X2Rail-5

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Stand Alone Fail-Safe Train Positioning

Laboratory description

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1 Executive Summary

The European Union Agency for Railways (ERA) defined different mid and longer term strategic challenges related to the ERTMS specifications roadmap in [3]. The objective was to identify the optimal balance between (a) ERTMS Specification stability on one side and (b) their evolution (enhancements and errors) and ERTMS products on the other side, while safeguarding interoperability in the most economical way. In particular, ERA states that *"The strategic challenges linked to the evolution are mainly linked to developments which support the need for* ***further capacity increase*** *and to developments that* ***decrease the overall life cycle costs*** *of the ERTMS implementations."* Furthermore, ERA has also recognized the satellite positioning as one of the main key elements of the future signalling system/concept aimed at allowing "*Potential reduction in* ***deployment*** *and* ***maintenance*** *of* ***balises*** *and* ***improved performance*** *due to* ***more accurate odometry****;"*

Previous projects focusing exclusively in GNSS, such as GSA STARS [5], have shown that the use of GNSS only is not enough neither for performance reasons nor for safety reasons. As a consequence, GNSS shall be combined with other sensors to ensure a more accurate and reliable inclusion of the technology.

In order to solve the train-positioning problem applicable to all environments, X2R2 defined a proposal in [4] with an architecture identifying the interfaces required for a fusion. In addition, the same X2R2 call also defined a preliminary laboratory-testing environment in [1] for verification and validation purposes. In this work, the objective is to extend the already developed simulation environment by inserting multiple error configurations, performance testing under a variety of sensor grades not only to corroborate the performance but also to ensure the confidence interval calculated by the algorithms under a controlled environment.

Clarification/Disclaimer: The solutions described in this document are guideline specifications for the preparation of demonstrators of a GNSS based positioning system in Shift2Rail IP2 TD 2.4, which will then be lab and field tested. The results from these tests will then be used to further refine the architecture, as well as functional and interface definitions and in making choices where options currently exist. The results will then be provided as input to the ERA Change Control Management process, where they will be transformed into an interoperable, European standard.

2 Table of Contents

3 Abbreviations and acronyms

Abbreviation / Acronyms	Description
Absolute Position	Absolute position refers to a position that defines the train location unambiguously. For instance, an absolute position can be given by WGS84 coordinates but it can also be given by a track identifier and the travelled distance within a specific track.
CMD	Cold Movement Detection
Confidence Interval	It refers to a range of values so defined that there is a specified probability that the value of a parameter lies within it.
E_ODO_TS	Enhanced ODOmetry Track Side.
E_ODO_OB	Enhanced ODOmetry On-board.
ETCS-OB	European Train Control system - On-board
FSTP	Fail Safe Train Position
TF_PVT	Train’s Front Position, Velocity and Timestamp
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
TCP	Transport Control Protocol
FTP	File Transfer Protocol
PLI	Protection Level Indicator
SUT	System Under Test
TDG	Train Data Generator
SFA	Safe Fusion Algorithm
SVL	Service Volume Simulator
RDG	Raw Data Generator
WAS	Wheel Angular Speed

4 Background

The present document constitutes the first issue of WP7's Deliverable D7.1 "Stand Alone Fail-Safe Train Positioning Laboratory description". The Deliverable is part of the framework of the Project titled "Completion of activities for Adaptable Communication, Moving Block, Fail safe Train Localisation (including satellite), Zero on site Testing, Formal Methods and Cyber Security"(Project Acronym: X2Rail-5; Grant Agreement No 101014520).

5 Objective / Aim

The objective of this document is twofold; on one hand, to document the laboratory environment extension to support errors for different sensors starting from [1] and on the other hand to evaluate the performance of the algorithm described in [6]. The analysis carried out here is expected to contribute to the background knowledge required by X2R5-WP5 when defining the final standardised solution for the Fail Safe Train Position (FSTP). Within the process, the following steps need to be completed:

- Developing a Simulation testing environment based on X2R2- WP3 deliverables.
- Enriching the simulation tool with error insertion models
- Test case definition
- Test case execution
- Test case result documentation

The activities reported in this document are focused on understanding the following two aspects

- Evaluate the performance of the algorithm to determine track discrimination
- Evaluate the performance of the algorithm with the assumption that the train knows which track it is on but not the exact position.

6 Laboratory Simulation Definition

6.1 Simulation Environment

The simulation environment is based on the following Figure 1 from [1]. Recall that the system under test is defined as the algorithms that calculate the train's position, named as SUT-SFA-CORE, whereas the grey boxes are the functional blocks that stimulate the algorithm. The simulation environment is executed with a simulated 32ms period, which currently matches with the SUT-SFA-Core execution cycle, though this could be modified if needed. Notice that the execution period of the simulation environment does not impose any contraints on the periodicity that different sensor may have. For instance, if GNSS related PVT value provides data every second, the simulation environment will provide this data every second to the SUT-SFA-Core. It is also important to note that there is a cycle difference between the ground truth and the algorithm estimated position. The reason behind this cycle difference is related to the real world. In real cases, the algorithm obtain the data at time K, it takes (at least) one cycle to compute the outcome and it outputs this outcome the world at K+1. Therefore the GT and the outcome of the algorithm are always one cycle apart. The static digital map is represented by a white database symbol and the test definition is responsible to set the configuration of each of the grey boxes how they should perform. Recall the following nomenclature:

- WAS: Wheel Angular Speed sensor
- Acc: Accelerometer
- Gyr: Gyroscope
- PVT: Position Velocity and time as given by a GNSS receiver
- Balise: Balise related data
- Train Dynamic Data: It is the active cab, train length … type of information
- CMD: Cold movement Detection information.
- Static Digital Map: Error in a static digital map.

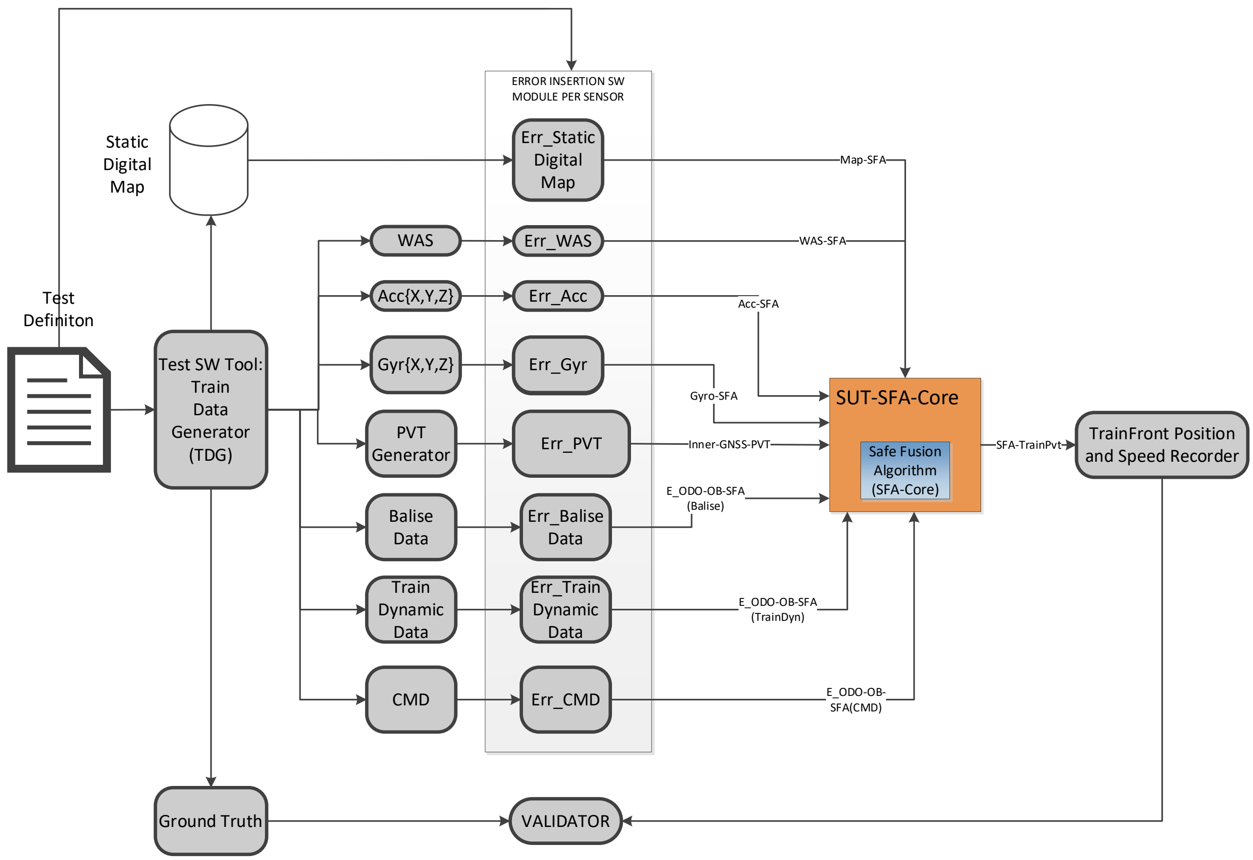

Figure 1 Testing Environment Design TEST-ENV-ALGO

6.2 Error Definitions

6.2.1 Sensor Error Definitions

The following type of errors has been designed to stimulate the algorithm.

6.2.1.1 Forced value

The testing environment allows bypassing any signal from the simulator to any value forced by the user.

6.2.1.2 Availability Flag

For each input data used by the algorithm, an availability flag is determined. This flag is used by the application before interpreting any input data. For instance, a simplification of a tunnel coverage loss can be simulated by selecting the PVT data Availability Flag to false. For PVT errors induced due to GNSS signal distorsion, see 6.2.1.6.

6.2.1.3 Gain Error

This error simulates the scale factor error in a sensor. It multiplies the simulated value of the sensor by a factor.

6.2.1.4 Offset Error

Offset error is defined by adding a concrete value to the original sensor signal. This can either be a fixed value or a percentage value of the sensor itself.

6.2.1.5 Noise Error

Noise error is defined by adding randomly sampled values with a defined standard deviation to the current signal. There is the possibility to make the noise samples dependent by adding a correlation between consecutive noise values. The noise value at instant k is generated as follows: $n_k = \alpha \cdot n_{k-1} + \sqrt{1-\alpha^2} \cdot \omega_k$, where ω_k is a white Gaussian noise with the defined standard deviation and $\alpha \in [0,1]$. The first noise value n_0 is assigned directlyω_0.

6.2.1.6 Noise Proportional Error

This error is the same as the Noise Error described in 6.2.1.5, but the standard deviation of the noise random variable added to the sensor reading is proportional to the value read by the sensor.

6.2.2 Sensor Error Types per Input

The following Table 1 represents the matrix that allows the type of error combinations allowed per input type.

	Forced Values	Availability Flag	Gain Error	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	No	Yes	Yes	Yes	Yes	Yes
Err_Acc	No	Yes	Yes	Yes	Yes	Yes
Err_Gyr	No	Yes	Yes	Yes	Yes	Yes
Err_PVT	No	Yes	No	No	Yes	Yes
Err_Balise	Yes	No	No	No	No	No
Err_Train_Dyn	Yes	Yes	No	No	No	No
Err_CMD	Yes	Yes	No	No	No	No
Err_Digital_Map	Yes	Yes	No	No	No	No

Table 1 Matrix Table with all possible error associated for each input.

Some of the errors defined within this table represent systematic faults of the developed solution. For instance, the fact that an erroneous Cab is detected from the Train Dynamic information does not focus on the objective of this document which is to stress the algorithm for obtaining an absolute position (see section 5). Consequently, the reduced list of errors managed by the following test case scenarios is described in Table 2 and therefore it is assumed there are no errors on Balise, train dynamic information, CMD information and Digital Map:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	Yes	Yes	Yes
Err_Acc	Yes	Yes	Yes
Err_Gyr	Yes	Yes	Yes
Err_PVT	No	Yes	Yes

Table 2 Matrix Table with meaningful errors associated for each input.

6.2.3 Error Types used as Inputs for tests

An analysis of the current state of the art in sensors, allows us to define the following error parameters considered as **realistic set up** for the major test samples so that the influence of each of them can be analysed. Notice, that sensor data range and the error range combination leads to a very high combination possibilities not achievable by the effort of the task. Therefore the following is a proposal for what the Authors have considered as meaningfull range of data with a meaningfull range of errors.

- Err_WAS 1% error
- Err_Acc: 0.04 m/s^2 (standard deviation) output noise
- Err_Gyr: 0.002 rad/s (standard deviation) output noise
- Err_PVT: No error

In the following subsection the appropriate argumentation for each of these values is described.

6.2.3.1 Err_Was proposal for tests

The Err_Was is configured in these tests as an offset of 1% error estimation. In the following figure, it can be seen that whenever the Err_Was is set as 1% offset error the following is obtained by the algorithm, where the estimated speed is centred at 70.7km/h which is just 1% from 70km/h. Notice that in this illustration the Err_Acc is considered as 0.04 STD which has a low impact on the speed and it explains the little noise in the speed estimation (see next section for Err_Acc) definition:

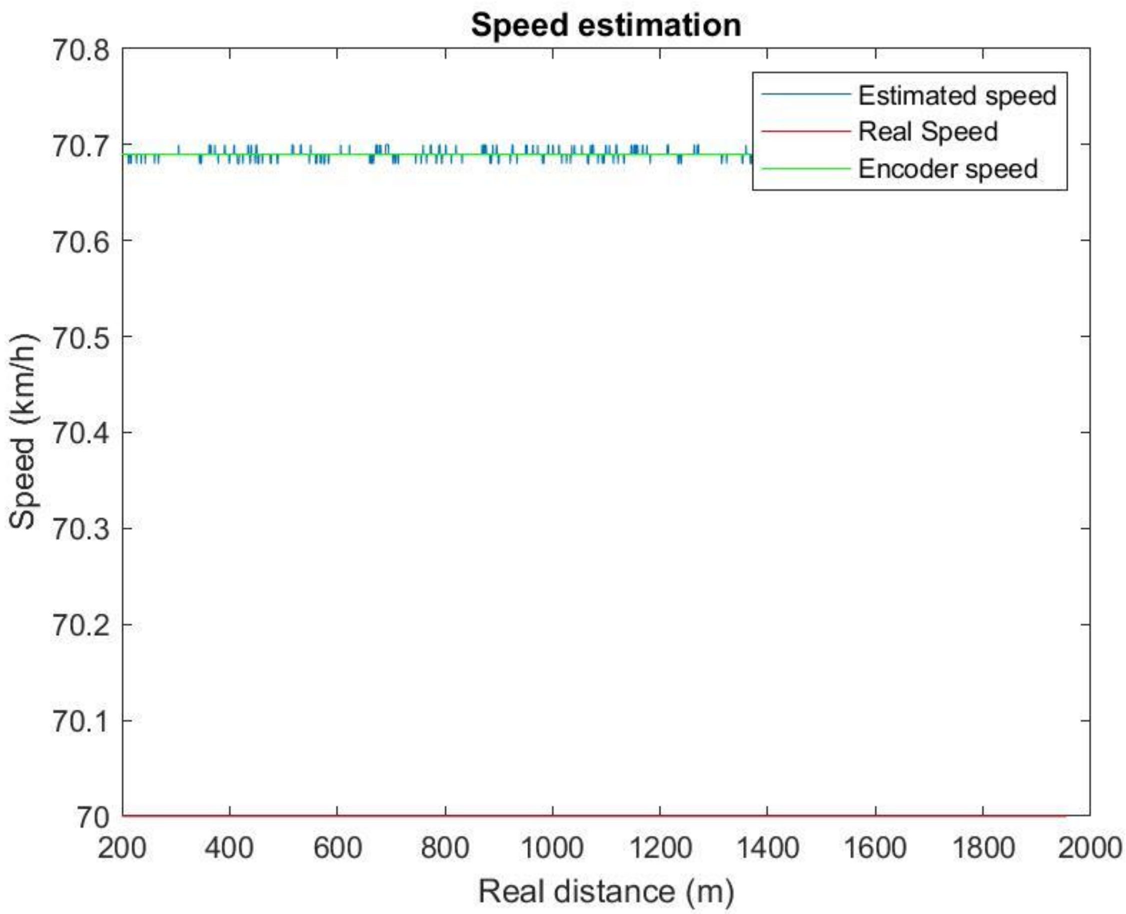

Figure 2 Encoder Speed error insertion as 1%

6.2.3.2 Err_Acc proposal for tests

The Err_Acc is configured in these tests as a Noise error of 0.04 m/s^2 with a correlation parameter $\alpha = 0$. Figure 2 is already shown the low impact of the accelerometer on the estimated speed. Nevertheless, for the sake of clarity, the following illustration shows what occurs to the speed estimation with STD = 0.4 m/s^2, which is 10 times worse than the datasheet specification of the sensor. As expected the accelerometer noise is clearer seen in the results where the noise is around +-0.1km/h. Notice that in the next figure the IMU acceleration value is used with the previous encoder speed value to calculate absolute speed. Although this may not be the final algorithm design, it is shown here to check that the Noise error configuration defined by the Err_Acc is working as expected:

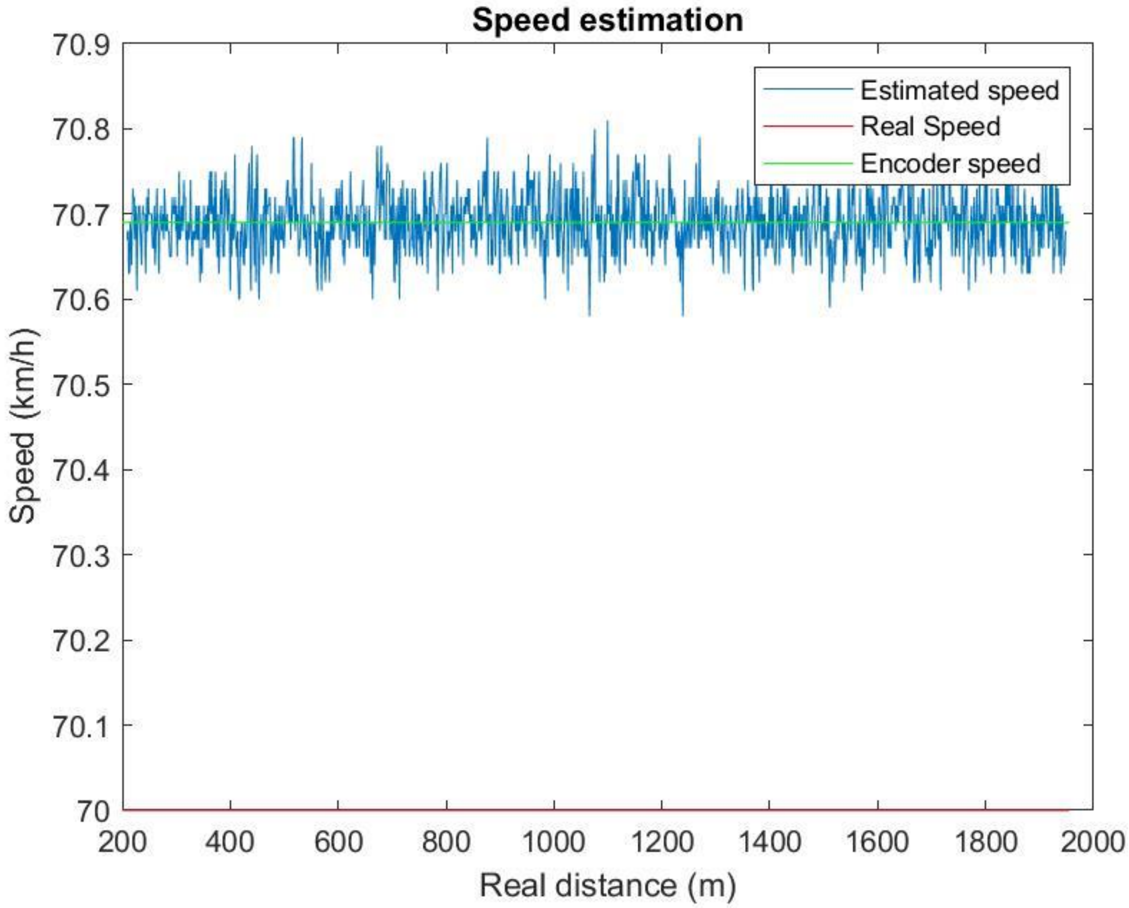

Figure 3 Speed estimation value with large Acc error

6.2.3.3 Err_Gyr proposal for tests

The Err_Gyr is configured in these tests as a Noise error of 0.002 rad/s with a correlation parameter $\alpha = 0$. In the next illustration it can be seen the performance of the vertical gyroscope against the estimated theoretical curvature of the train based on the digital map and speed values.

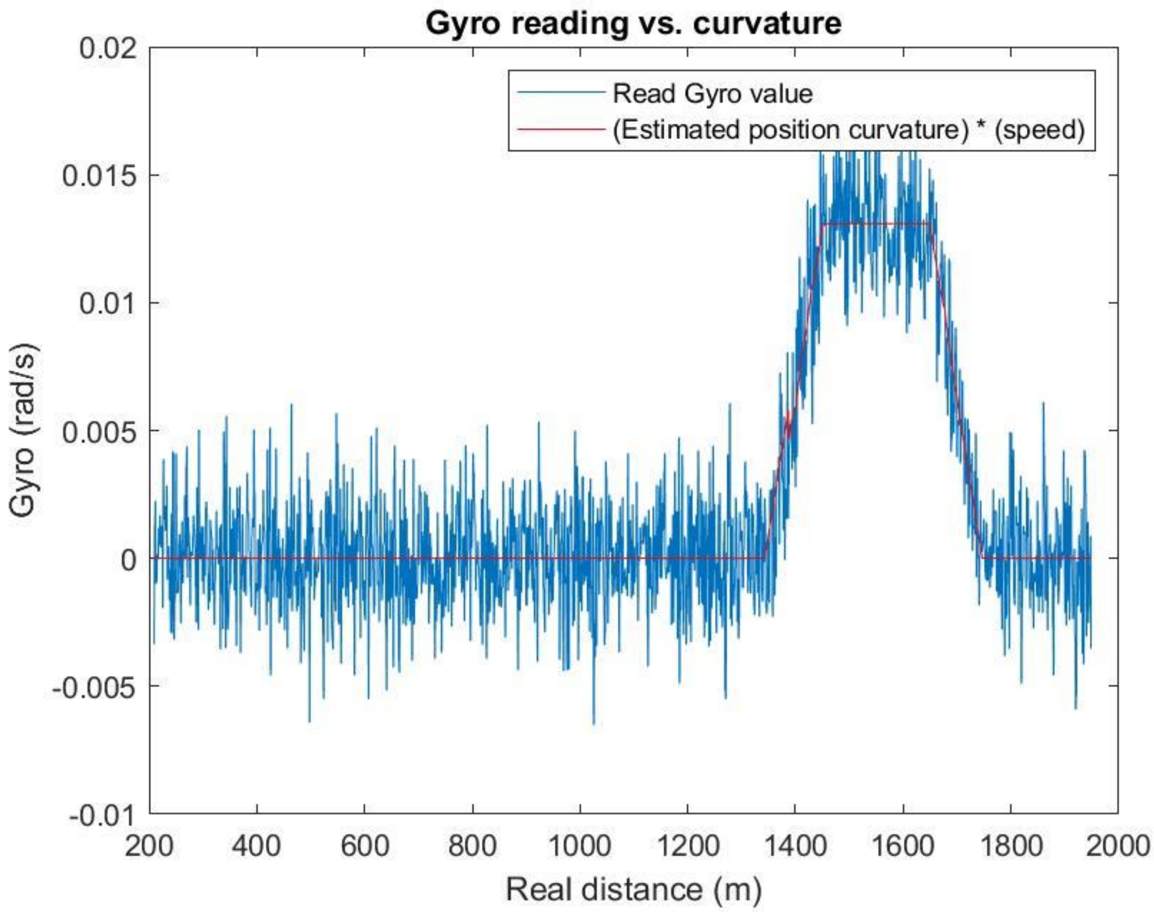

Figure 4 Gyroscope estimation based on current train position and digital map against the sensor information based on realistic values.

For the sake of clarity, it is also defined the case of defining the Err_Gyr with 10 times worse scenario that is 0.02 rad/s with a correlation parameter $\alpha = 0$. In such case, the contribution of the gyroscope to the algorithm can be tested.

