope Sensor Applications. NASA Special Publication SP-8096*, NASA, Washington, DC.

[4] Titterton, D. H., Weston, J. L. (2004), *Gyroscopes for Orientation and Inertial Navigation Systems. In: Strapdown Inertial Navigation Technology (2nd ed.)*, The Institution of Engineering and Technology

[5] Donley, E. A. (2012), *Advances in atomic gyroscopes: A view from inertial navigation systems*, Sensors, 12(5), 6331–6356

[6] Mohamed, A., & Schwarz, K. P. (2019), *Inertial sensors technologies for navigation applications: State of the art. IEEE Sensors Journal*, 19(15), 6797–6810

[7] Ma, W., Zhang, Y., Tang, W., et al. (2024), *Accurate integrated position and orientation method for vehicles based on strapdown inertial navigation system + Doppler radar*, Measurement, 232, 113455