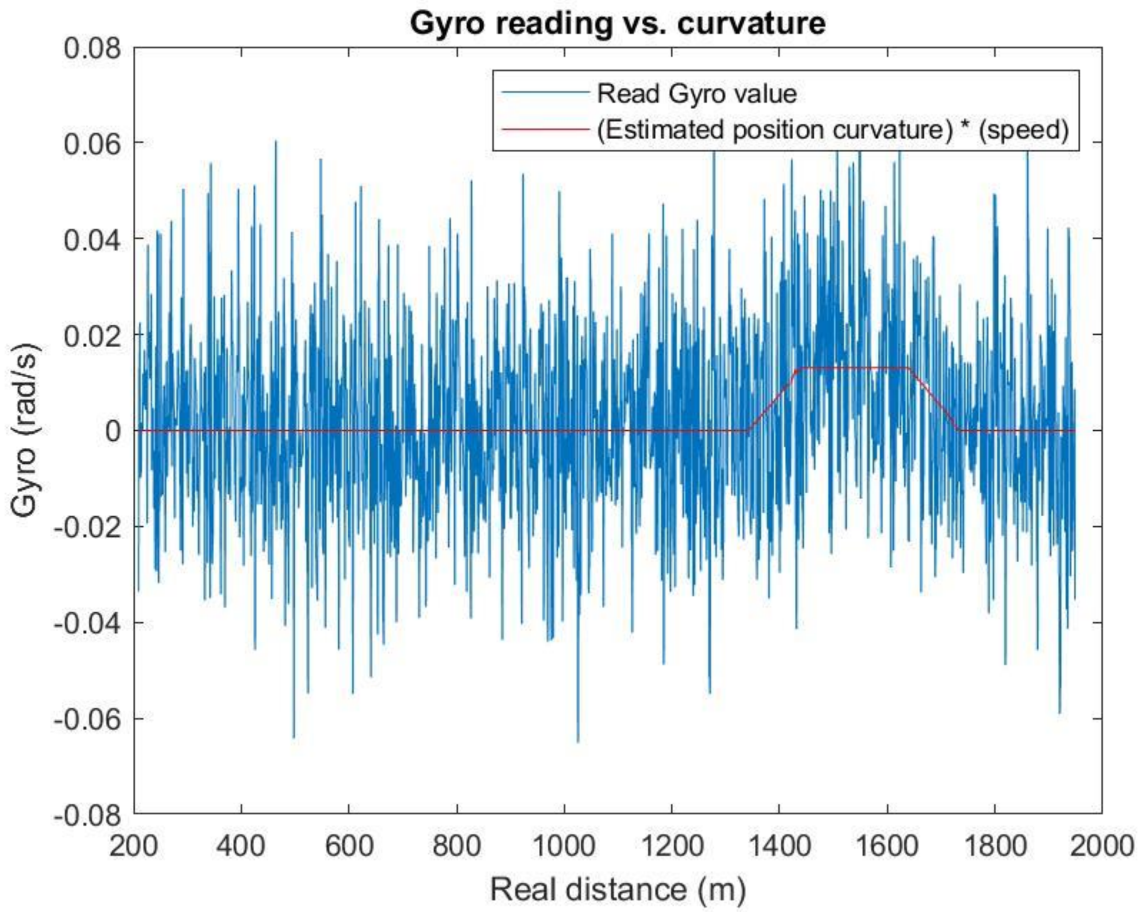

Figure 5 Gyroscope estimation based on current train position and digital map against the sensor information based on 10 times worse gyroscope values.

6.2.3.4 Err_Pvt realistic

The Err_PVT is configured for most of the tests with no errors. The reason behind this procedure is that the current algorithm does not foresee the direct usage of the PVT but it rather discriminates the searching scope of the algorithm within the map. As such, the following figure it is shown the minimum error inserted by the algorithm at the start point, where it can be seen with no PVT error the error is close to 0 meters.

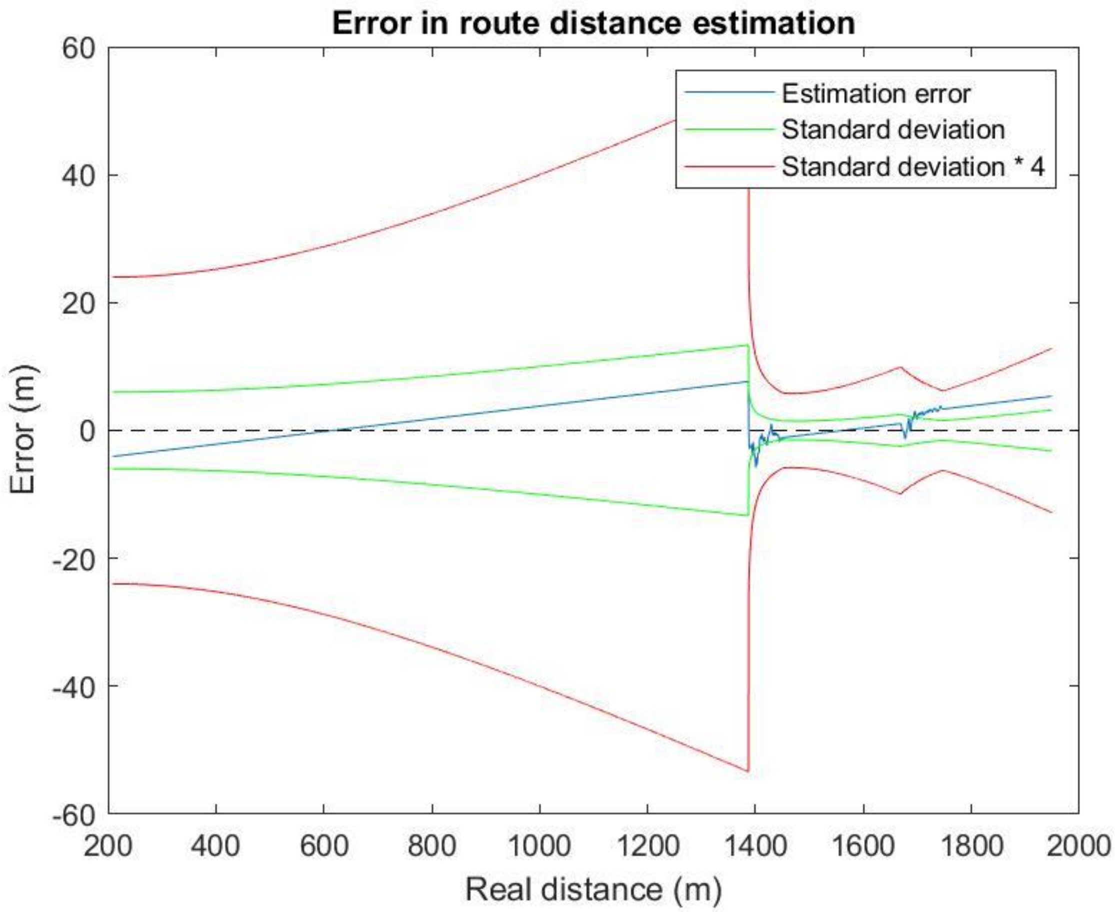

Figure 6 Err_PVT with no error input to estimation train position.

Nevertheless, in order to define the specific impact of PVT error in the algorithm specific test a dedicated test with STD 0.0003 meters and correlation value $\alpha = 0.9$ is carried out. The following illustration is a representation of such error, where the initial error of the estimator is around 90meters. The effects of such errors are analysed in the particular test.

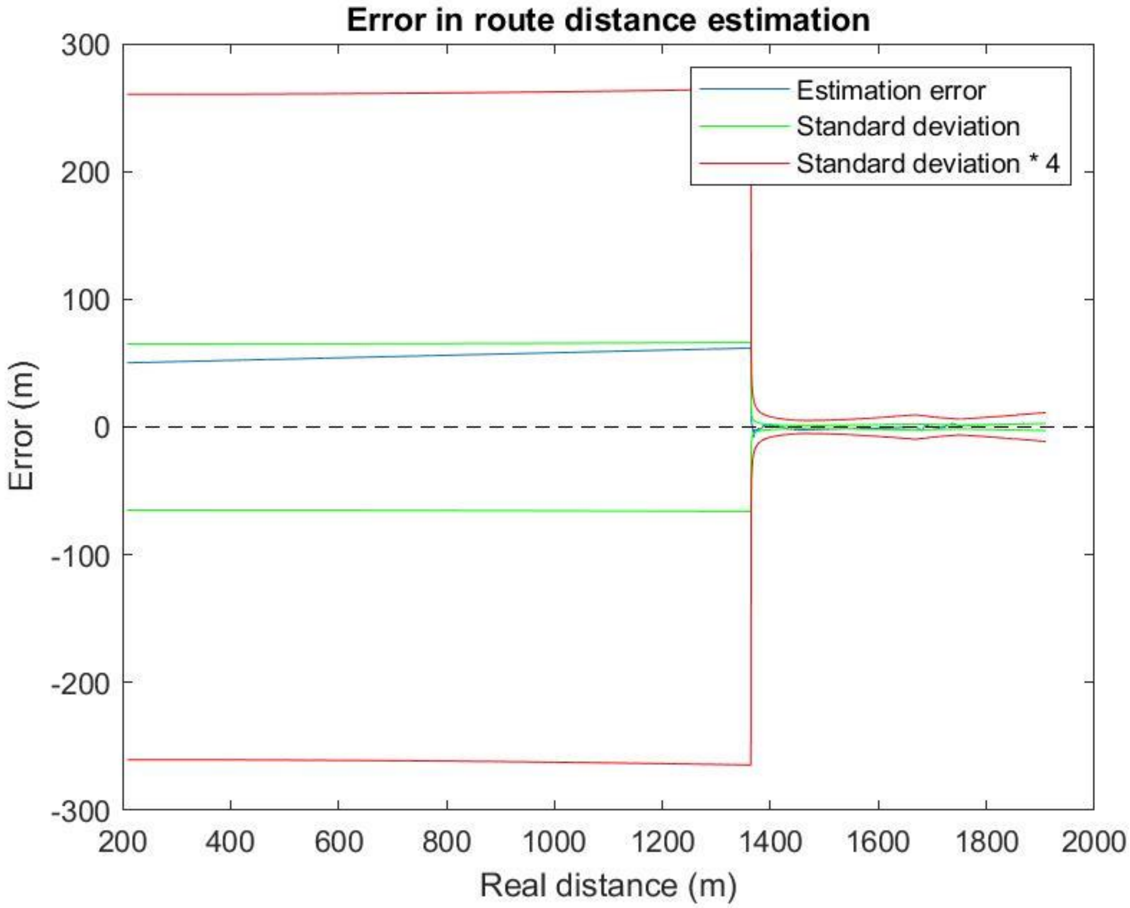

Figure 7 Err_PVT with error input to estimation train position.

6.3 Digital Map Framework for Test Scenario definition

Due to the necessity of stressing out the algorithm under specific circumstances, a synthetic digital map is created. The digital map has to contain at least the following two cases: parallel tracks with different curvatures and switch points (see Appendix A for further details).

6.3.1 Parallel track definition

A parallel track is defined in the following Figure 8, where there are two tracks. The bottom track is a straight line of two segments of 1000 meters, see Segment 1 and Segment 2.The upper track is 4 metters apart from the bottom one which means that between Segment 3 and Segment 1 there is a continuouse distance of 4 meters. The upper track after 1000 meters generates a left-hand side curve, see Segment 4. The left-hand side curve starts 200 meters after the new segment starts, i.e. 1200 meters from the start of the route, with a clothoid of 100 meters, 200 meters of a circular curve and 100 meters of clothoid to end in a straight line. Additionally, the combination of the segments define a route to be followed by the simulator, this is represented by RT1 and RT2 in this case.

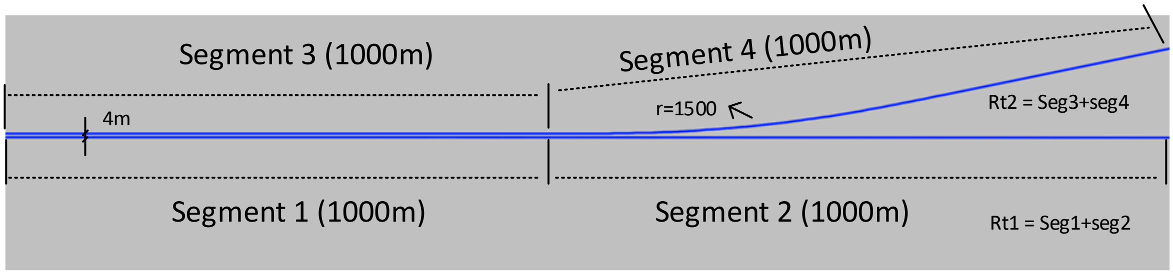

Figure 8 Parallel track representation

6.3.2 Switch Point definition

A switch point is represented by the following Figure 9, where there is a 1000 meters length segment divided into a straight-line segment and a segment that defines a curve. The left-hand side curve starts with a 100 meters clothoid followed by 200 meters of a circular curve and 100 meters clothoid of 100 meters to end in a straight line.

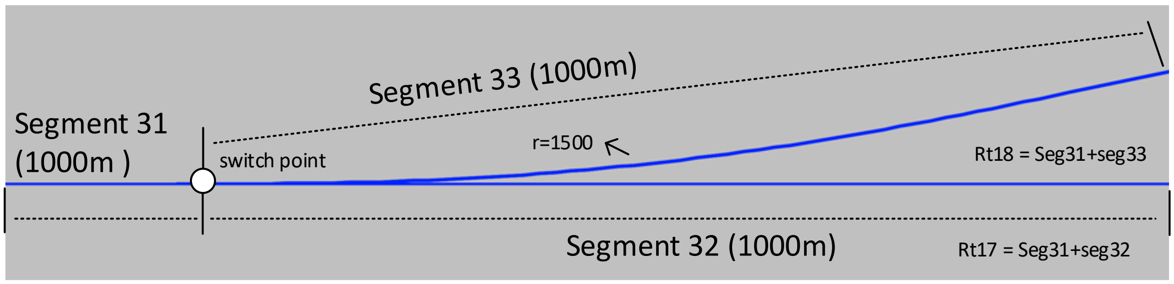

Figure 9 Switch point representation

6.3.3 Overall Map View

Based on the previously described type of case the following synthetic digital map is generated with different curvatures to allow the testing of the algorithm under various circumstances. On one hand, the upper figures are parallel tracks with 200, 750 and 1500 meters radius of curvature defined for both left and right-hand side curve types. Similarly, the switch points are illustrated at the bottom of the figure where the switch-point always has a straight line and a curve section. Additionally, each section is tagged with a number named 'Rtxx' that defines the route. For instance, route 1, labelled as Rt1, is a straight line whereas the parallel track to it with a left-hand side curve is labelled as Rt2. With the use of these routes, different case scenarios can be tested.

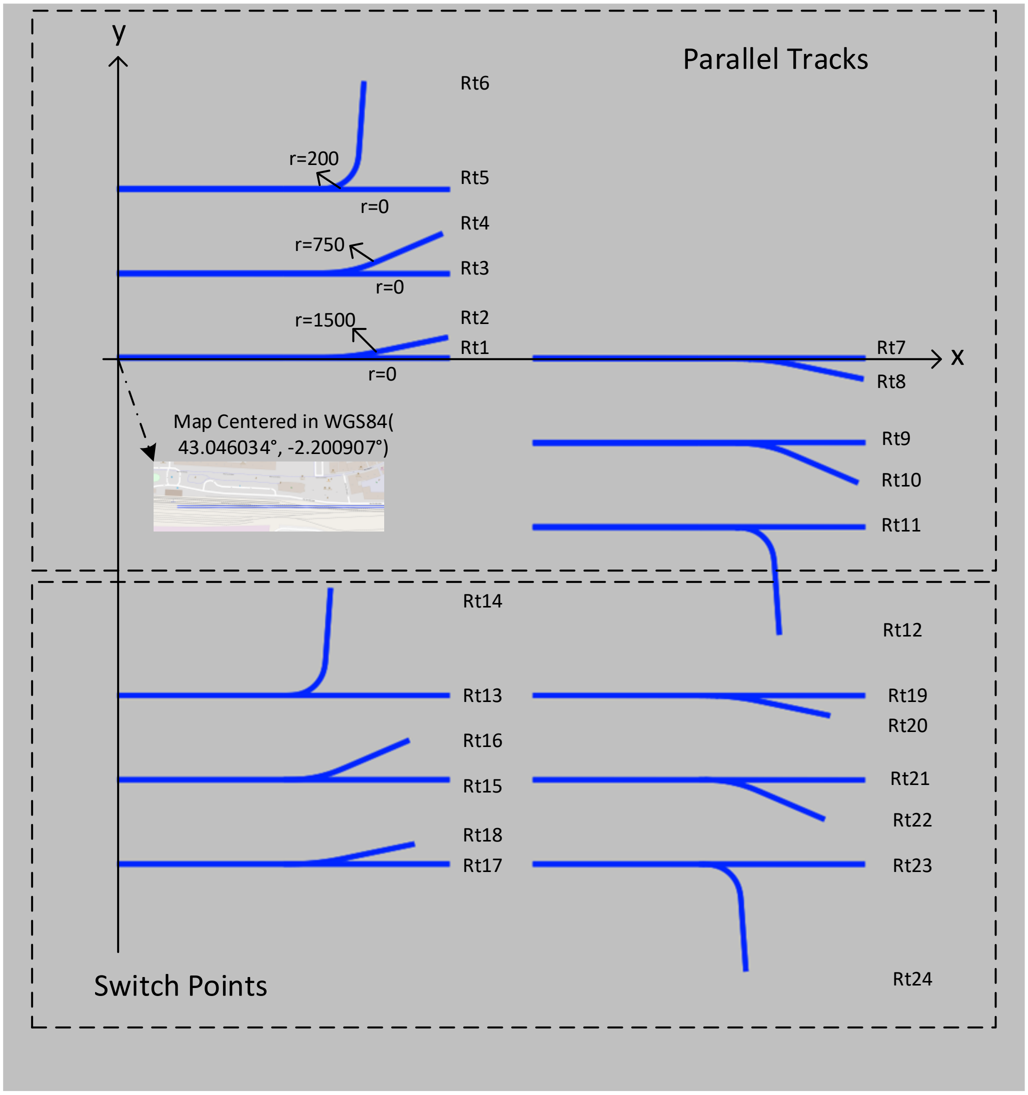

Figure 10 Synthetic digital map illustration showing all possible cases

6.4 Test Case description

For each test case, the following is defined for the simulation:

- Error type insertion: based on Table 2
- Speed profile
- Route followed (see section 6.3) which determines whether a parallel track problem or a switch point problem is tackled.
- Define whether the route position of the train is known to the test case or not

6.4.1 Test Case definition strategy

Test cases are grouped in the following strategy tree.

- Test case definition strategy tree
  - **Test labels from 1 to 100**, are defined for track discrimination purposes. In other words, that means the track is not known by the positioning algorithm in advance.
    - **Test from 1 to 20** are defined for tests dealing with parallel tracks routes (1 to 6)
    - **Test from 21 to 40** are defined for tests dealing with switch points
  - **Test labels from 100 to 200**, are defined for track positioning assuming the train is positioned on the track with different error types. Executing parallel track types further than the cases for route1 and route2 does not add any further value since there is not a switch point to be evaluated.

6.4.2 Test Case Speed profile definition

For the feasibility study of the algorithm two speed profiles are utilised in this tests. Recall from [6] that the algorithm is based on the detection of curves to resposition itself. As such, the higher the speed the easier is to detect a curve since the angular velocity read by the vertical gyroscopes is greater. For the sake of this study, two constant speed profiles are considered, 5km/h and 70km/h. That means that a test starts either at 5 or 70 km/h and finishes ate 5 or 70km/h. Although it is known that the lack of speed change is not a realistic approach it is considered the best approach to extrack clear conclusion on whether this approach is feasible or not. In the end, if with constant speed, the algorithm is not able to reposition the estimated location it will not work neither under speed changing scenarios.

6.4.3 Test Case Results presentation

In this subsection, it is described how the results of each test case are presented. The analysis is focused on determining the position of the train against the ground truth. The position of the train in 1D and it is determined as follows:

- Segment Id
- Travelled distance within the segment.

The illustrations to prove the segment Id correct or not are provided in the following Figure 11. On one hand, the graph shows 0 value if the results from the ground truth and the estimated segment id is different. On the other hand, if the segment id from the ground truth is the same the outcome in the graph is represented by a ‘1’ value. Focusing on illustration shown below, the example shows a case where the algorithm estimated position does not match with the GT until 1400 meters, which is represented by zero value and just after this 1400 meters the algorithm estimated position matches exactly with the segment id, and therefore the one value is shown in the illustration.

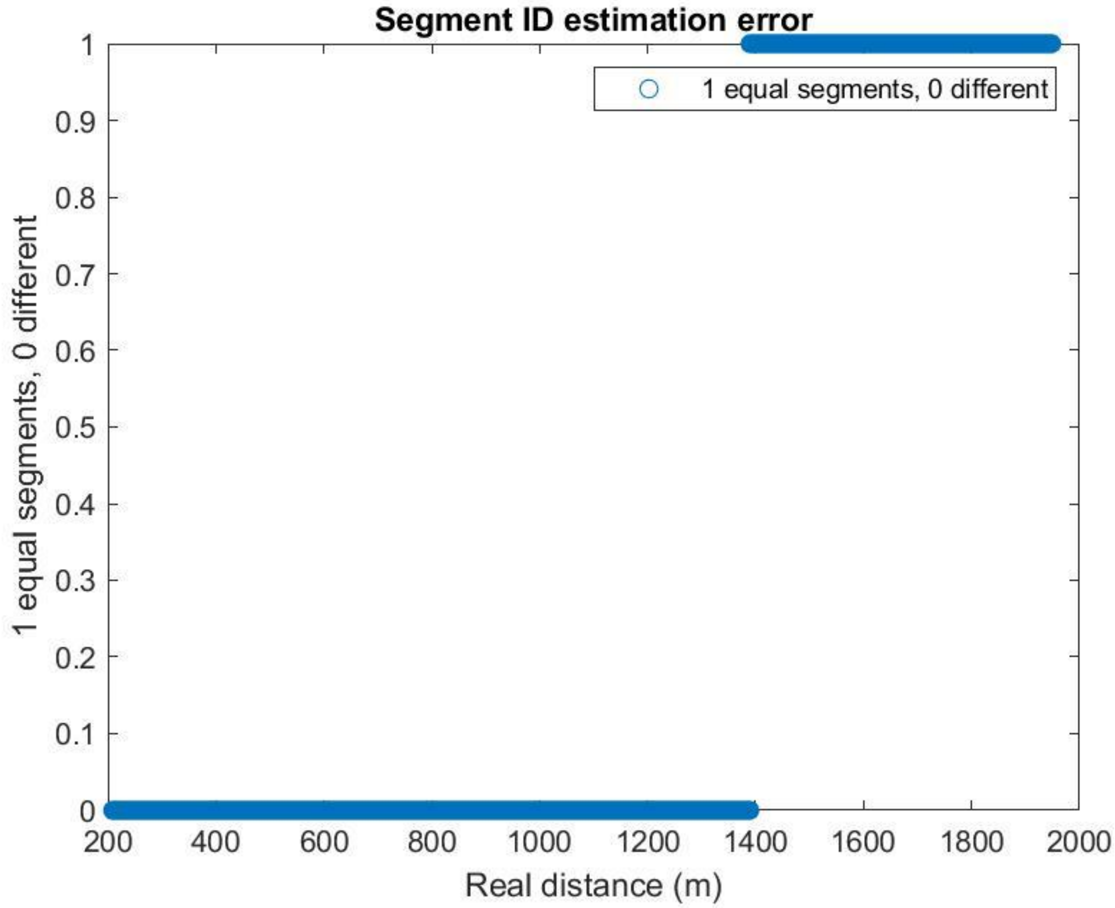

Figure 11 Segment Id representation example

With regards to the travelled distance within the segment, the error made by the algorithm is represented. In Figure 12, it is shown an example that matches the result presentation shown in Figure 11. Whenever there is not a segment Id defined by the algorithm or their segment Id is incorrect, the error representation in terms of travelled distance is represented by a zero. Once the segment id has a valid value, three main values are represented: The estimation error, the associated standard deviation and 4 times the standard deviation. The distance estimation is the difference between the ground truths estimated travelled distance against the algorithm estimated distance. To represent the protection level, four times the standard deviationis used for the test cases. Nevertheless, this protection level indicator (PLI) is a value to show case the results but it will need further study to select a final appropriate value with regards to the THR requirements of the algorithm.

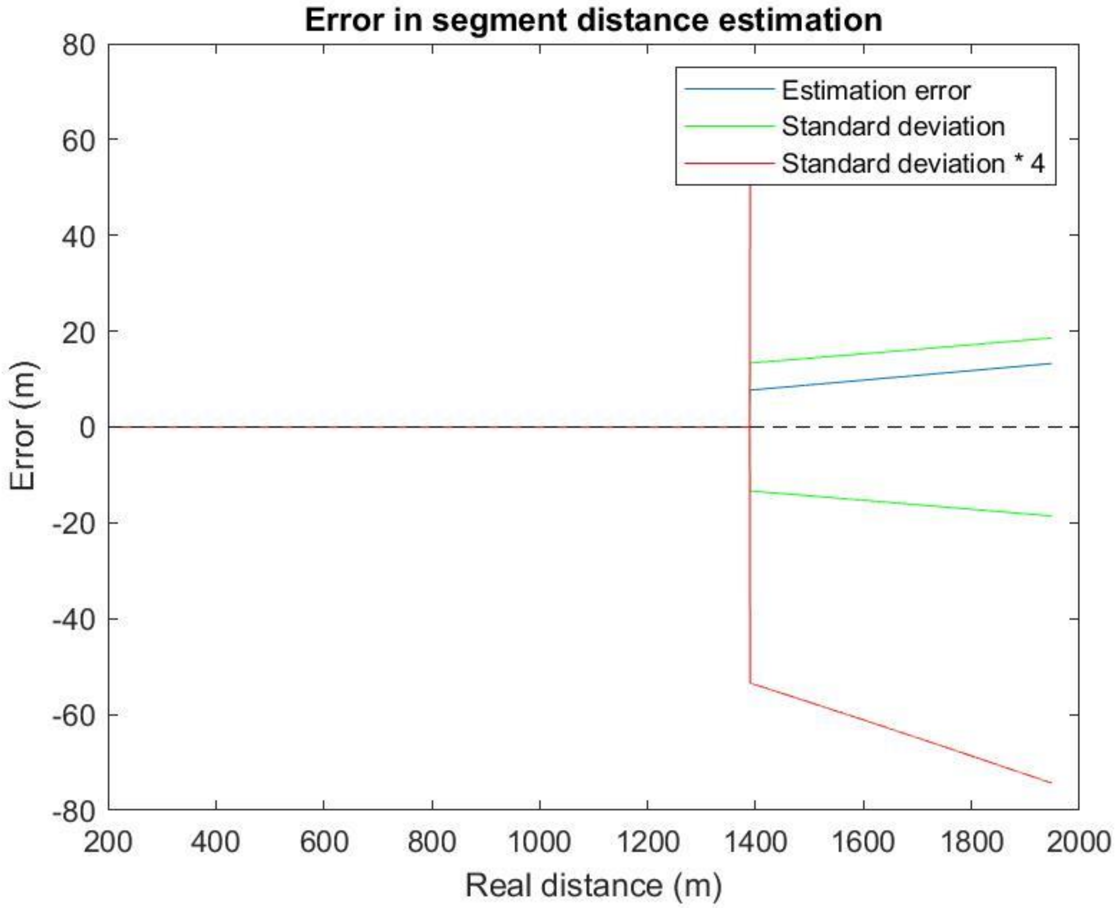

Figure 12 Segment Distance error representation

In addition, if it is known that the algorithm knows the train position from the start of the test, i.e. the segment id is correct from the start to the end, the route travelled distance can also be represented as shown in the following Figure 13. In this illustration, the terms presented as the estimated error based on the PLI definition.

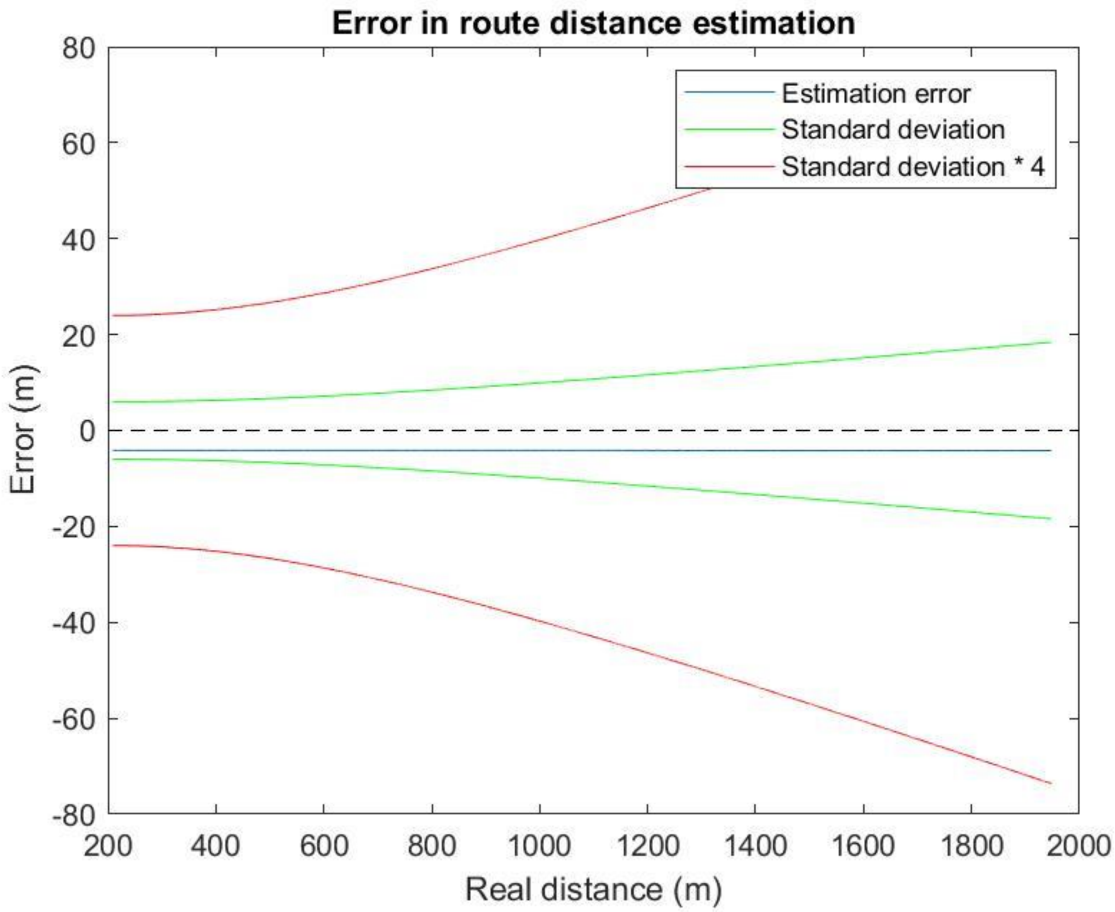

Figure 13 Route Distance error representation

Finally, notice that for some specific tests speed value is also represented, this is because the travelled distance already implies the speed error determination and because to define controlled test scenarios the speed profiles are considered constant values.

6.4.4 Test Case PASSED Criteria

Recall from [6] that the algorithm under test is based on the detection curvature point as part of the positioning system. As such, a test is considered passed if the algorithm is able to detect the curve and reposition itself in the right track. For instance, a test where the train is at an unknown position, then it moves until it crosses the curve. If the algorithm is able to detect this curve and reposition itself the test is considered as PASSED. If the algorithm is not able to reposition after the curve is passed the test is considered NOT PASSED.

7 Algorithm Under Test Overview

In this section, an overview of the algorithm described in [6] is presented. The objective is to recall the basis of the algorithm in a broad manner, without entering into details. However if the reader is interested in further understanding the algorithm it is recommended to use reference [6] for further details.

In the following Figure 14 it is illustrated the main functional blocks of the algorithm under test (SUT-SAFE-Core from Figure 1). In blue colour, the sensor inputs are shown, based on wheel speed sensors, accelerometers and gyroscopes. In addition, the GNSS position calculated based on raw GNSS information is also used to define the first candidate position of the algorithm. Notice, that the number of sensors are here for reference and the final number of them depends on the safety analysis of the whole system. The general scheme of the algorithm is depicted by defining two main function blocks named as “Curve as Reference points” and “Diagnostic”. There could be as many as N number of “Curve as Reference points” defined by the algorithm that provide a mapping figure to determine its likelihood of the train to be in that segment. So the algorithm needs to pick the best of them until it can safely discard the rest of the cases. The “Curve as Reference Point” algorithm is based on an given initial position of the train plus speed sensor data, plus an Inertial Measurement Unit (IMU) and a digital map. Notice that the algorithm does not address the issue of pre-processing the data but it rather assumes that the input data is within the trains dynamic values, with regards to possible range of speeds, acceleration and gyroscope values. Furhtermore, the calibrations steps for IMU sensors or slip and slide phenomena mitigation from speed sensor or any other pre-filtering that may be carried out in this pre-proessing phase is out of the scope here. It is also worth to mention that the IMU sensor data may only use x-axis accelerometer (longitudinal acceleration) and the z-axis gyroscope (yaw gyro) if the information regarding the cant and slope can be obtained from the digital map, which is the case.

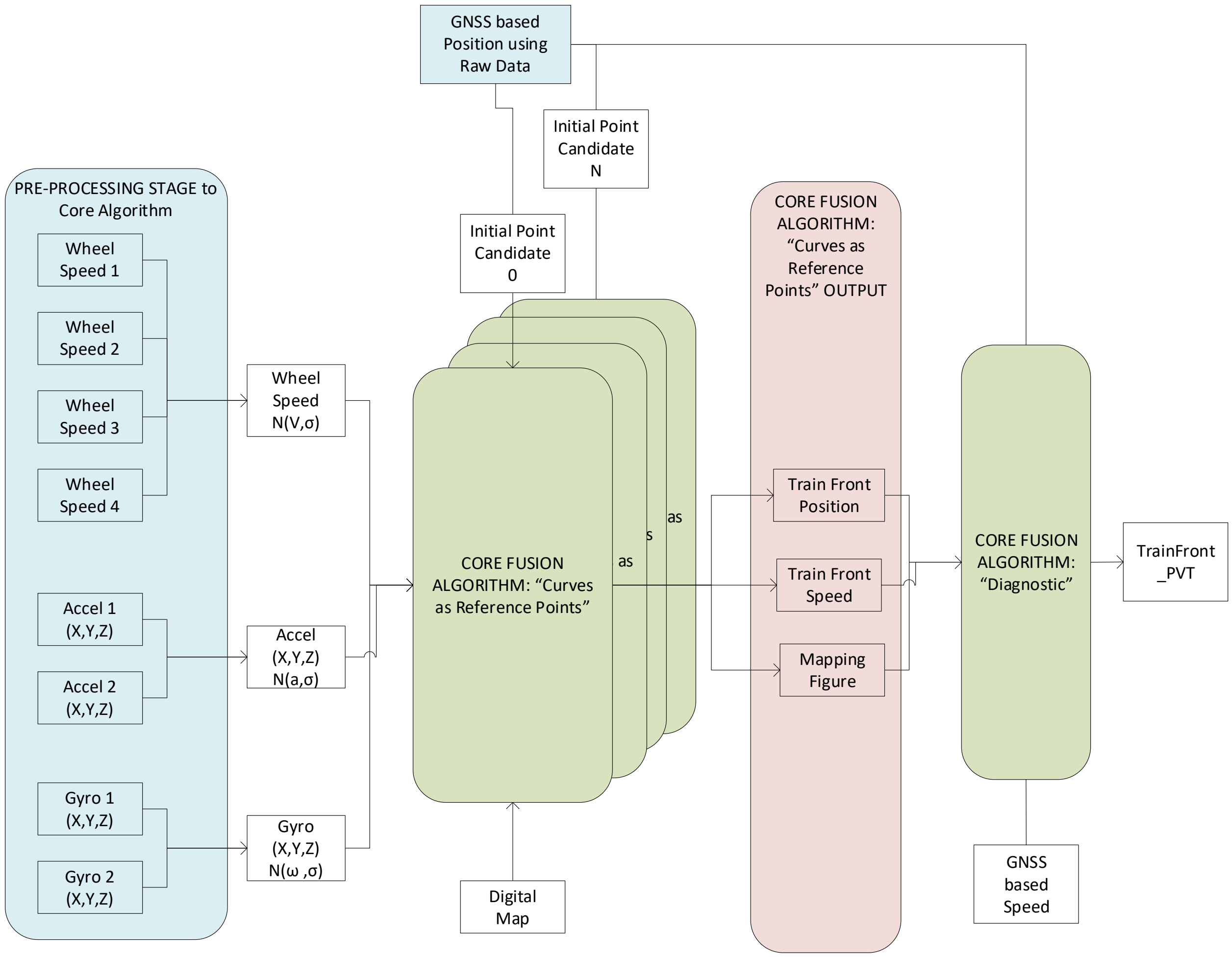

Figure 14 Algorithm under test overview

Finally, the presented algorithm overview foresees multiple sensors but for simplicity in these laboratory cases the inputs are limited to one sensor per type.

8 Test Case Definitions and Results

The following is a list of the test case definition and result to stress the algorithm under a variety of circumstances. The list is not exhaustive but it should provide a hint on how to define the specification of such algorithms.

8.1 Test Case 1

8.1.1 Test Definition

8.1.1.1 Description

The train is switched on Route 1 (Rt1) in a parallel track environment as shown in section 6.3.3. The train has an invalid position at the start. The train starts moving at 70km/h from the start to the end at a constant speed.

8.1.1.2 Input Error Specification:

	Offset Error	**Noise Error**	**Noise Proportional Error**
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\},\ \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\},\ \alpha = 0$	No
Err_PVT	No	No	No

Table 3 Error definition for test.

8.1.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.1.2 Test Results

8.1.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 2 with a curve is discarded due to algorithm determination.

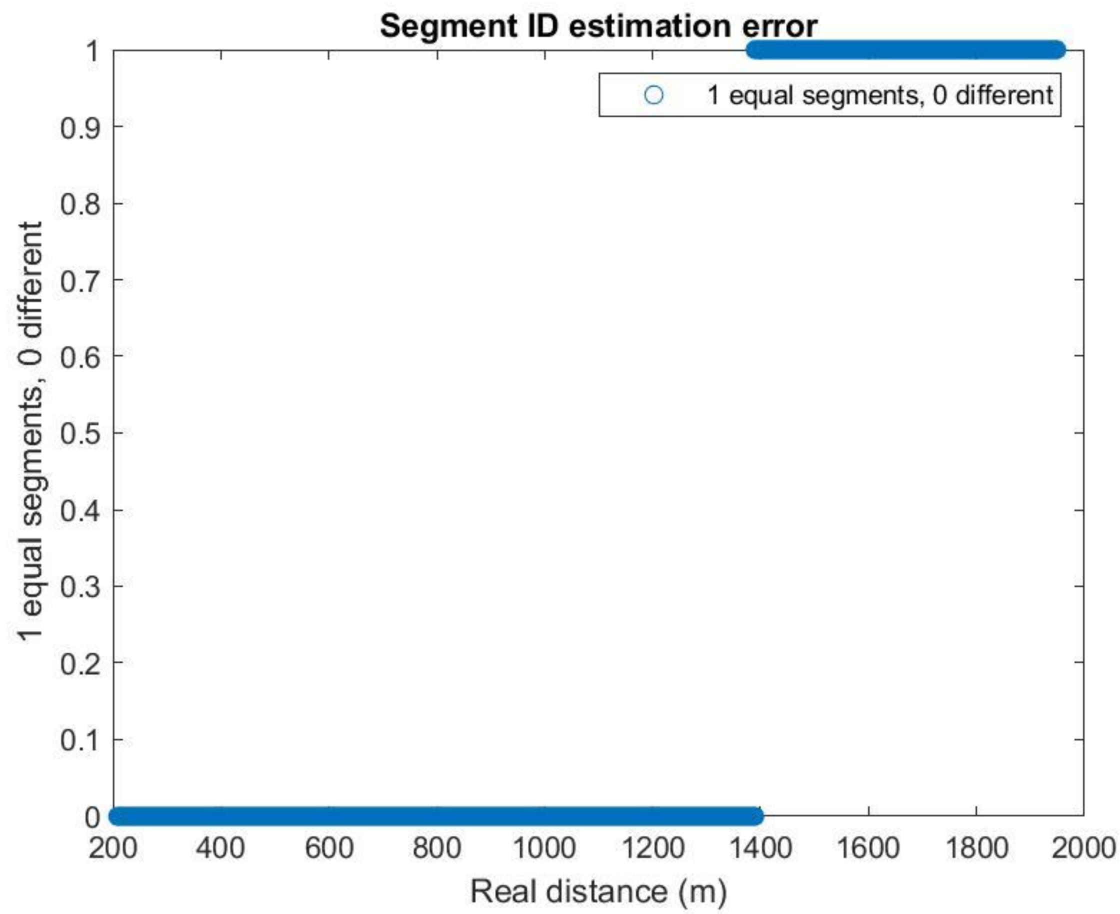

Figure 15 Segment determination illustration, 0 segment not located, 1 segment located

8.1.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position and the PLI.

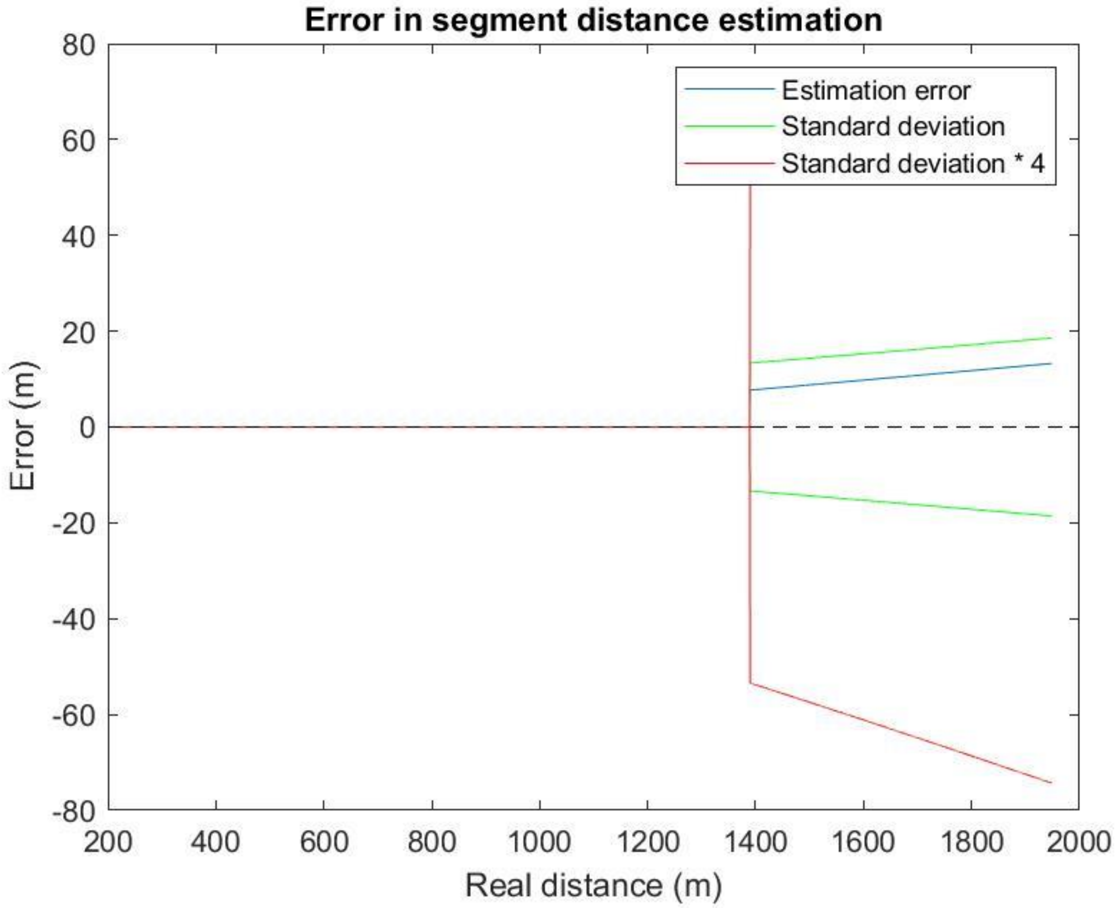

Figure 16 Segment distance error

8.1.2.3 Conclusion

The test is considered passed.

8.2 Test Case 2

8.2.1 Test Definition

8.2.1.1 Description

The train is switched on Route 2 (Rt2) in a parallel track environment as shown in section 6.3.3. The train has Invalid position at the start off. The train starts moving at 70km/h from the start to the end at constant speed.

8.2.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 4 Error definition for test.

8.2.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment, the position shall be valid.

8.2.2 Test Results

8.2.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 1 with a straight line is discarded due to algorithm determination.

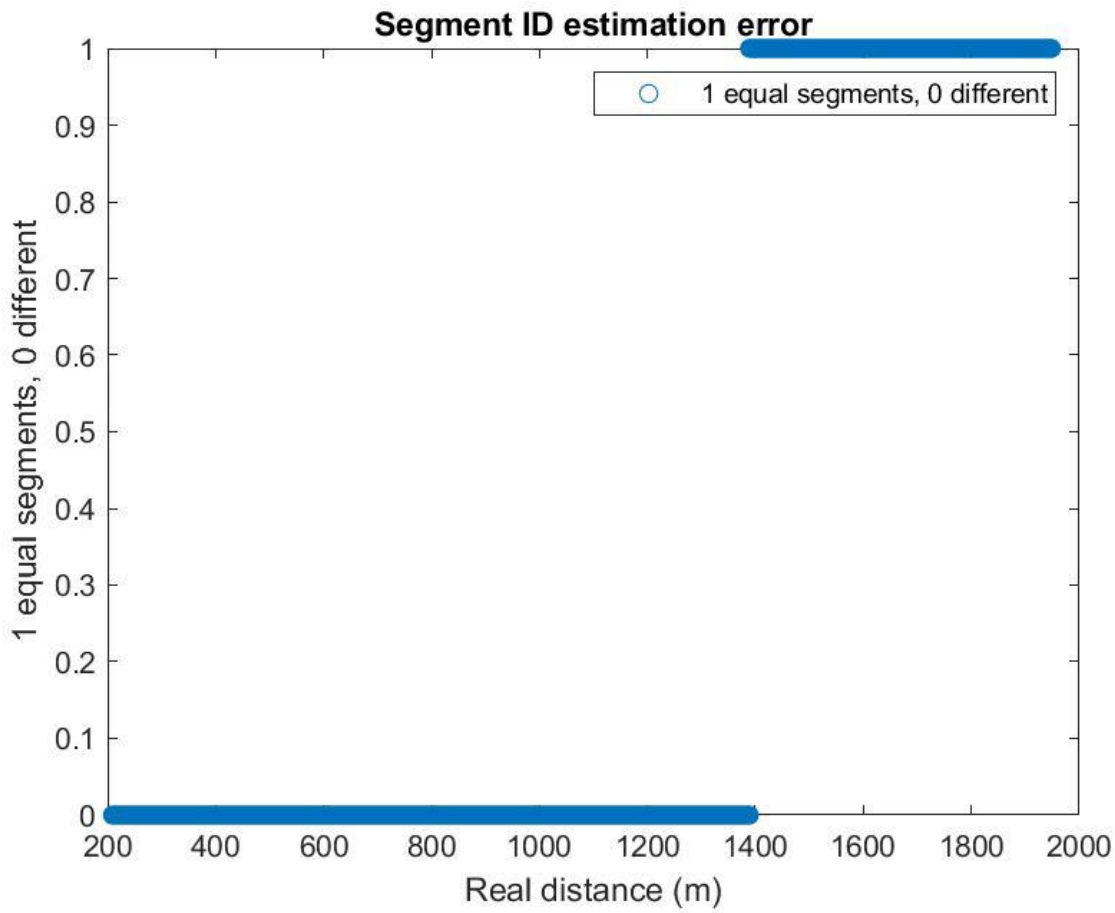

Figure 17 Segment determination illustration, 0 segment not located, 1 segment located

8.2.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference. In this case, the distance error estimation is more noise as it depends upon the curve speed and primarily the noise introduced to the sensor.

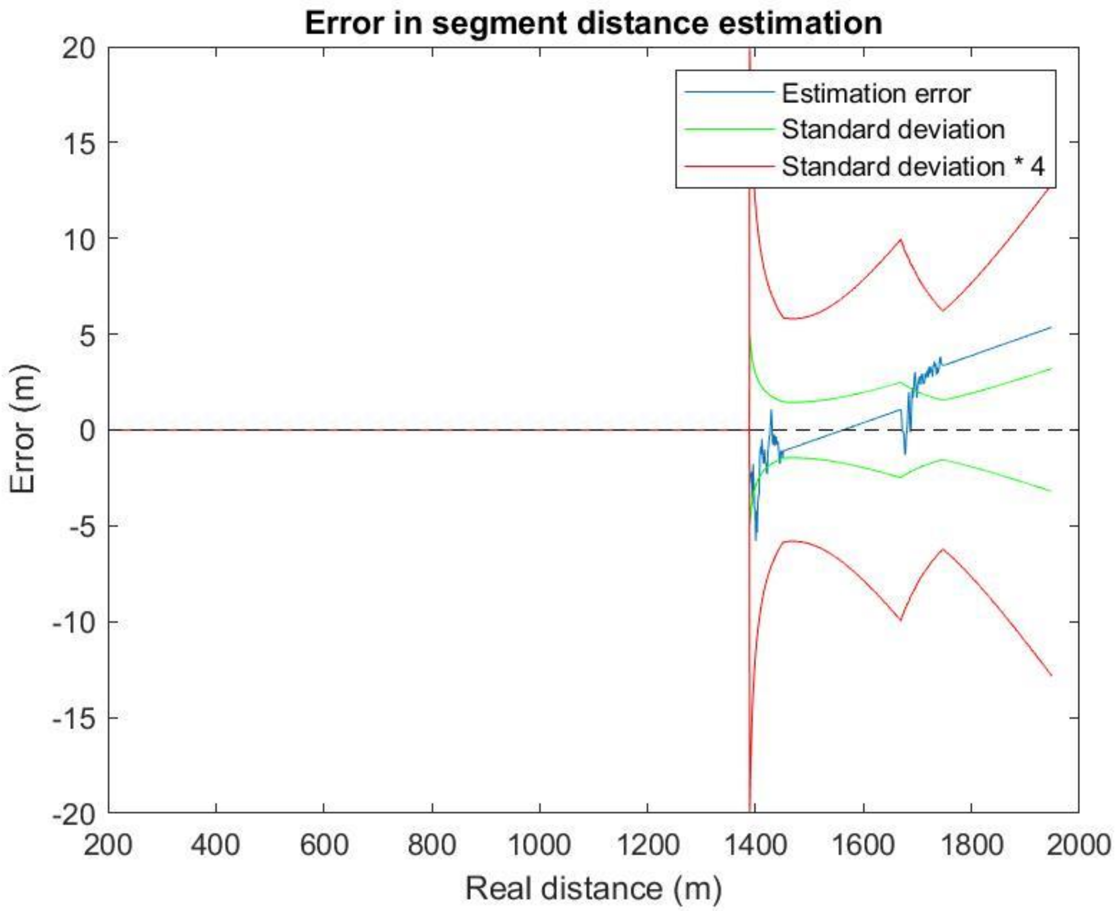

Figure 18 Segment distance error

If the gyroscope data is illustrated it can be seen the magnitude of error is introduced with respect to the expected curvature reading (see Figure 19). In this image, the read gyroscope value from the algorithm is only plotted once the train is positioned in the segment. In order to position the train in the segment, there must be an estimation of the position within the segment, so that it can be seen that the estimation matches well with the curvature.

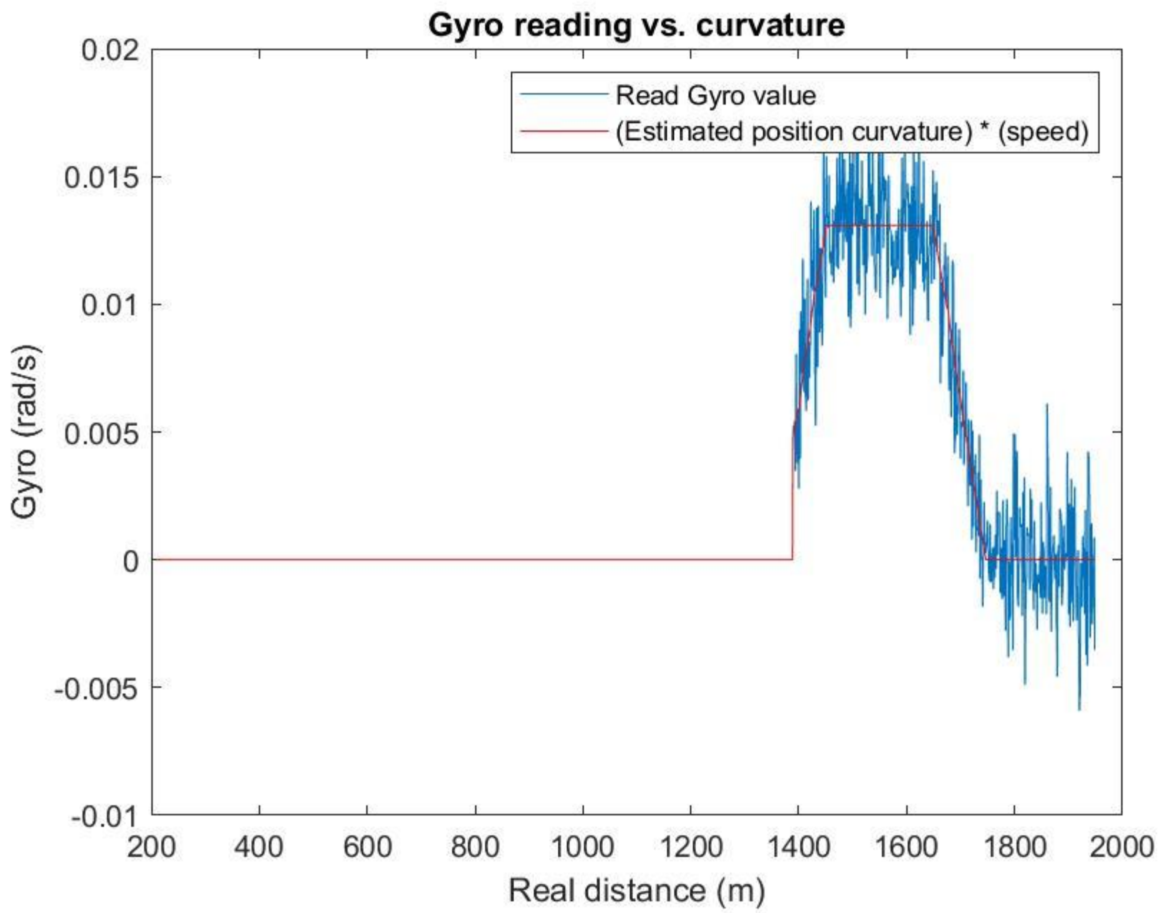

Figure 19 Gyroscope reading vs theoretical curvature

8.2.2.3 Conclusion

The test is considered passed. The noise value added to the gyroscope it is also seen as part of the position estimation error which provides a hint on the importance of the gyroscope noise determination. In other words, whenever a gyroscope sensor is integrated in this algorithm the capability of repositioning or detecting the curve is directly related to the noise defined by the sensor specification.

8.3 Test Case 3

8.3.1 Test Definition

8.3.1.1 Description

The train is switched on Route 3 (Rt3) in a parallel track environment as shown in section 6.3.3. The train has an Invalid position at the start off. The train starts moving at 70km/h from the start to the end at a constant speed.

8.3.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 5 Error definition for the test.

8.3.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment, the position shall be valid.

8.3.2 Test Results

8.3.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 3 with a curve is discarded due to sensor reading.

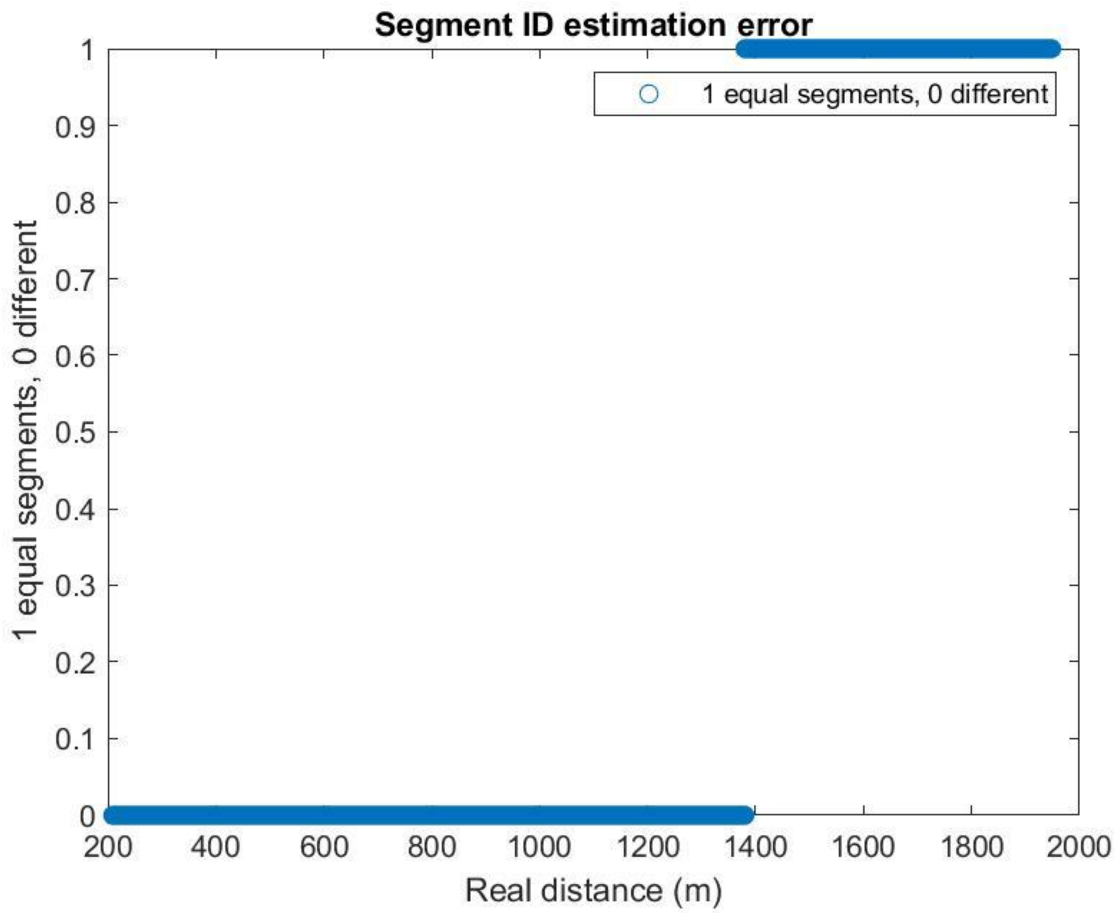

Figure 20 Segment determination illustration, 0 segment not located, 1 segment located

8.3.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference.

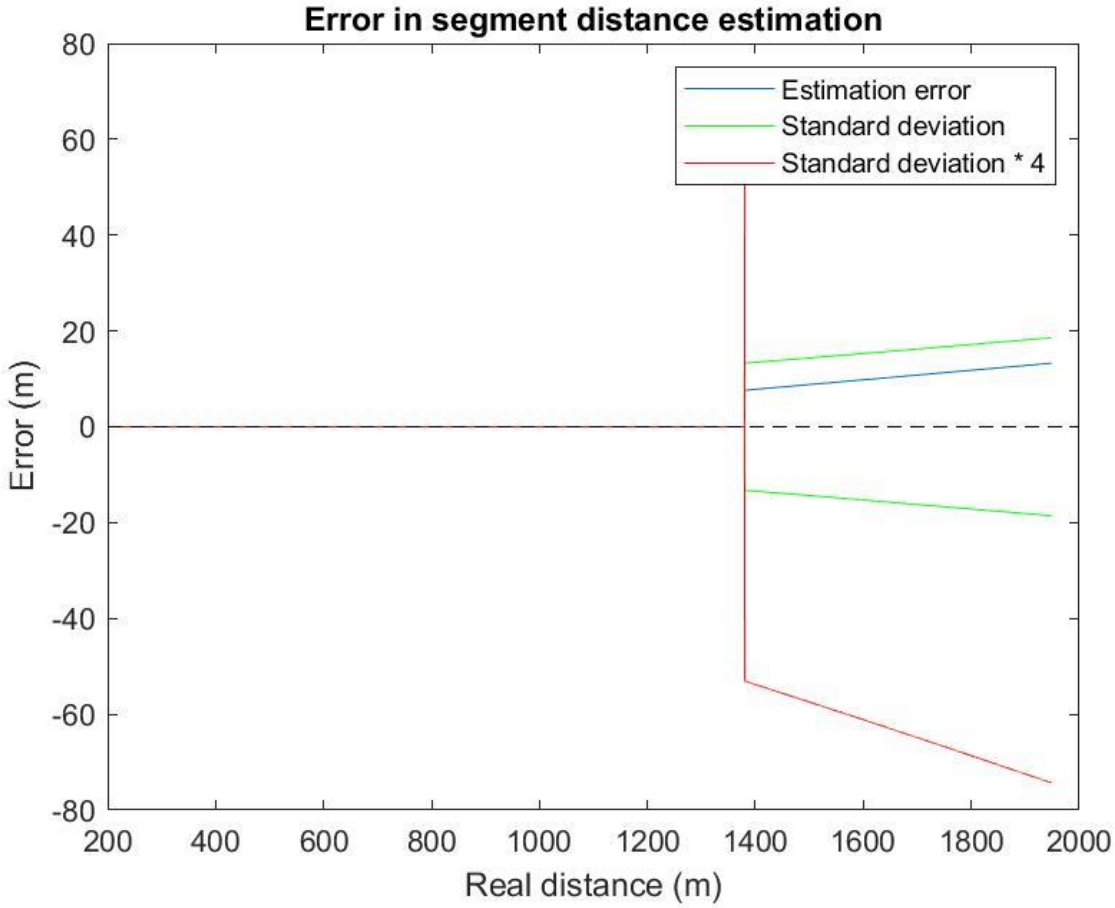

Figure 21 Segment distance error

8.3.2.3 Conclusion

The test is considered passed. The test obtains very similar results compared to Test case 1 as the scenario is very similar but with different curvature. The conclusion is that it does not add any value to test with greater curvatures as the results are very similar.

8.4 Test Case 4

8.4.1 Test Definition

8.4.1.1 Description

The train is switched on Route 4 (Rt4) in a parallel track environment as shown in section 6.3.3. The train has Invalid position at the start off. The train starts moving at 70km/h from the start to the end at constant speed.

8.4.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}$, $\alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}$, $\alpha = 0$	No
Err_PVT	No	No	No

Table 6 Error definition for test.

8.4.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.4.2 Test Results

8.4.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 4 with a straight line is discarded due to sensor reading.

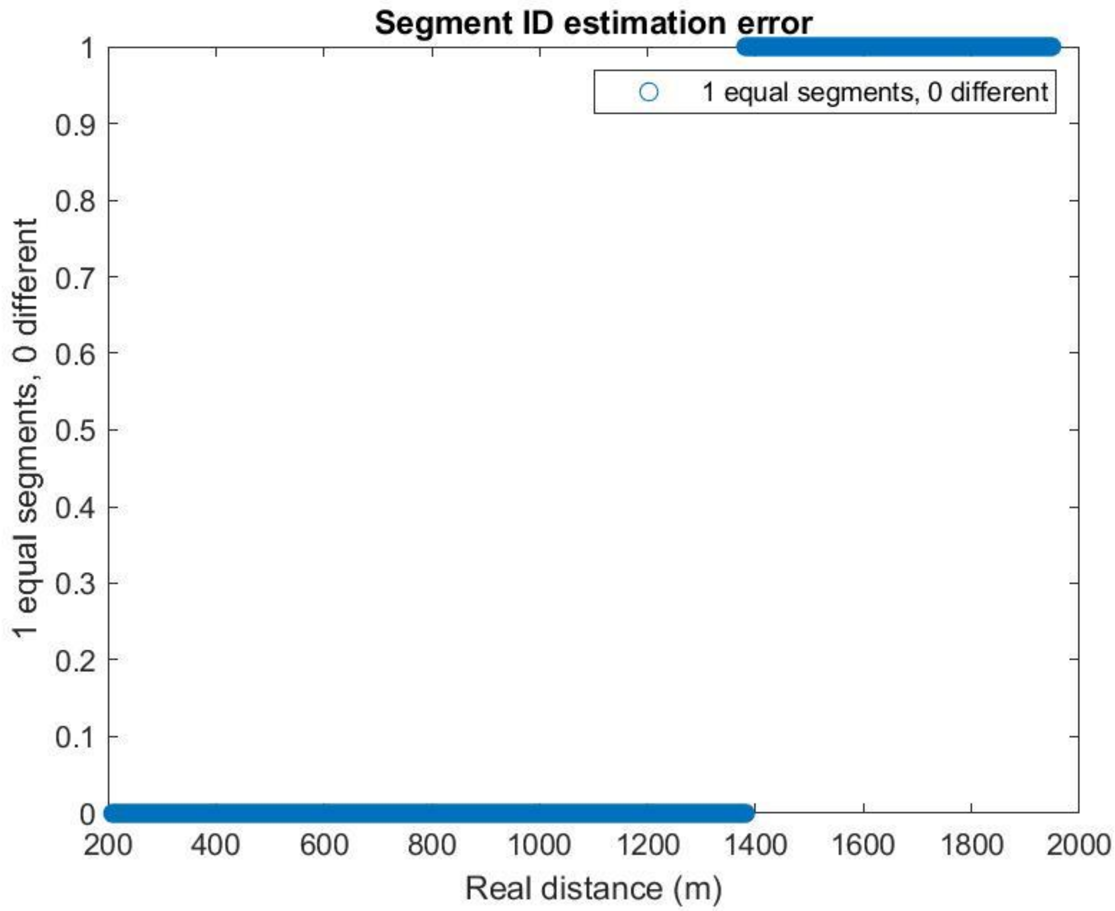

Figure 22 Segment determination illustration, 0 segment not located, 1 segment located

8.4.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference. In this case, the distance error estimation is more noise as it depends upon the curve speed and primarily the noise introduced to the sensor.

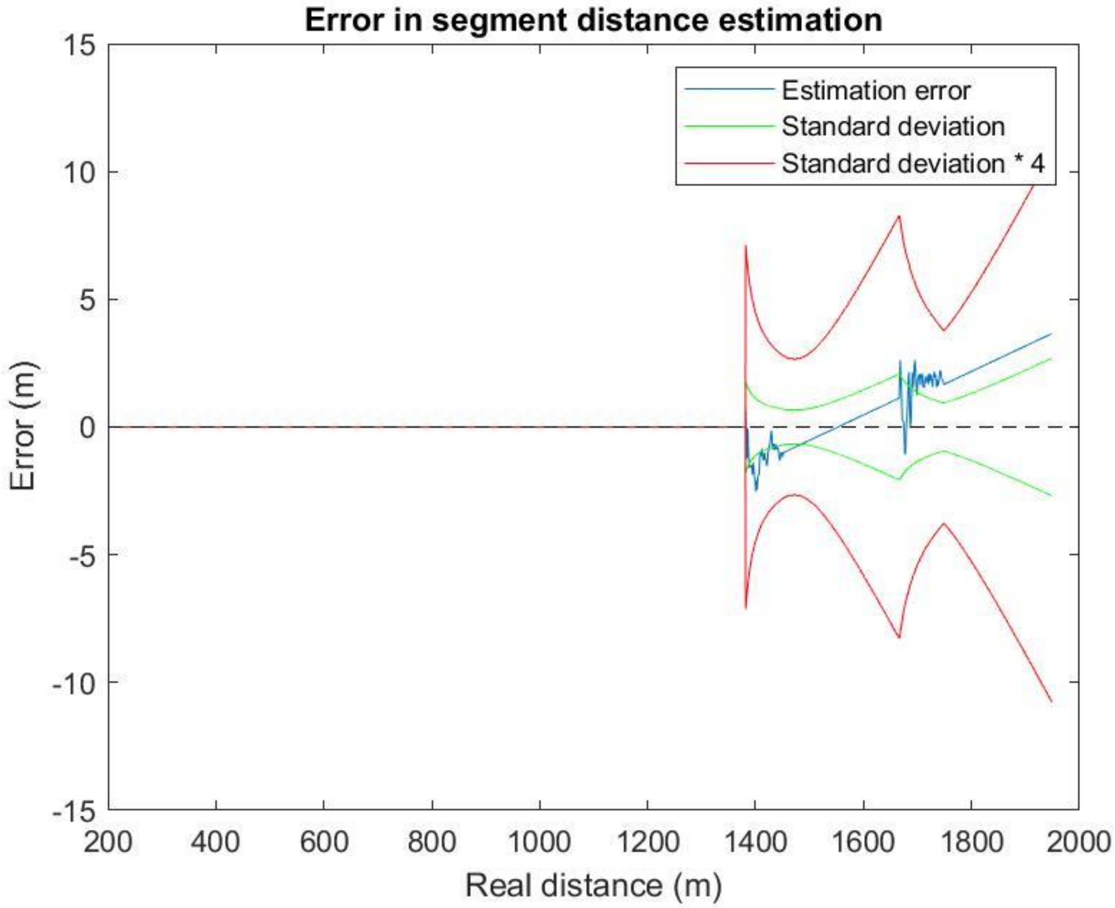

Figure 23 Segment distance error

If the gyroscope data is illustrated it can be seen the magnitude of error introduced with respect of the expected curvature reading (see Figure 24). In this image, the read gyroscope value from the algorithm is only plotted once the train is positioned in the segment. In order to position the train in the segment there must an estimation of the position within the segment, so that it can be seen that the estimation matches well with the curvature.

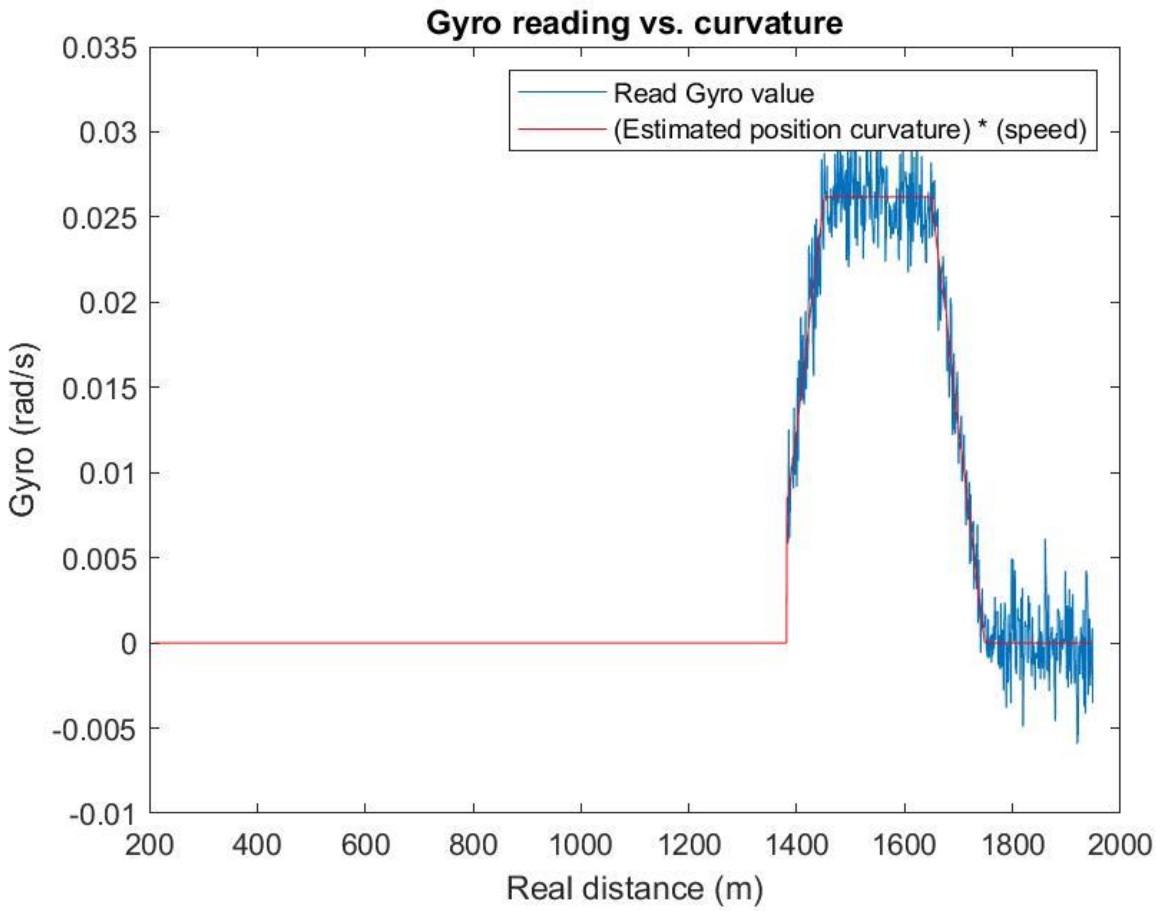

Figure 24 Gyroscope reading vs theoretical curvature

8.4.2.3 Conclusion

The test is considered passed. The noise value added to the gyroscope is also seen as part of the position estimation error which provides a hint on the importance of the gyroscope noise determination. One important point to highlight is the comparison of this test with Test Case 2 where the scenario is the same but with different curvature. In this Test Case 2 it can be seen that the estimated distance error is much greater than the one obtained by this Test Case 4. The reason is that running at the same speed but with greater curvature length the noise of the gyroscope has less impact on the resulting estimation. As a conclusion, performing further test with greater radius curvature will only provide better results as expected.

8.5 Test Case 5

8.5.1 Test Definition

8.5.1.1 Description

Test Equal to Test Case 1 with constant speed of 5km/h.

8.5.1.2 Input Error Specification:

Test Equal to Test Case 1

8.5.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.5.2 Test Results

8.5.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 1 with a curve is discarded due to sensor reading.

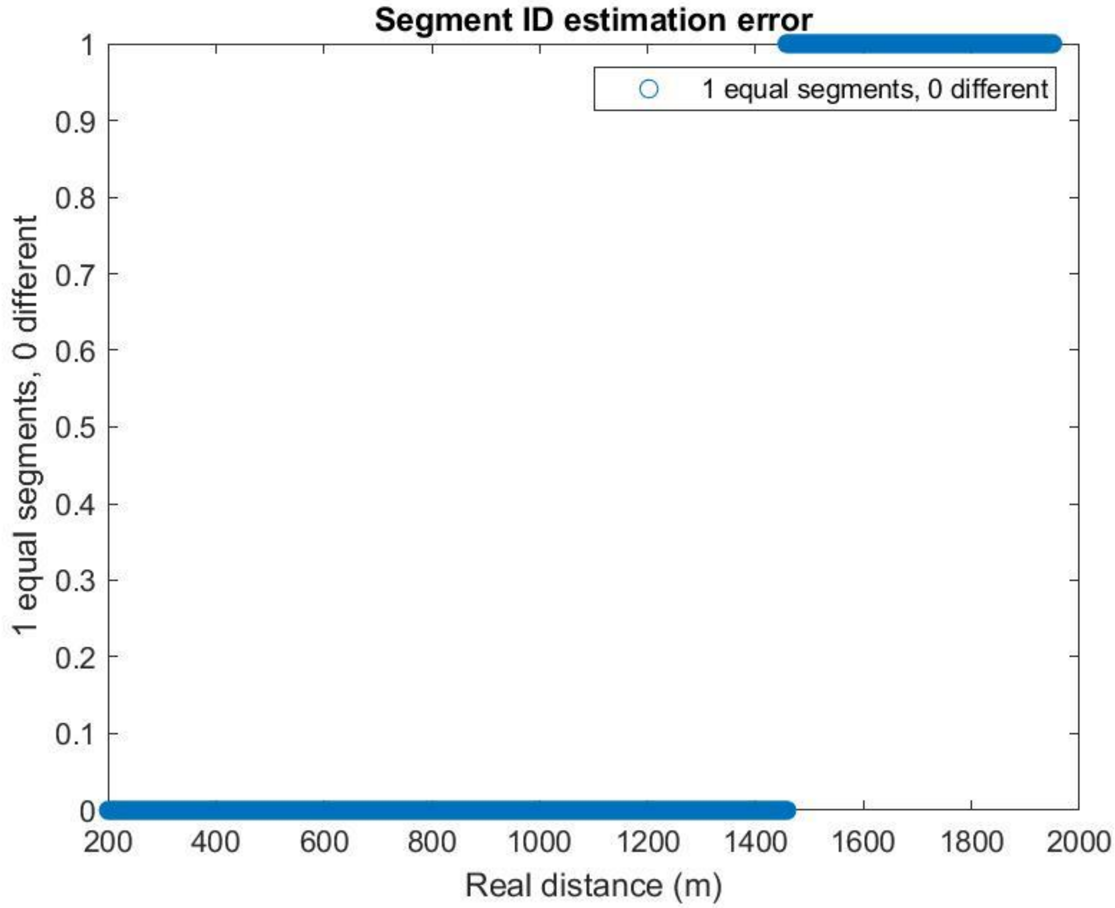

Figure 25 Segment determination illustration, 0 segment not located, 1 segment located

8.5.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference.

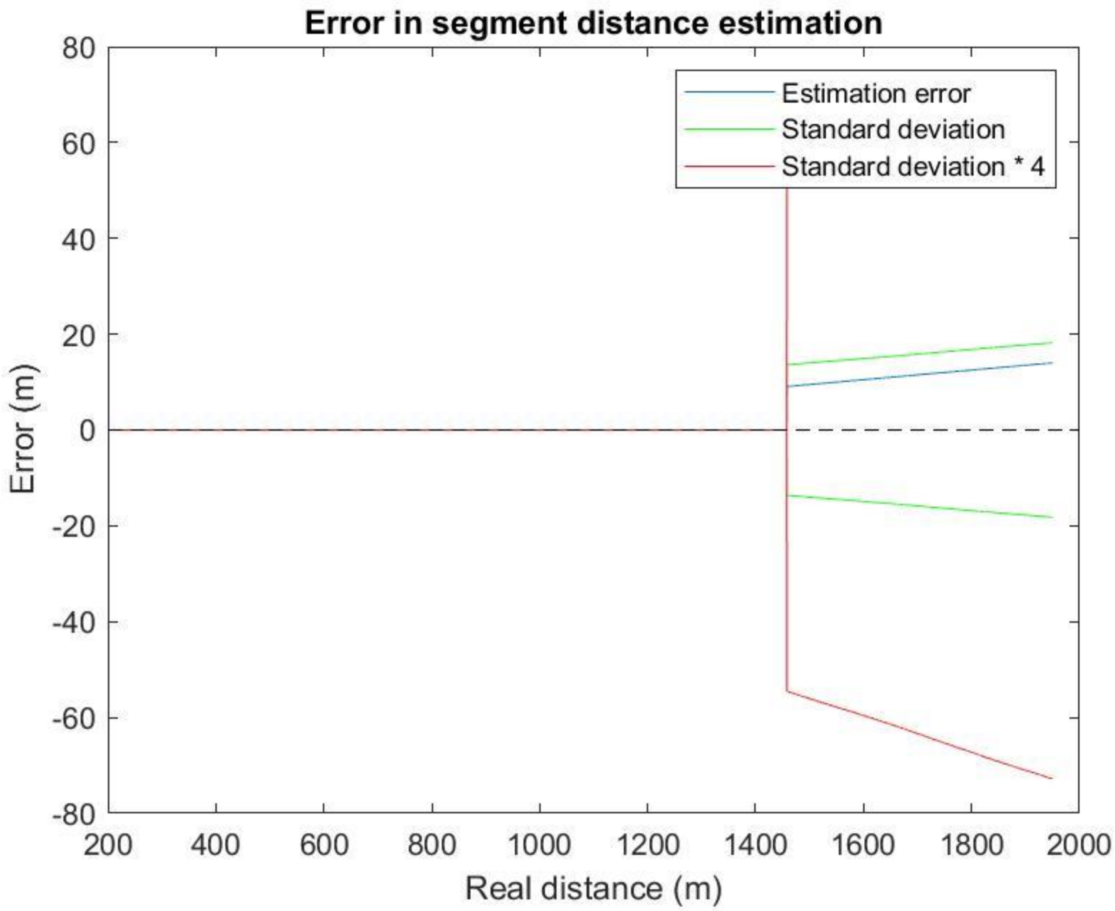

Figure 26 Segment distance error

8.5.2.3 Conclusion

The test is considered passed. The test obtains very similar results compared to Test case 1 as the scenario is very similar but with different speed value. The conclusion is that in Test Case 1 since the speed is greater the positioning of the train is obtained around 1400 meters whereas in this test case the train took longer to determine in which segment it is, close to 1480 meters.

8.6 Test Case 6

8.6.1 Test Definition

8.6.1.1 Description

Test Equal to Test Case 2 with constant speed of 5km/h.

8.6.1.2 Input Error Specification:

Test equal to Test Case 2

8.6.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.6.2 Test Results

8.6.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 2 with a straight line is discarded due to sensor reading.

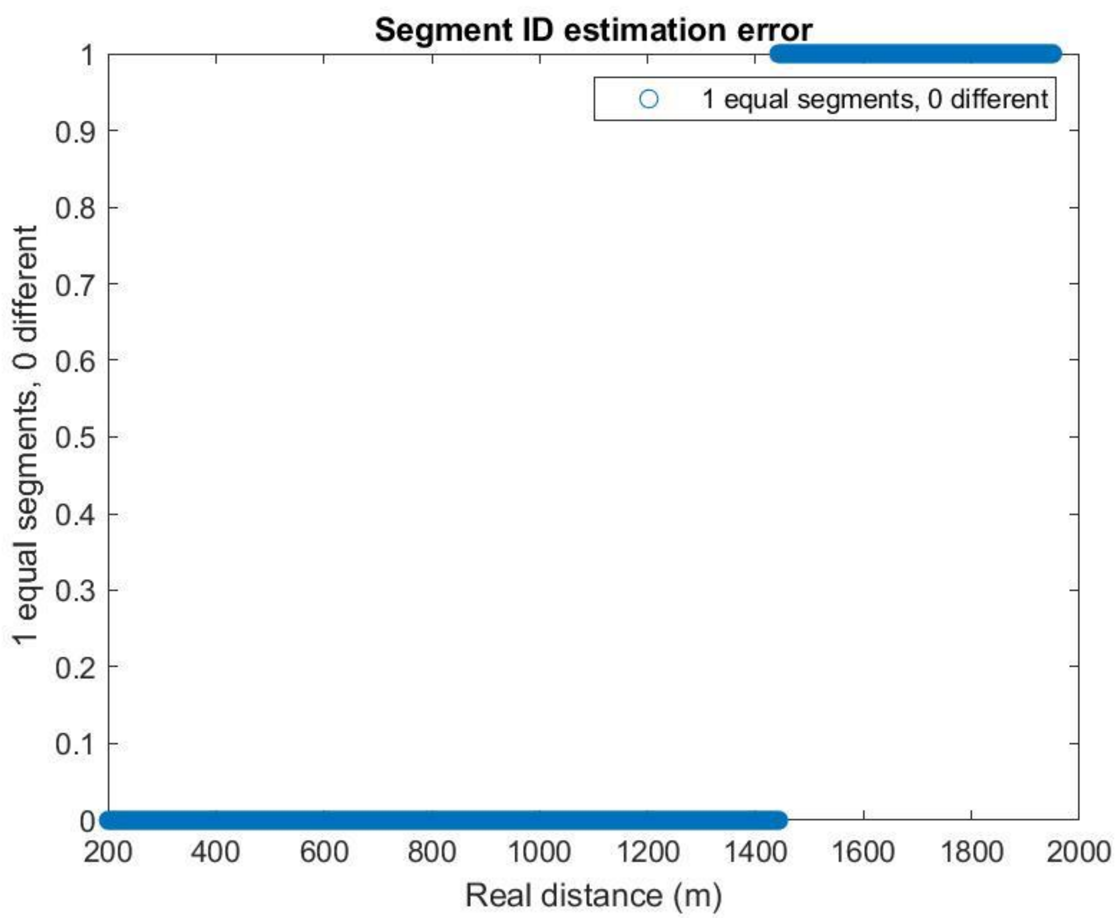

Figure 27 Segment determination illustration, 0 segment not located, 1 segment located

8.6.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference. In this case, the distance error estimation is more noise as it depends upon the curve speed and primarily the noise introduced to the sensor.

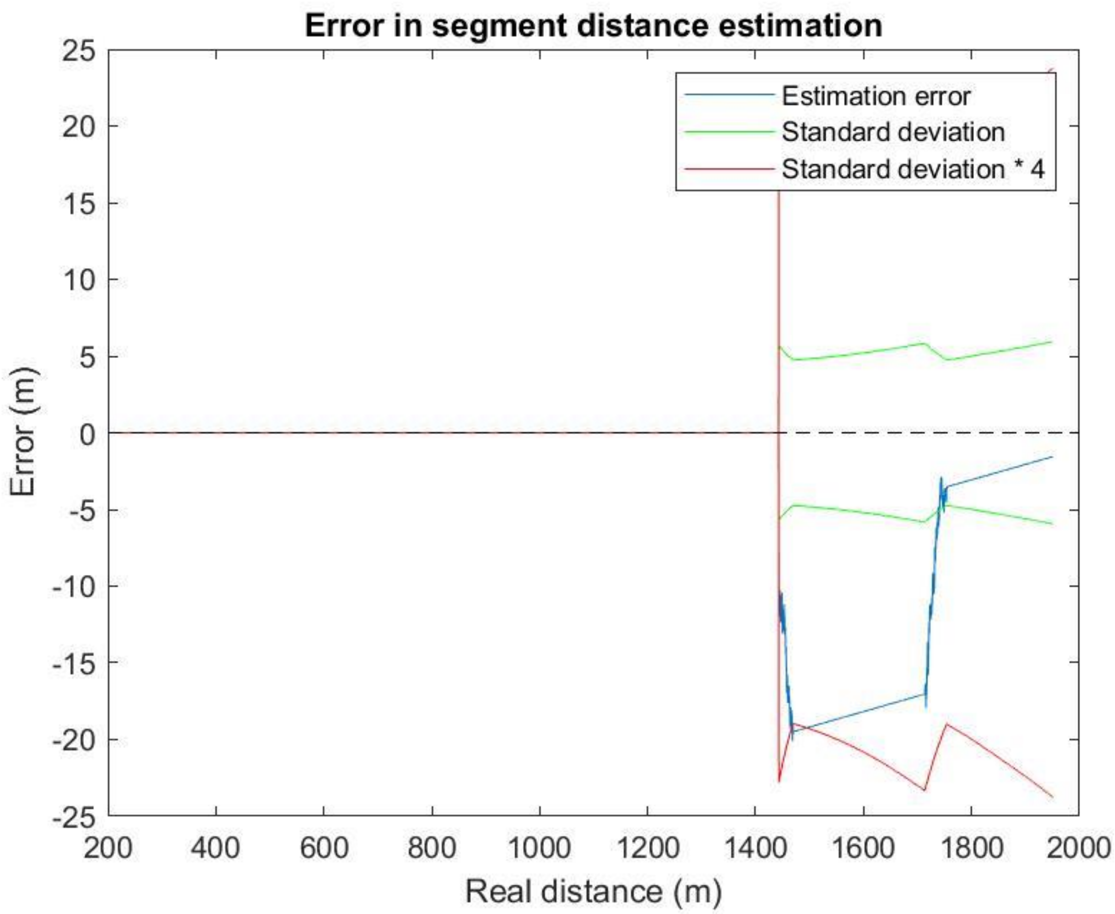

Figure 28 Segment distance error

If the gyroscope data is illustrated it can be seen the magnitude of error introduced with respect of the expected curvature reading (see Figure 29). In this image, the read gyroscope value from the algorithm is only plotted once the train is positioned in the segment. In order to position the train in the segment there must an estimation of the position within the segment, so that it can be seen that the noise of the gyroscope is significantly major that the expected theoretical curvature and even at this situation the algorithm is able to position itself.

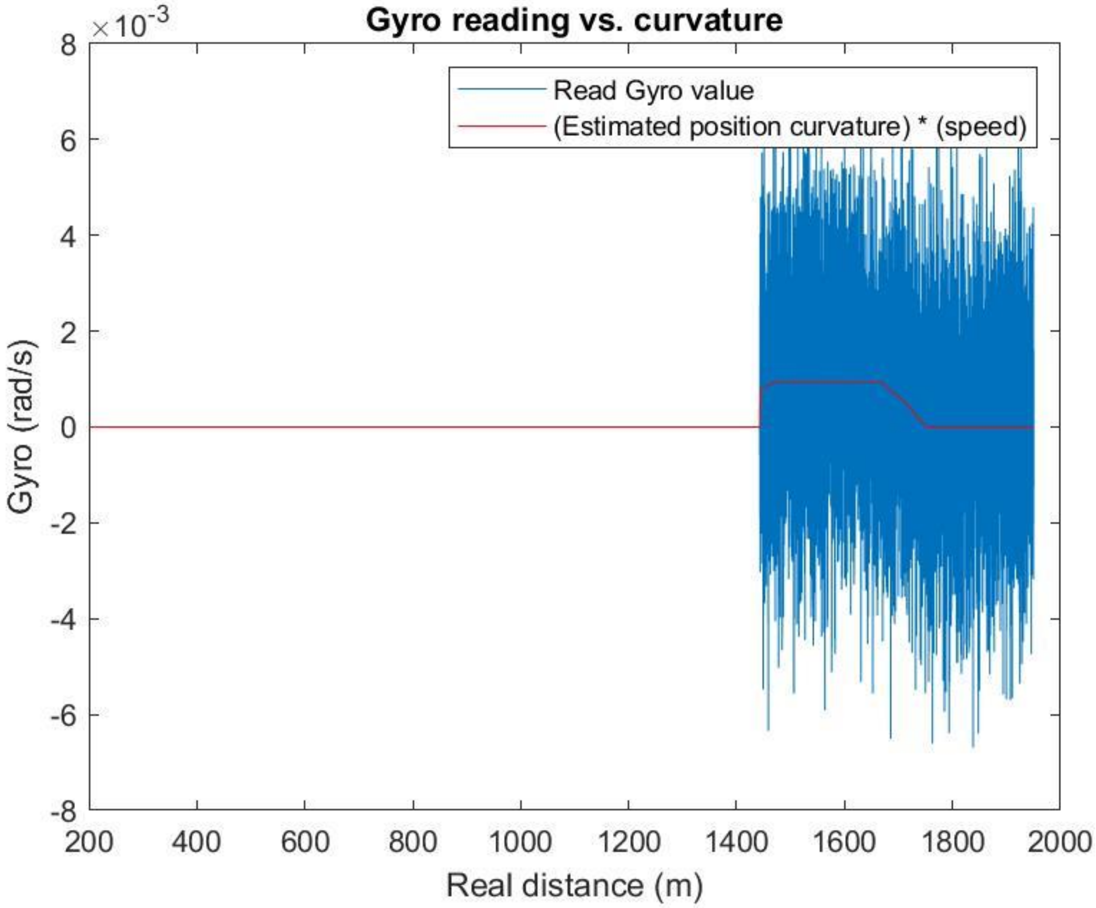

Figure 29 Gyroscope reading vs theoretical curvature

8.6.2.3 Conclusion

The test is considered passed. The noise value added to the gyroscope it is also seen as part of the position estimation error which provides a hint on the importance of the gyroscope noise determination. One interesting comparison to highlight is with Test Case 2 where the scenario is the same but with different speed. In this Test Case 2 it can be seen that the estimated distance error is much better than the one obtain by this Test Case 6. The reason is that running at the same curvature but with lower speed the noise of the gyroscope is very significant compared to the expected curvature value. This leads that the position estimation can only discriminate further in position (approximately around 1480m) which is the result of having lower speed.

8.7 Test Case 7

8.7.1 Test Definition

8.7.1.1 Description

Test Equal to Test Case 3 with constant speed of 5km/h.

8.7.1.2 Input Error Specification:

Test Equal to Test Case 3

8.7.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.7.2 Test Results

8.7.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 3 with a curve is discarded due to sensor reading.

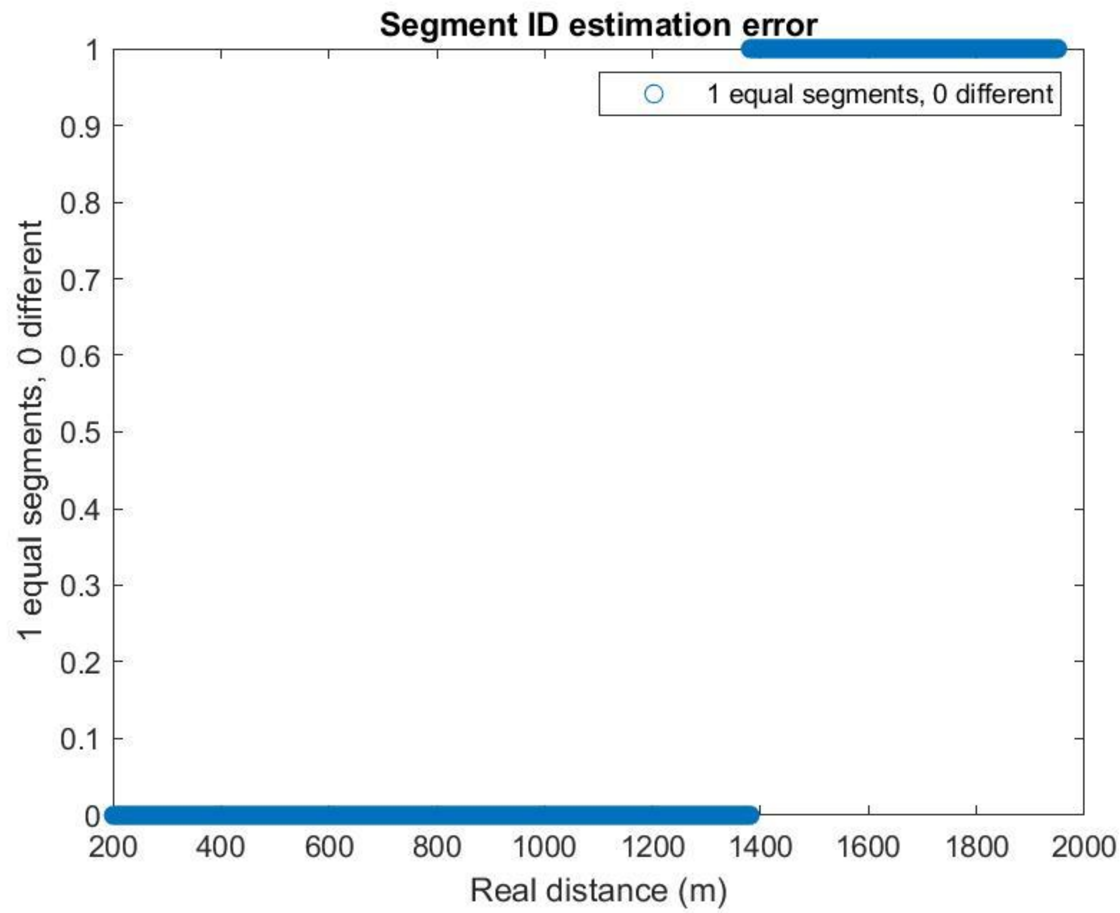

Figure 30 Segment determination illustration, 0 segment not located, 1 segment located

8.7.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference.

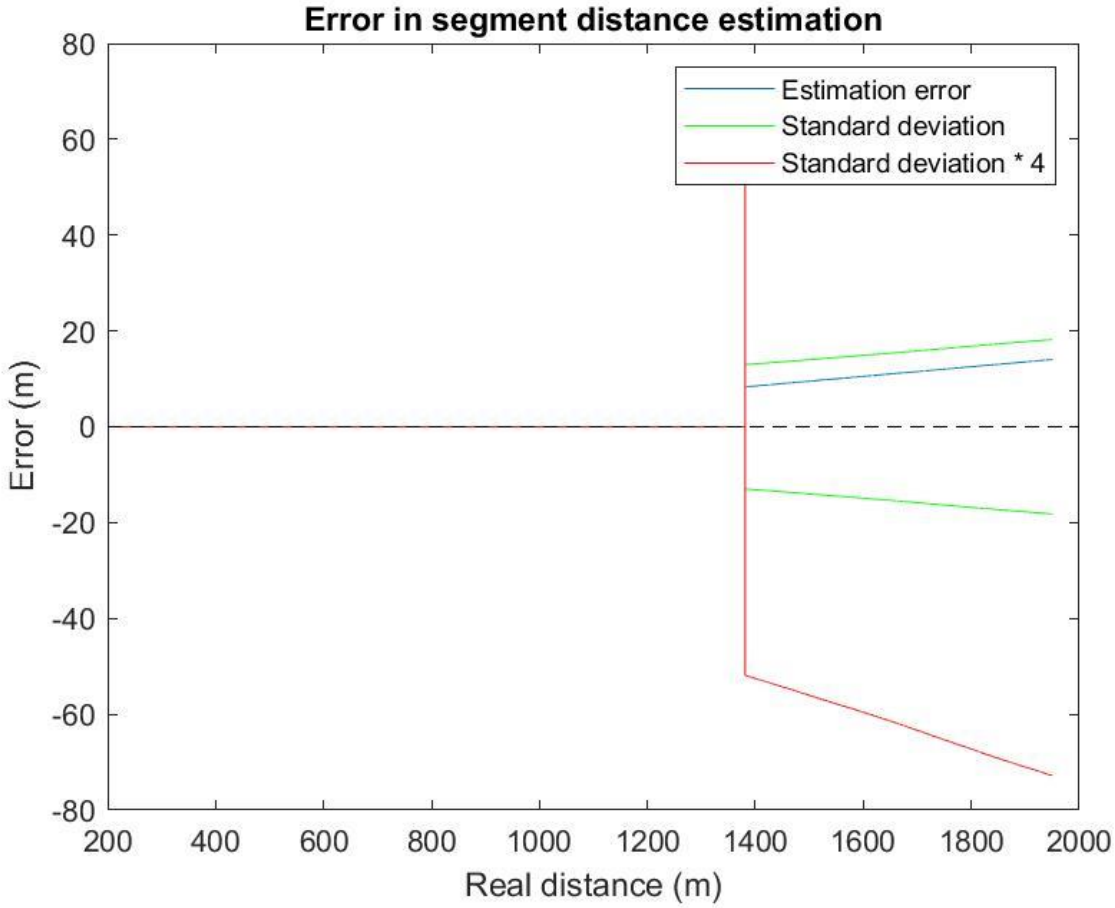

Figure 31 Segment distance error

8.7.2.3 Conclusion

The test is considered passed. The test obtains very similar results compared to Test case 5 as the scenario is very similar but with different curvature value. This test is also similar to Test Case 3 also but the speed value is different. The conclusion obtained from this test is that thanks to the greater curvature value the train is positioning earlier than Test Case 5 and very similar to Test Case 3.

8.8 Test Case 8

8.8.1 Test Definition

8.8.1.1 Description

Test Equal to Test Case 4 with constant speed of 5km/h.

8.8.1.2 Input Error Specification:

Test equal to Test Case 4

8.8.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.8.2 Test Results

8.8.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached at around 1400 meters. This is expected as the train starts with an invalid position with a parallel track and it is not until the position candidate of route 4 with a straight line is discarded due to sensor reading.

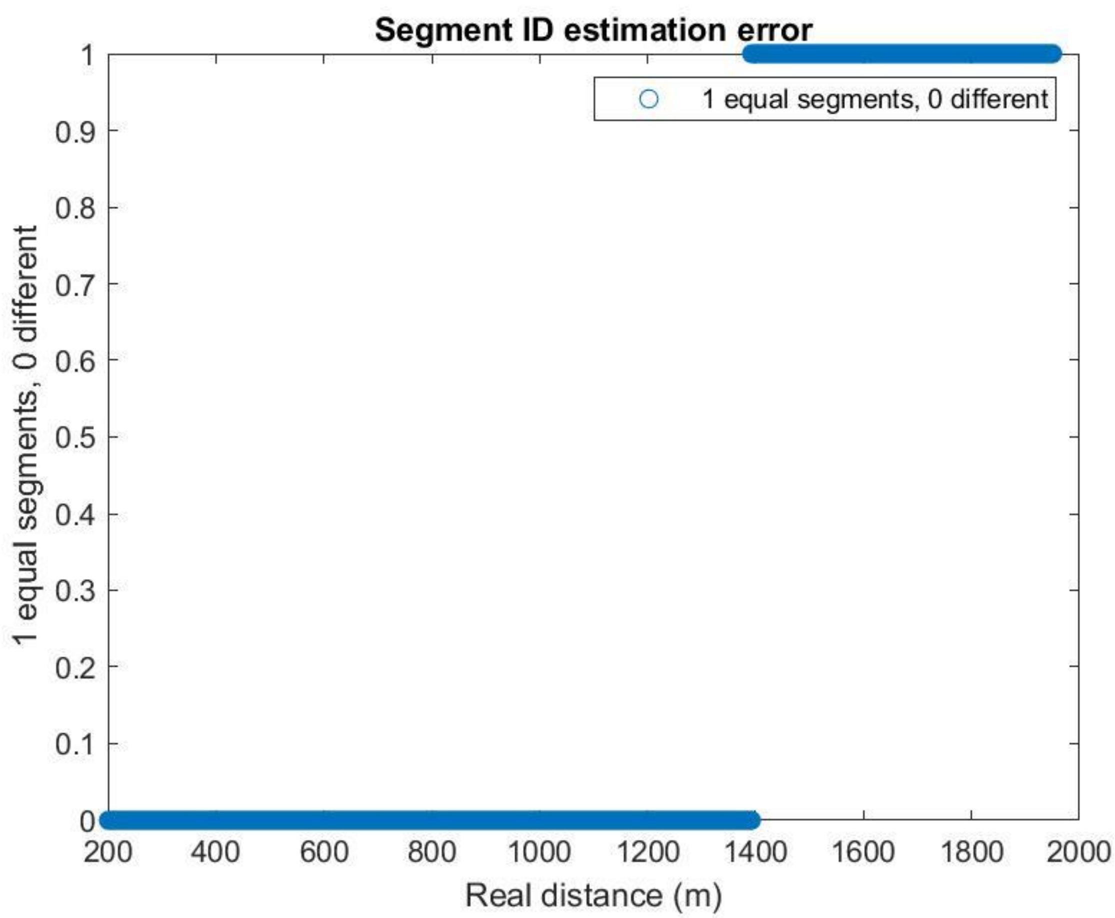

Figure 32 Segment determination illustration, 0 segment not located, 1 segment located

8.8.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. Notice that the zero error value until around 1400 meters needs to be understood as Maximum error since the segment value is not determined until 1400 meters. Once the segment is defined three values are represented, the estimation error of the algorithm, the standard deviation of the position, meaning the protection level, and 4 times the standard deviation value as a reference. In this case, the distance error estimation is more noise as it depends upon the curve speed and primarily the noise introduced to the sensor.

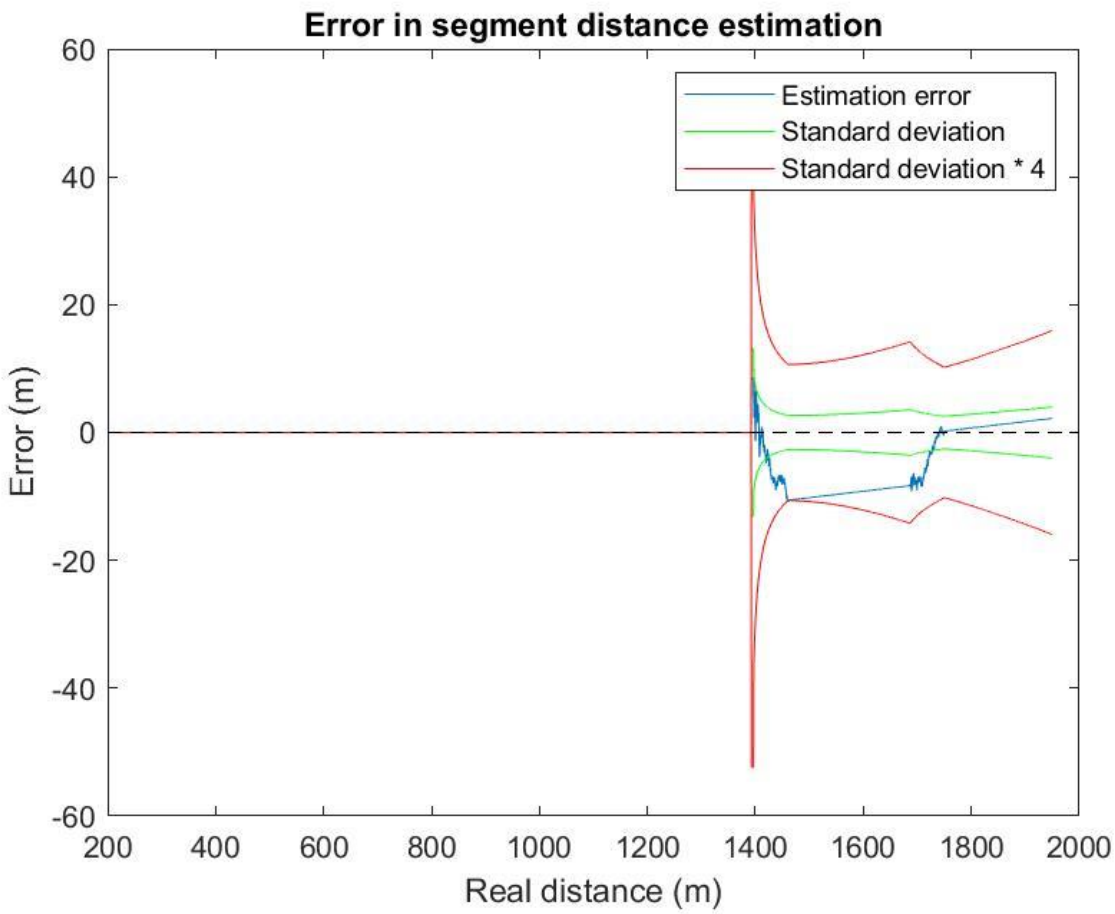

Figure 33 Segment distance error

If the gyroscope data is illustrated it can be seen the magnitude of error introduced with respect of the expected curvature reading (see Figure 34). In this image, the read gyroscope value from the algorithm is only plotted once the train is positioned in the segment. In order to position the train in the segment there must an estimation of the position within the segment, so that it can be seen that the noise of the gyroscope is significantly major that the expected theoretical curvature and even at this situation the algorithm is able to position itself.

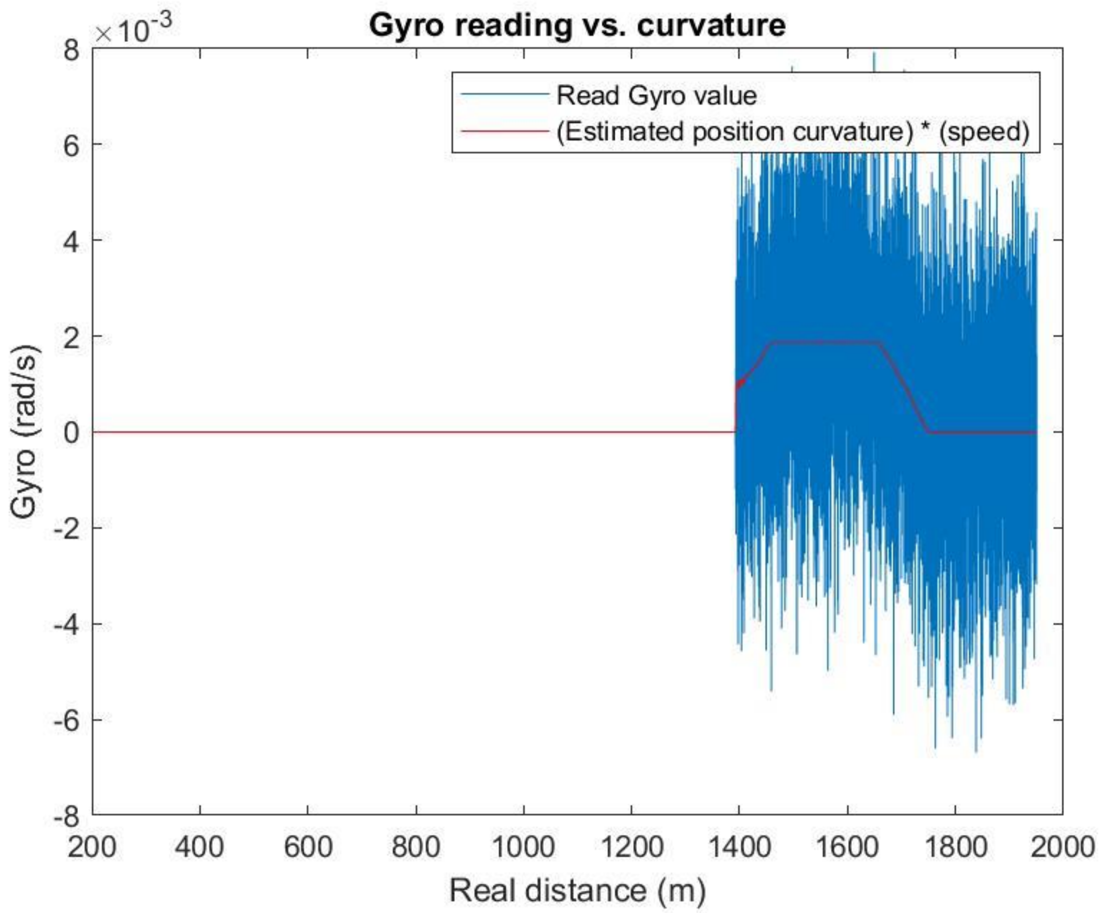

Figure 34 Gyroscope reading vs theoretical curvature

8.8.2.3 Conclusion

The test is considered passed. The noise value added to the gyroscope it is also seen as part of the position estimation error which provides a hint on the importance of the gyroscope noise determination.

8.9 Test Case 9

8.9.1 Test Definition

8.9.1.1 Description

Test Equal to Test Case 1 with constant speed of 5km/h.

8.9.1.2 Input Error Specification:

Gyroscope noise is 10 times greater than Test Case 1 .

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}$, $\alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.02\}$, $\alpha = 0$	No
Err_PVT	No	No	No

Table 7 Error definition for test.

8.9.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.9.2 Test Results

8.9.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is never achieved. The reason behind is that the error introduced by the IMU is greater than the possible options to exclude the parallel segment.

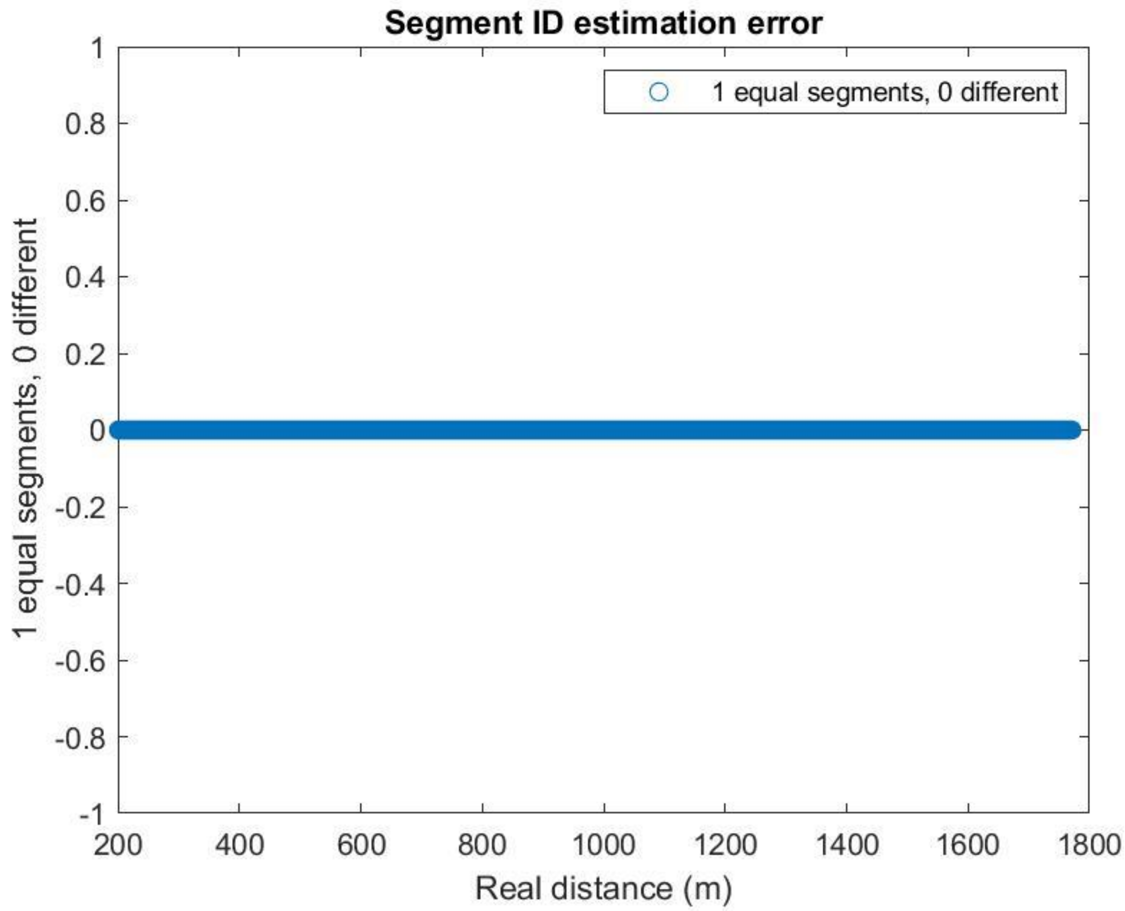

Figure 35 Segment determination illustration, 0 segment not located, 1 segment located

8.9.2.2 Conclusion

The test is considered NOT passed.

8.10 Test Case 10

8.10.1 Test Definition

8.10.1.1 Description

Test Equal to Test Case 2 with constant speed of 5km/h.

8.10.1.2 Input Error Specification:

Gyroscope noise is 10 times greater than Test Case 2 .

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\},\ \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.02\},\ \alpha = 0$	No
Err_PVT	No	No	No

Table 8 Error definition for test.

8.10.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.10.2 Test Results

8.10.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is never achieved. The reason behind is that the error introduced by the IMU is greater than the possible options to exclude the parallel segment.

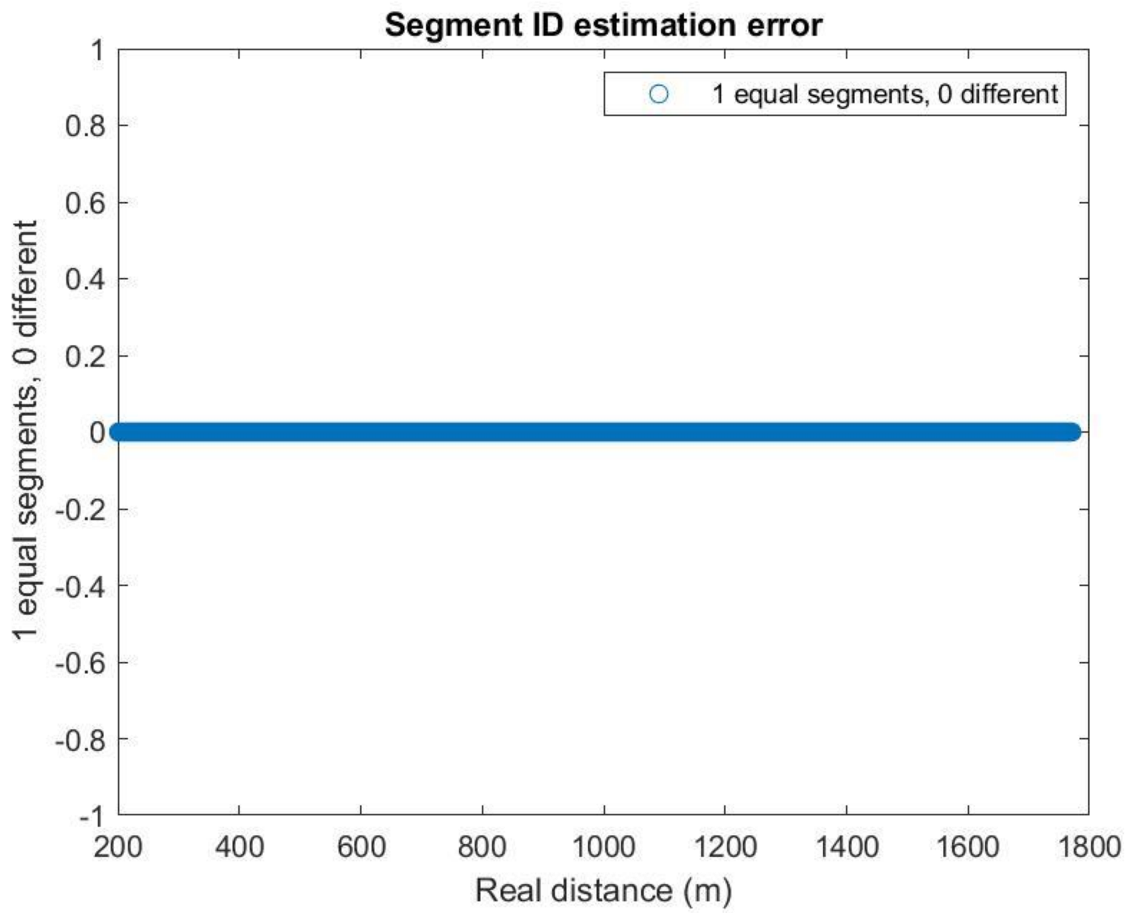

Figure 36 Segment determination illustration, 0 segment not located, 1 segment located

8.10.2.2 Conclusion

The test is considered NOT passed.

8.11 Test Case 11

8.11.1 Test Definition

8.11.1.1 Description

Test Equal to Test Case 1

8.11.1.2 Input Error Specification:

Accelerometer noise is 10 times greater than Test Case 1 .

	Offset Error	**Noise Error**	**Noise Proportional Error**
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.4\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 9 Error definition for test.

8.11.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.11.2 Test Results

8.11.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is achieved with the same accuracy as Test 1 since the only parameter that differs is the accelerometer and the weight associated to its standard deviation has low impact in the final result.

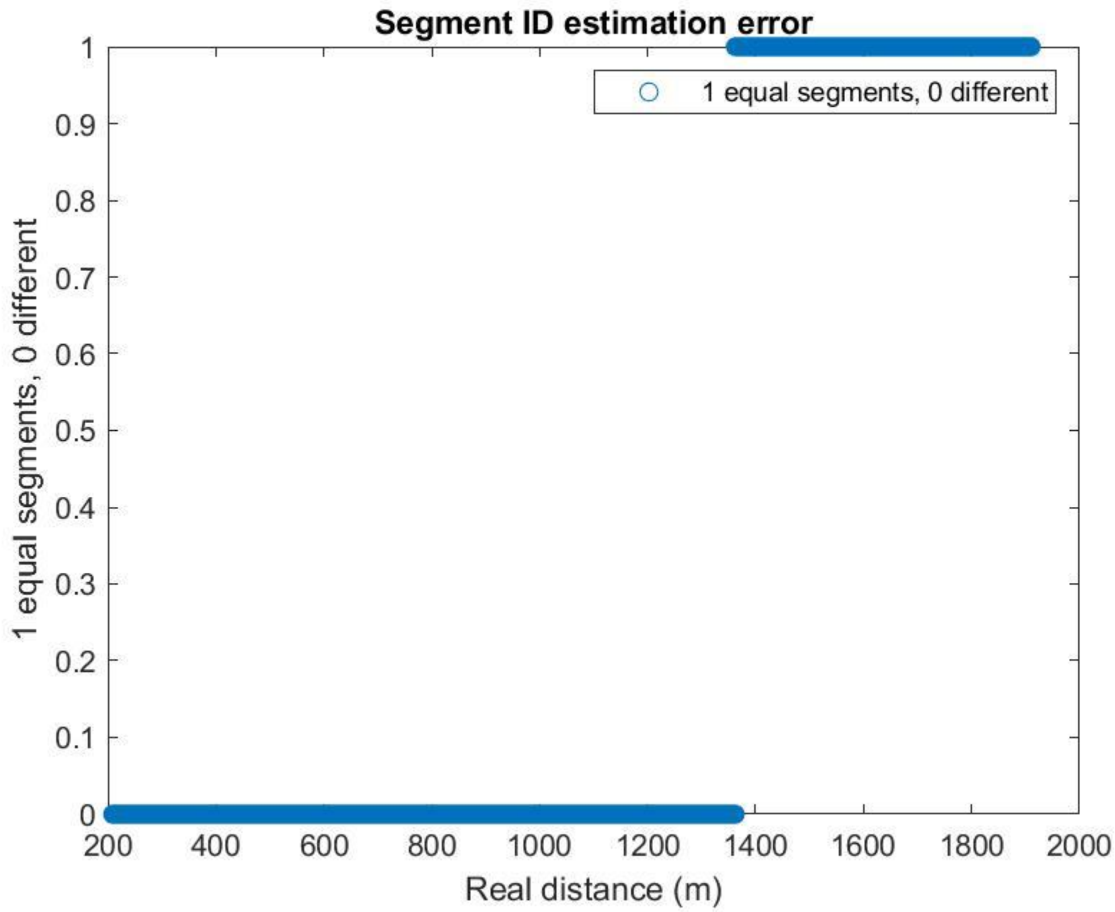

Figure 37 Segment determination illustration, 0 segment not located, 1 segment located

8.11.2.2 Distance Error

In the following illustration it is shown the estimation error where the estimated travelled distance is just above the standard deviation. This illustration, if compared to the results from Test Case 1 it can be seen that the performance it is slightly worst. This behaviour makes sense because the travelled distance is directly related to the speed estimation and the speed estimation is biased by the accelerometer errors.

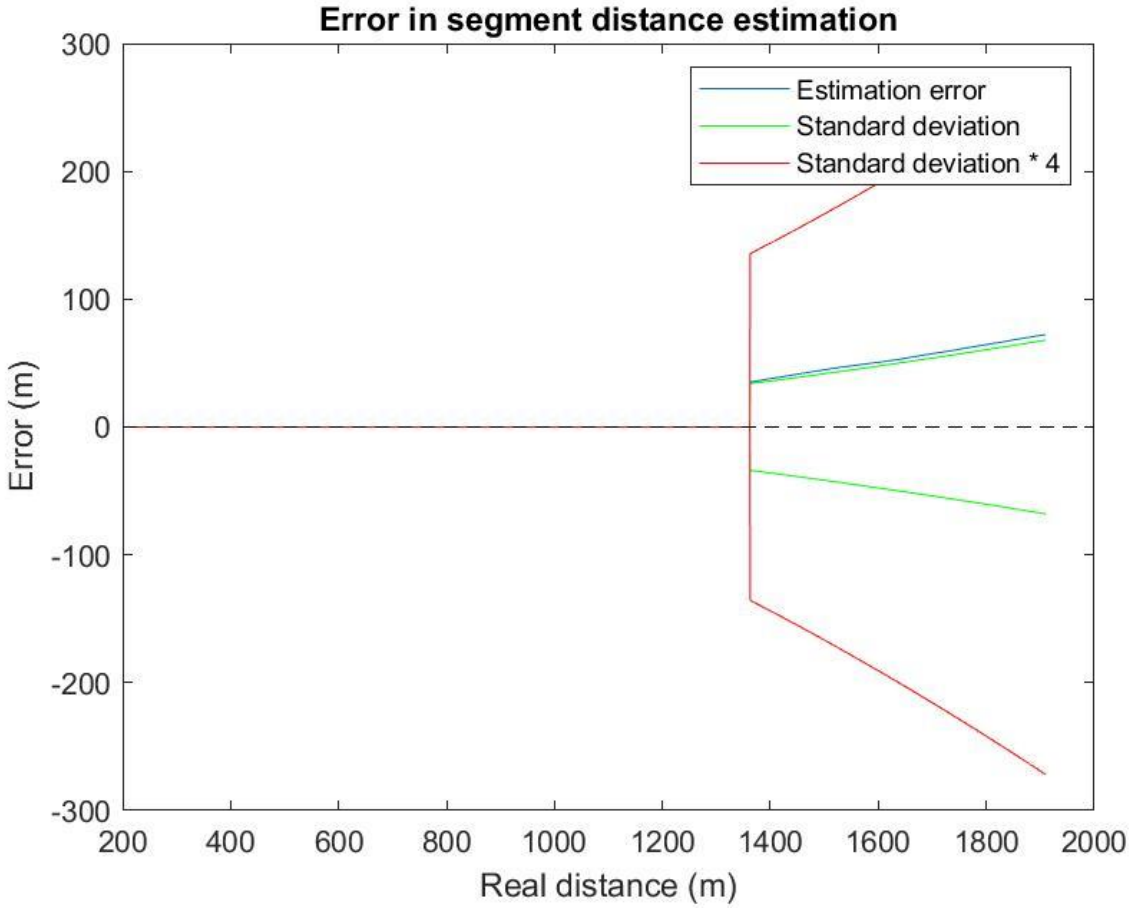

Figure 38 Segment distance error

8.11.2.3 Speed Error

In this test, the accelerometer introduces an extra error in speed determination which has an impact on the overall travelled distance performance. In order to show this impact the following Figure 39 is shown. The illustration shows some values until the train is positioned but it is not until the point the segment id is known that it shall be analysed. At this point, it can be seen the real speed, the error introduced by the encoder as 1% and the deviation introduced by the accelerometer sensor integration to determine the speed computation.

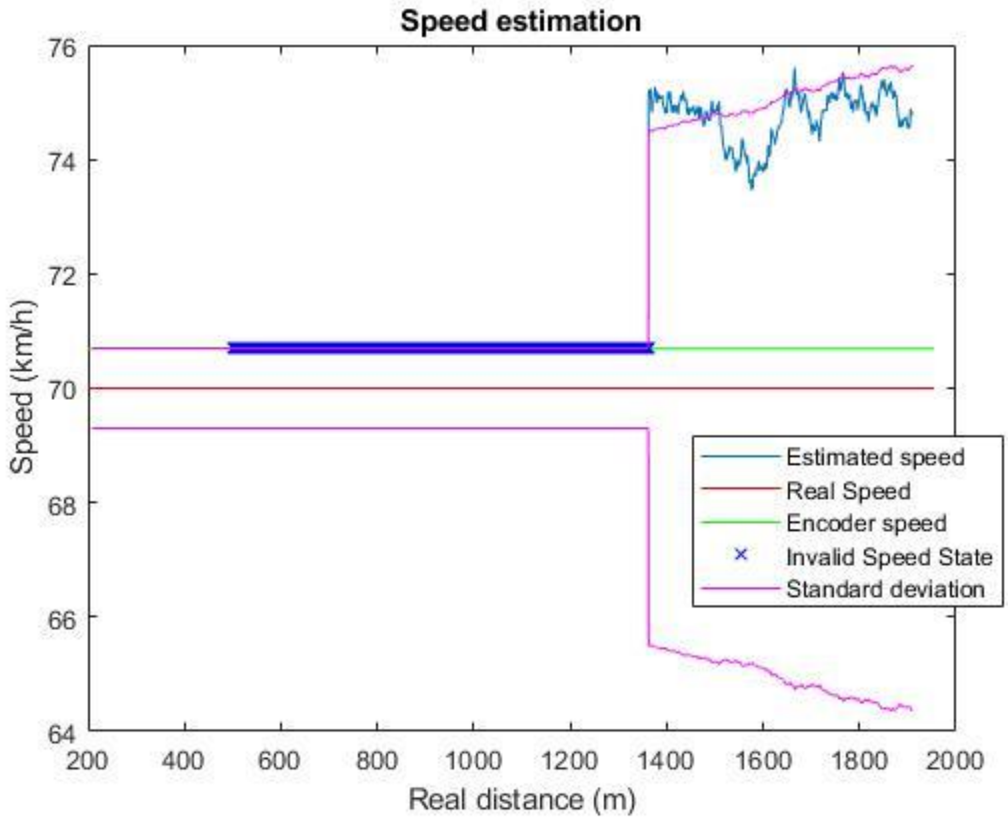

Figure 39 Speed error

8.11.2.4 Conclusion

The test is considered passed because the train is positioned but it is clear that an STD of 0.4 within the test induces a bad speed estimation, that it is compensated by the gyroscope readings at the travel distance.

8.12 Test Case 12

8.12.1 Test Definition

8.12.1.1 Description

Test Equal to Test Case 2

8.12.1.2 Input Error Specification:

Accelerometer noise is 10 times greater than Test Case 2

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.4\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 10 Error definition for test.

8.12.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.12.2 Test Results

8.12.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is achieved.

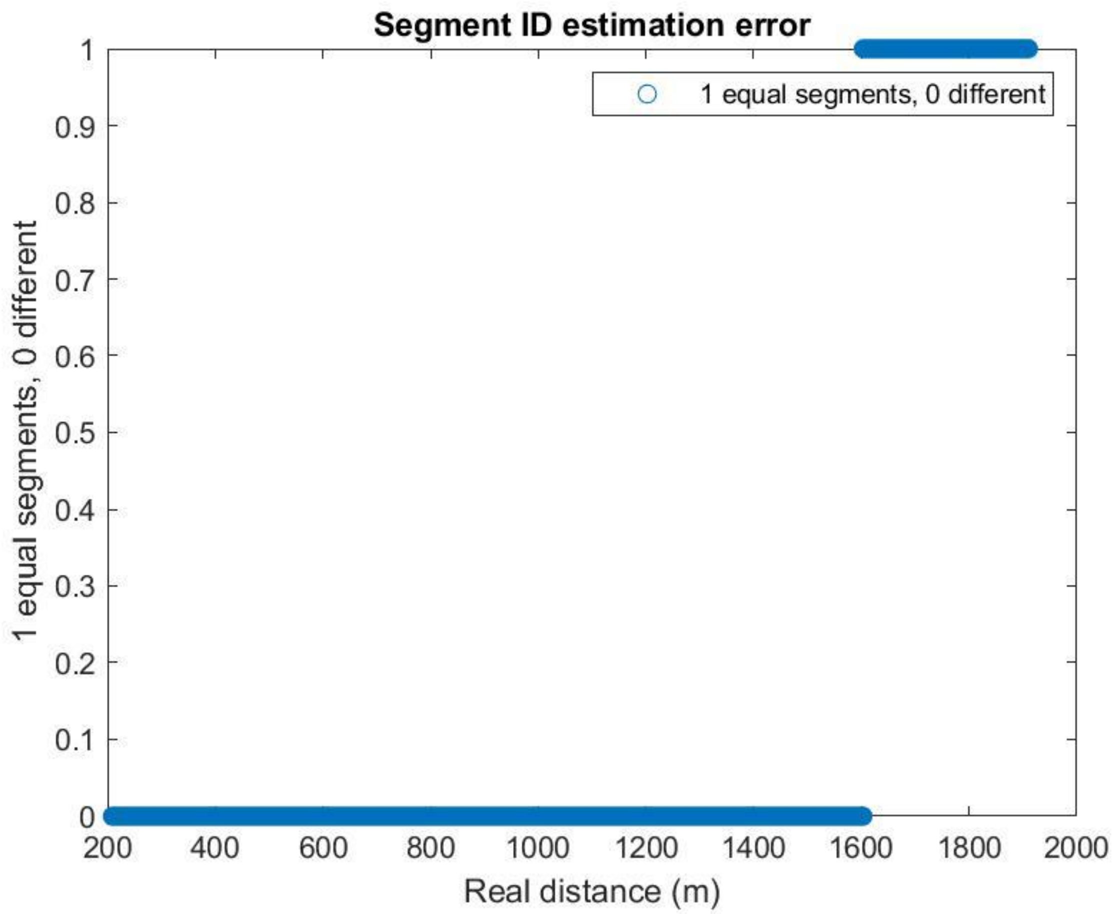

Figure 40 Segment determination illustration, 0 segment not located, 1 segment located

8.12.2.2 Distance Error

In the following illustration it is shown the estimation error where the estimated travelled distance is just above the standard deviation. This illustration, if compared to the results from Test Case 2 it can be seen that the performance it is slightly worst. This behaviour makes sense because the travelled distance is directly related to the speed estimation and the speed estimation is biased by the accelerometer errors.

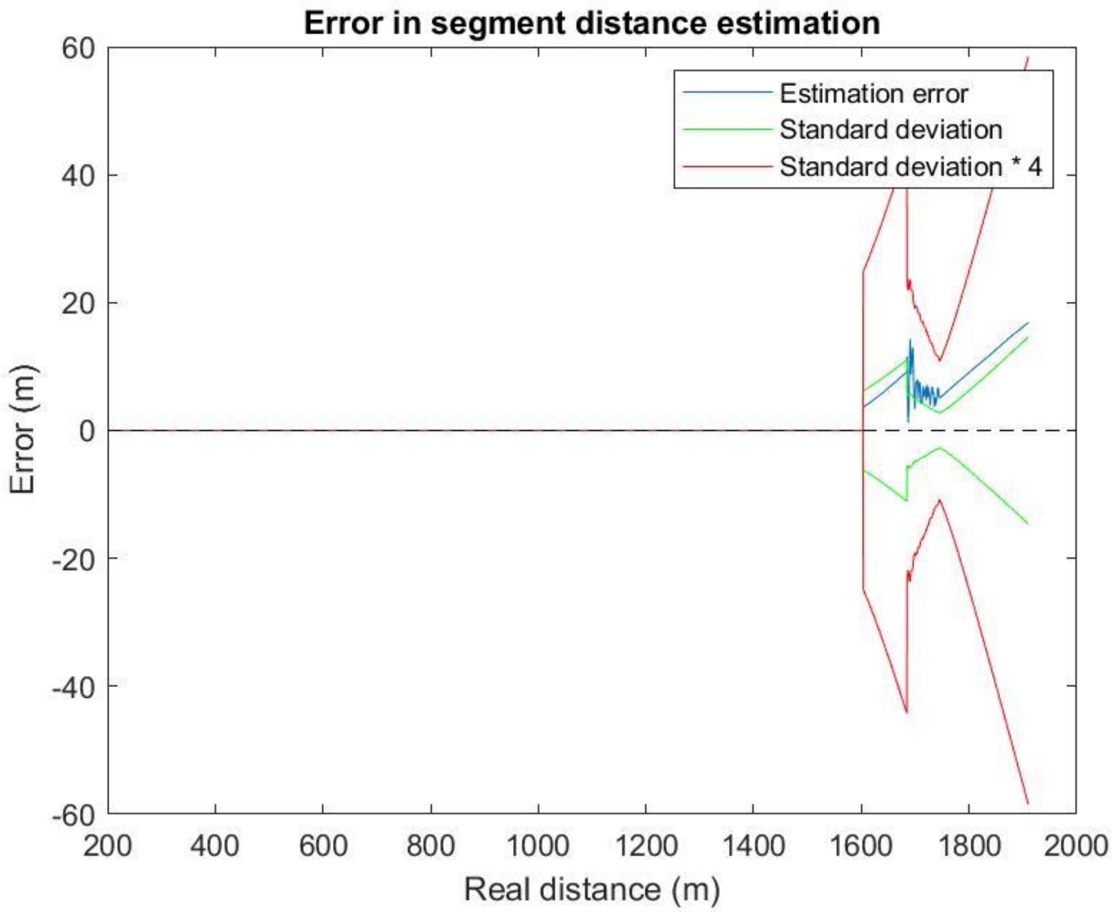

Figure 41 Segment distance error

8.12.2.3 Speed Error

In this test, the accelerometer introduces an extra error in speed determination which has an impact on the overall travelled distance performance. In order to show this impact the following Figure 42 is shown. The illustration shows some values until the train is positioned but it is not until the point the segment id is known that it shall be analysed. At this point, it can be seen the real speed, the error introduced by the encoder as 1% and the deviation introduced by the accelerometer sensor integration to determine the speed computation.

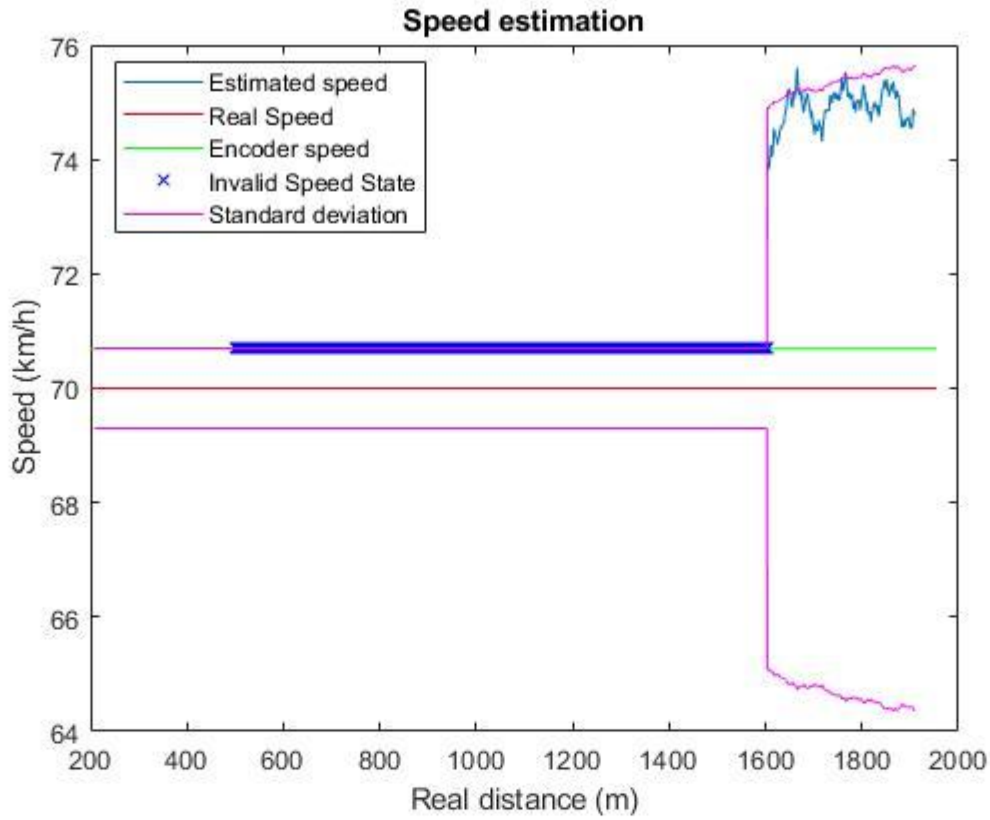

Figure 42 Speed error

8.12.2.4 Conclusion

The test is considered passed because the train is positioned but it is clear that an STD of 0.4 within the test induces a bad speed estimation, that it is compensated by the gyroscope readings at the travel distance.

8.13 Test Case 13

8.13.1 Test Definition

8.13.1.1 Description

Test Equal to Test Case 2

8.13.1.2 Input Error Specification:

In comparison to Test Case 2, this test introduces GNSS error as STD 0.00003 meters with a correlation factor of 0.9.

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	$\omega_k\{STD = 0.00003\}, \alpha = 0.9$	Yes

Table 11 Error definition for test.

8.13.1.3 Expected result of the Test

The train position is INVALID until it passes the first segment. After this first segment is passed and before the end of the second segment the position shall be valid.

8.13.2 Test Results

8.13.2.1 Segment determination

In the following illustration, it can be seen that the position’s segment determination is achieved.

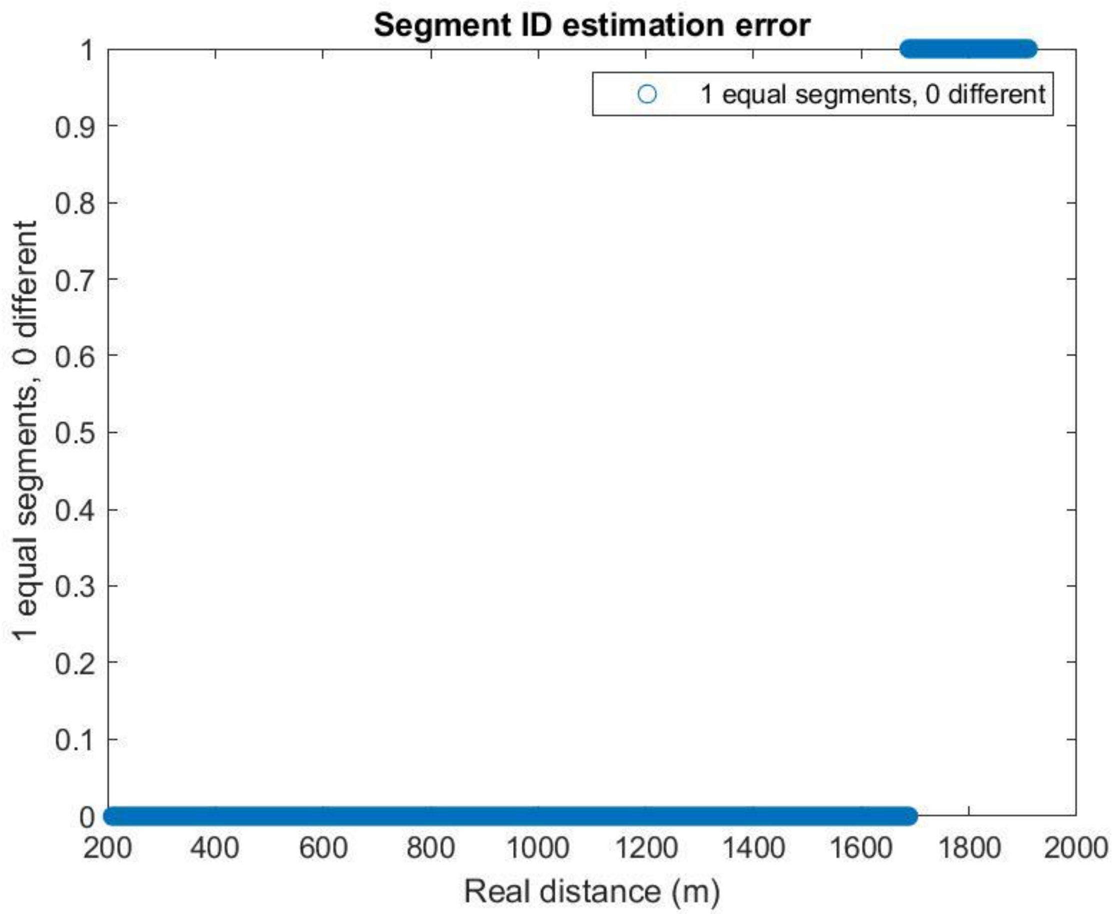

Figure 43 Segment determination illustration, 0 segment not located, 1 segment located

8.13.2.2 Distance Error

In the following illustration it is shown the estimation error where the estimated travelled distance is just above the standard deviation. This illustration, if compared to the results from Test Case 2 it can be seen that the distance at which a valid position is provided occurs later, around 1700 meters. But due to the good gyroscope and accelerometer values the overall performance once positioned is similar.

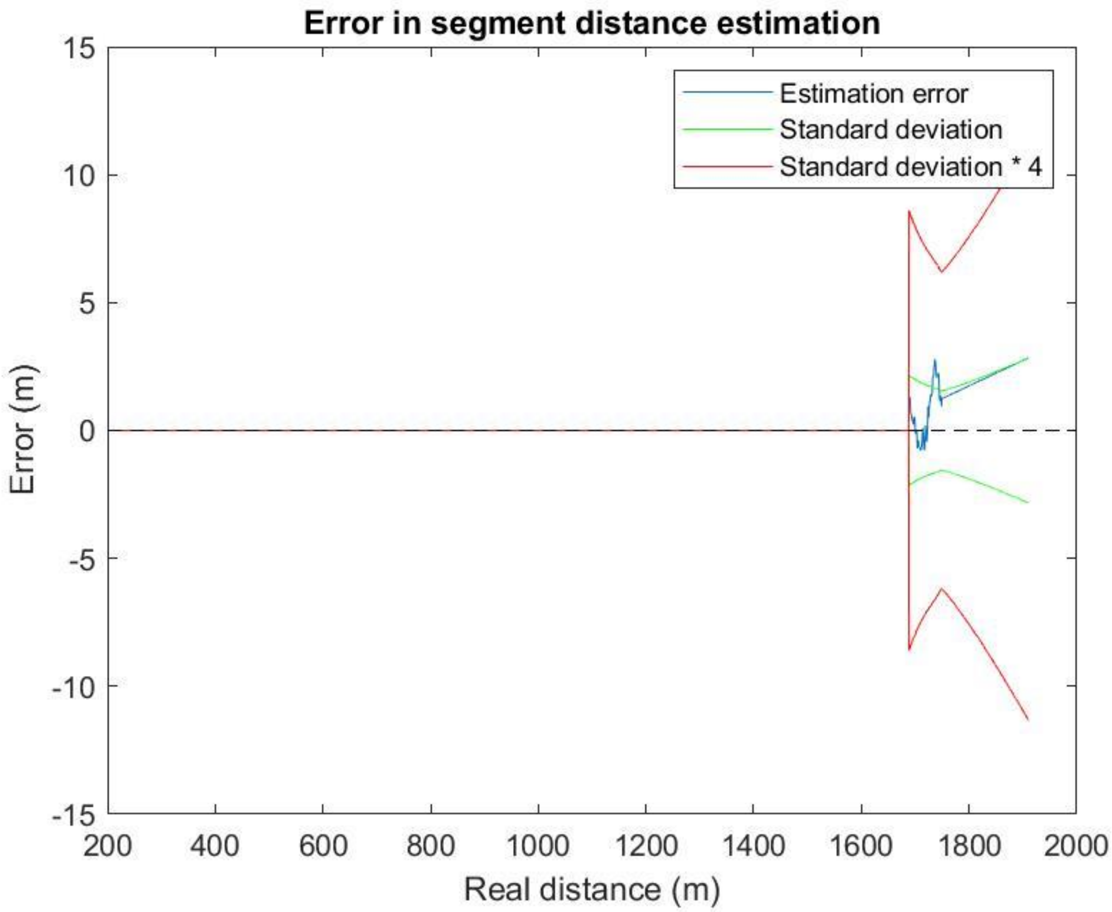

Figure 44 Segment distance error

8.13.2.3 Conclusion

The test is considered passed because the train is positioned but it is clear that a GNSS error induces an initial position estimation that delays the positioning of the train.

8.14 Test Case 21

8.14.1 Test Definition

8.14.1.1 Description

The train is switched on Route 17 (Rt17) in a track that is divided by a switch point as shown in section 6.3.3. The train has Invalid position at the start off. The train starts moving at 70km/h from the start to the end at constant speed.

8.14.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}$, $\alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}$, $\alpha = 0$	No
Err_PVT	No	No	No

Table 12 Error definition for test.

8.14.1.3 Expected result of the Test

The train position has a VALID position from the start of the test case because there is not any other track around. Once the train reaches the switch point it is accepted to have an INVALID position for certain distance. However, before the end of the second segment the position shall be valid again.

8.14.2 Test Results

8.14.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached from the beginning because there is not any other parallel track. The uncertainty of track determination it reaches when the train starts passing the switch point where two new candidate segments are present. At this point, until the reading of the IMU determines where the train moved to there is a time without segment determination. Finally, the test results how is the algorithm is able to determine the position of the train.

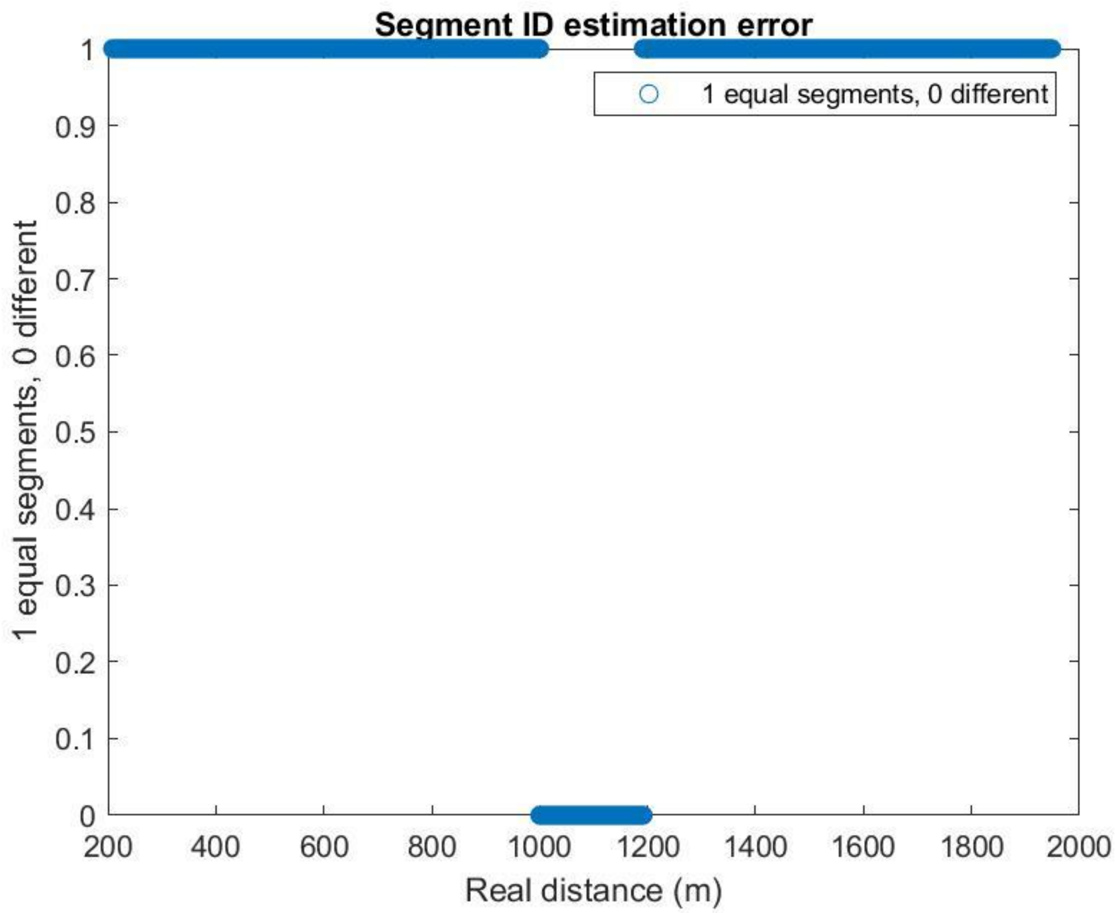

Figure 45 Segment determination illustration, 0 segment not located, 1 segment located

8.14.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value until 1000 meters which means that the error grows linearly with the travelled distance until it reaches the switch point. At this point in time, the figure shows zero error value due to the absence of segment determination not because is zero error value. Once the train is positioned there is a straight jump into the new segment value. Notice that this test case is based on a straight line and therefore the IMU information allows to determine the track by exclusion.

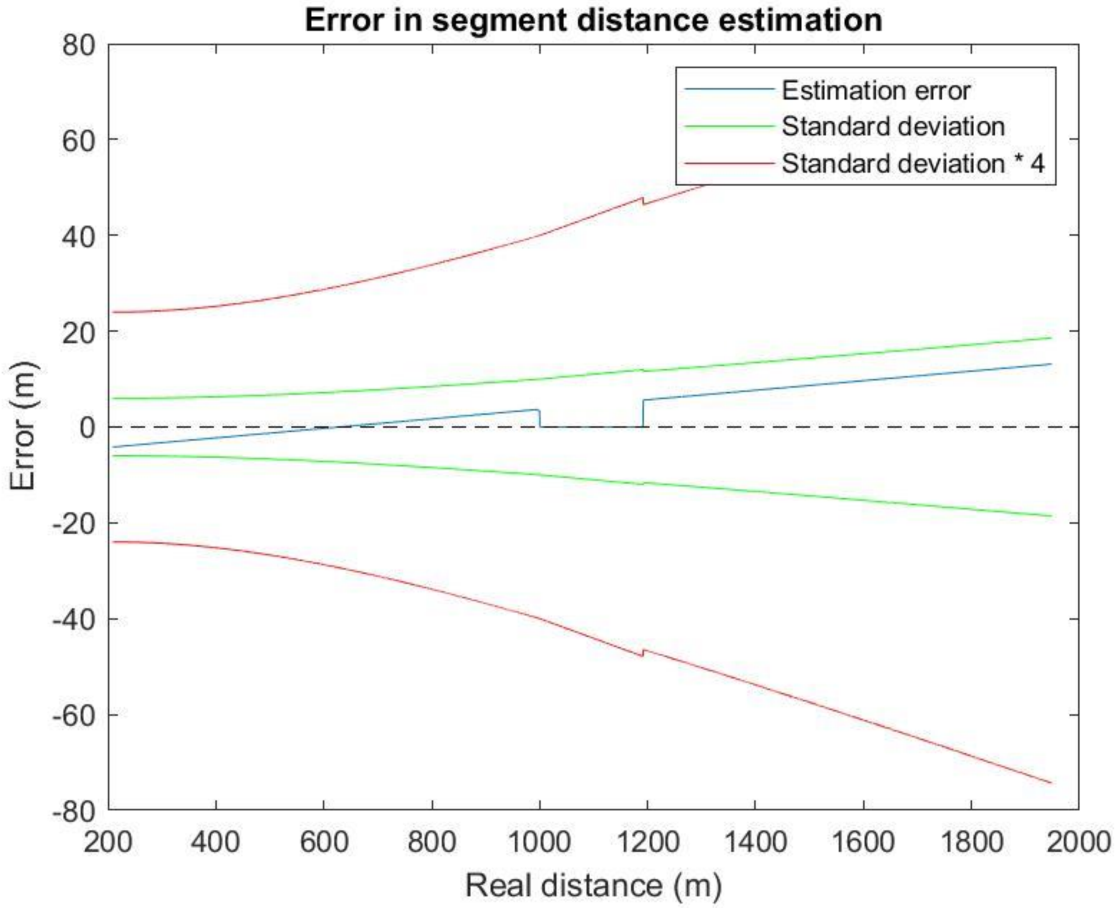

Figure 46 Segment distance error

8.14.2.3 Conclusion

The test is considered passed. The test show case the possibility of detecting the segment taken after a switch point.

8.15 Test Case 22

8.15.1 Test Definition

8.15.1.1 Description

The train is switched on Route 18 (Rt18) in a track that is divided by a switch point as shown in section 6.3.3. The train has Invalid position at the start off. The train starts moving at 70km/h from the start to the end at constant speed.

8.15.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 13 Error definition for test.

8.15.1.3 Expected result of the Test

The train position has a VALID position from the start of the test case because there is not any other track around. Once the train reaches the switch point it is accepted to have an INVALID position for certain distance. However, before the end of the second segment the position shall be valid again.

8.15.2 Test Results

8.15.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached from the beginning because there is not any other parallel track. The uncertainty of track determination it reaches when the train starts passing the switch point where two new candidate segments are present. At this point, until the reading of the IMU determines where the train moved to there is a time without segment determination. Finally, the test results how is the algorithm is able to determine the position of the train.

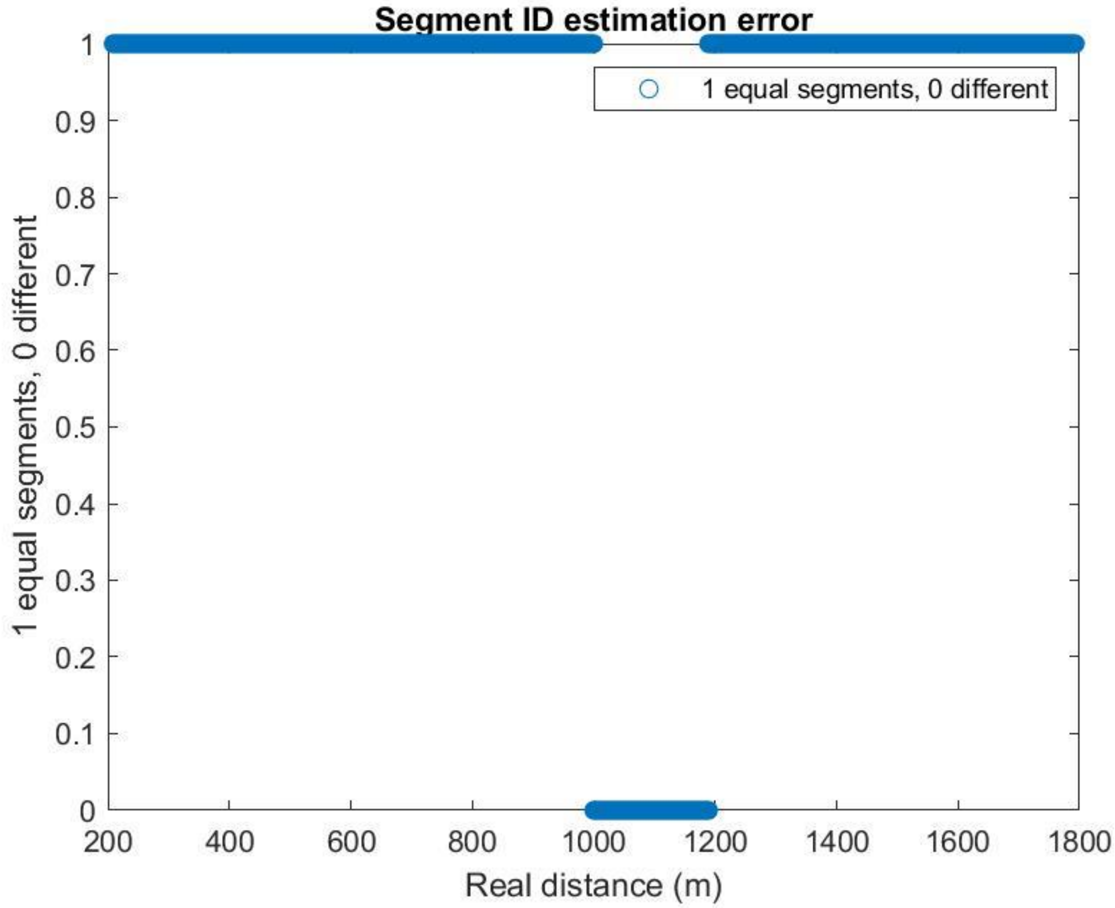

Figure 47 Segment determination illustration, 0 segment not located, 1 segment located

8.15.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value until 1000 meters which means that the error grows linearly with the travelled distance until it reaches the switch point. At this point in time, the figure shows zero error value due to the absence of segment determination not because is zero error value. Once the train is positioned there some perturbation to the distance calculation due to the IMU signal input that directly affects the positioning. Notice that the standard deviation is greatly reduced thanks to the reading of the IMU.

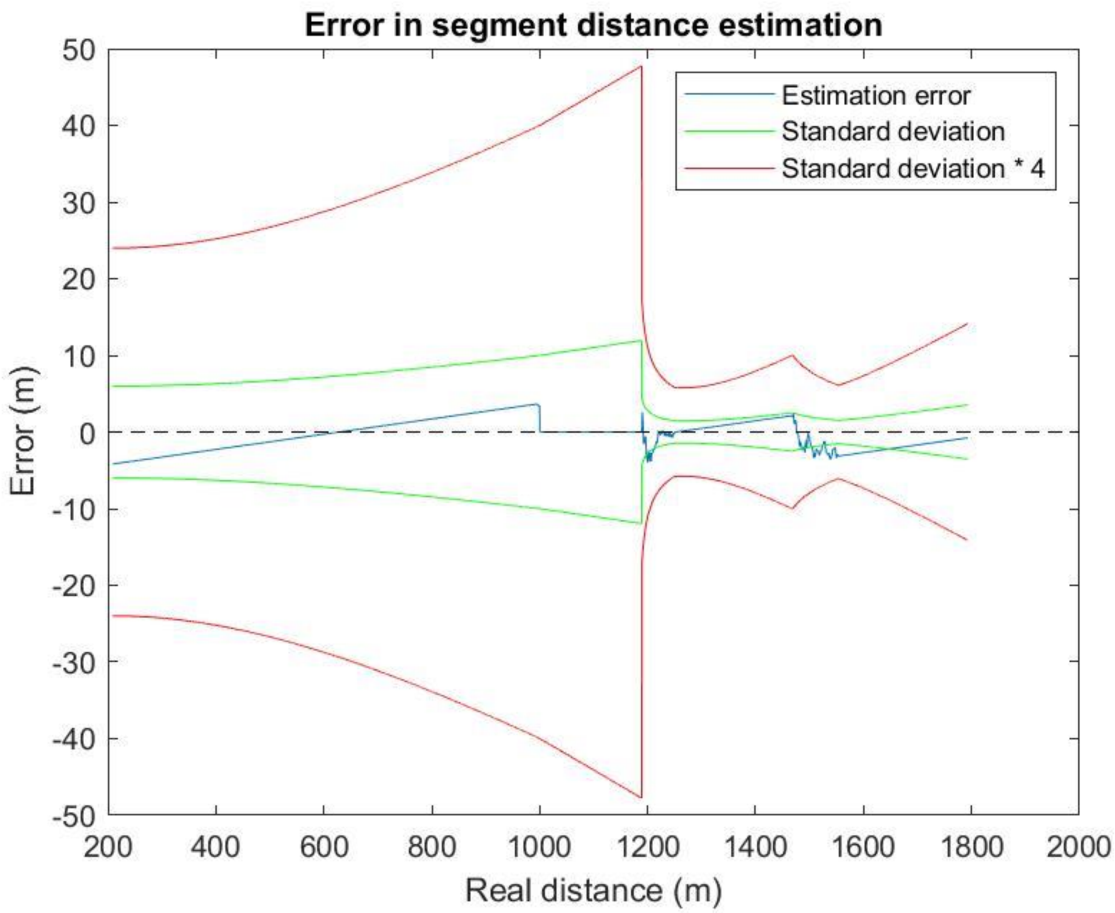

Figure 48 Segment distance error

8.15.2.3 Conclusion

The test is considered passed. The test show case the possibility of detecting the segment taken after a switch point.

8.16 Test Case 23

8.16.1 Test Definition

8.16.1.1 Description

The train is switched on Route 17 (Rt17) in a track that is divided by a switch point as shown in section 6.3.3. The train has Invalid position at the start off. The train starts moving at 5km/h from the start to the end at constant speed.

8.16.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\},\, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\},\, \alpha = 0$	No
Err_PVT	No	No	No

Table 14 Error definition for test.

8.16.1.3 Expected result of the Test

The train position has a VALID position from the start of the test case because there is not any other track around. Once the train reaches the switch point it is accepted to have an INVALID position for certain distance. However, before the end of the second segment the position shall be valid again.

8.16.2 Test Results

8.16.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached from the beginning because there is not any other parallel track. The uncertainty of track determination it reaches when the train starts passing the switch point where two new candidate segments are present. At this point, until the reading of the IMU determines where the train moved to there is a time without segment determination. Finally, the test results how is the algorithm is able to determine the position of the train.

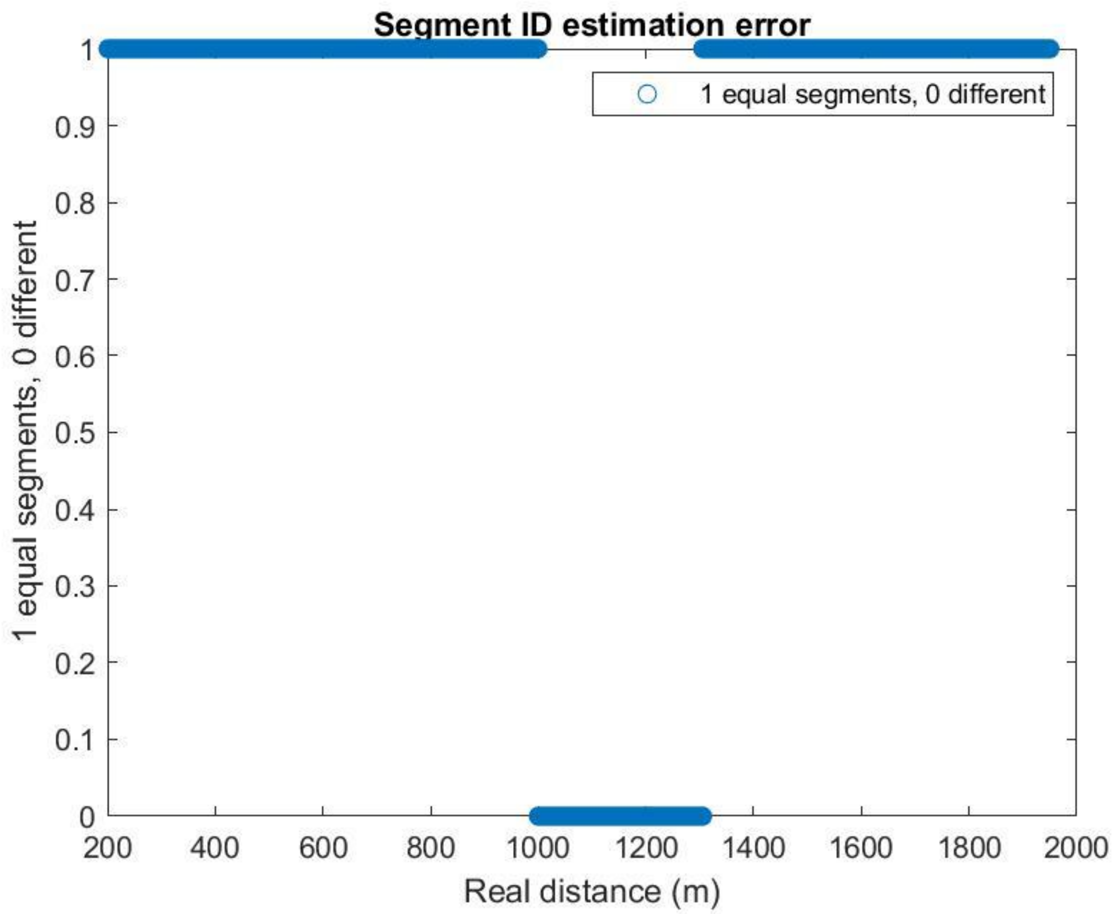

Figure 49 Segment determination illustration, 0 segment not located, 1 segment located

8.16.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value until 1000 meters which means that the error grows linearly with the travelled distance until it reaches the switch point. At this point in time, the figure shows zero error value due to the absence of segment determination not because is zero error value. Once the train is positioned there is a straight jump into the new segment value. Notice that this test case is based on a straight line and therefore the IMU information allows to determine the track by exclusion. In comparison with Test Case 21, the confidence interval associated to the positioning is greater this time, this is mainly due to the limited speed/curvature relation of this test running at 5km/h.

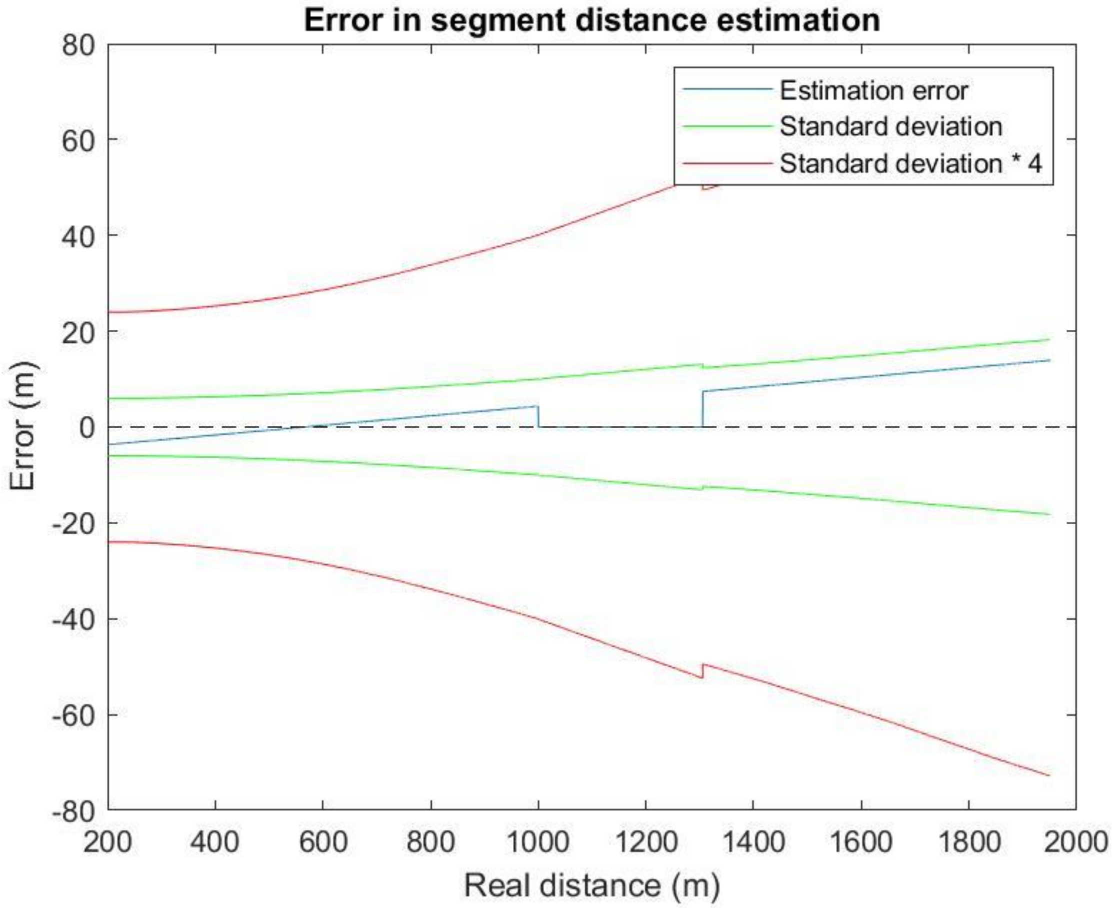

Figure 50 Segment distance error

8.16.2.3 Gyroscope Reading Detail

In the following illustration the relation of the gyroscope reading versus the estimated position curvature is shown. The noise of the gyroscope is proportional to the test case definition values.

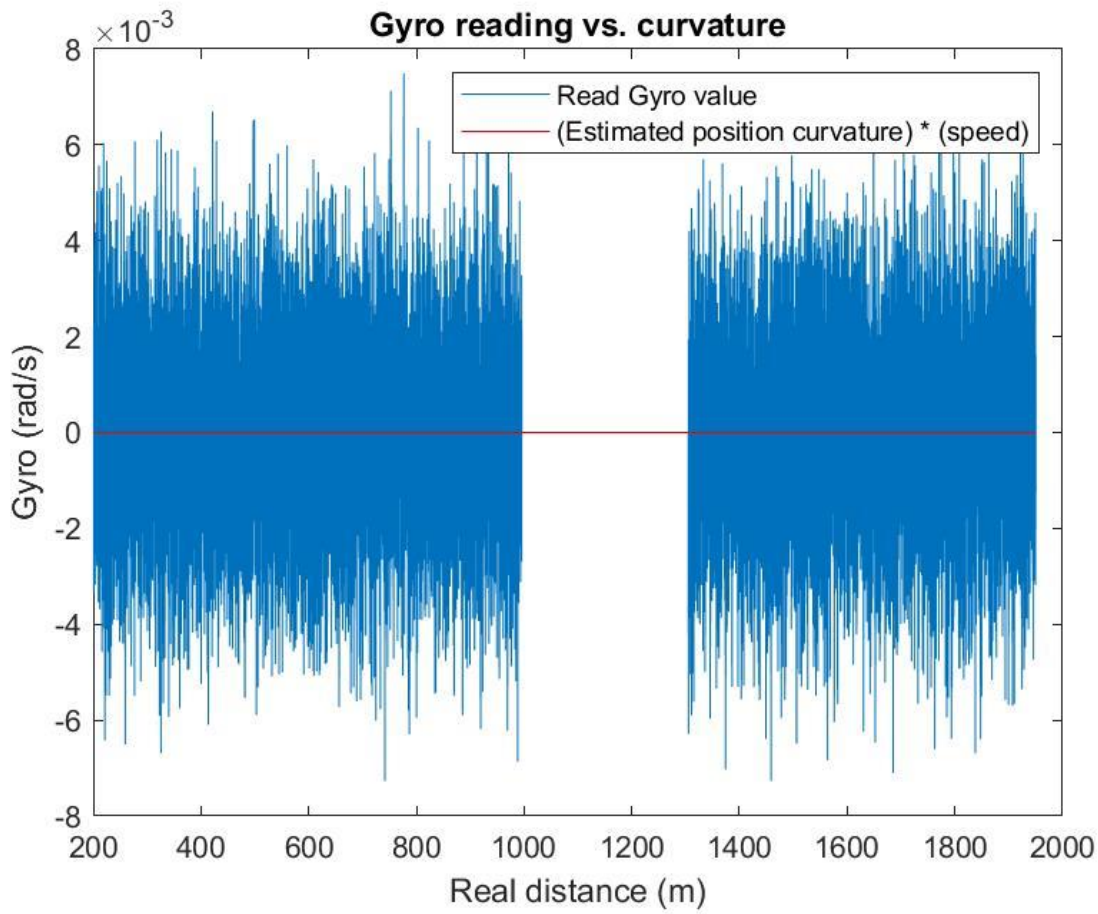

Figure 51 Vertical Gyroscope reading

8.16.2.4 Conclusion

The test is considered passed

8.17 Test Case 24

8.17.1 Test Definition

8.17.1.1 Description

The train is switched on Route 18 (Rt18) in a track that is divided by a switch point as shown in section 6.3.3. The train has Invalid position at the start off. The train starts moving at 5km/h from the start to the end at constant speed.

8.17.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 15 Error definition for test.

8.17.1.3 Expected result of the Test

The train position has a VALID position from the start of the test case because there is not any other track around. Once the train reaches the switch point it is accepted to have an INVALID position for certain distance. However, before the end of the second segment the position shall be valid again.

8.17.2 Test Results

8.17.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is reached from the beginning at the beginning because there is not any other parallel track. The uncertainty of track determination it reaches when the train starts passing the switch point where two new candidate segments are present. At this point, until the reading of the IMU determines where the train moved to there is a time without segment determination. Finally, the test results how is the algorithm is able to determine the position of the train.

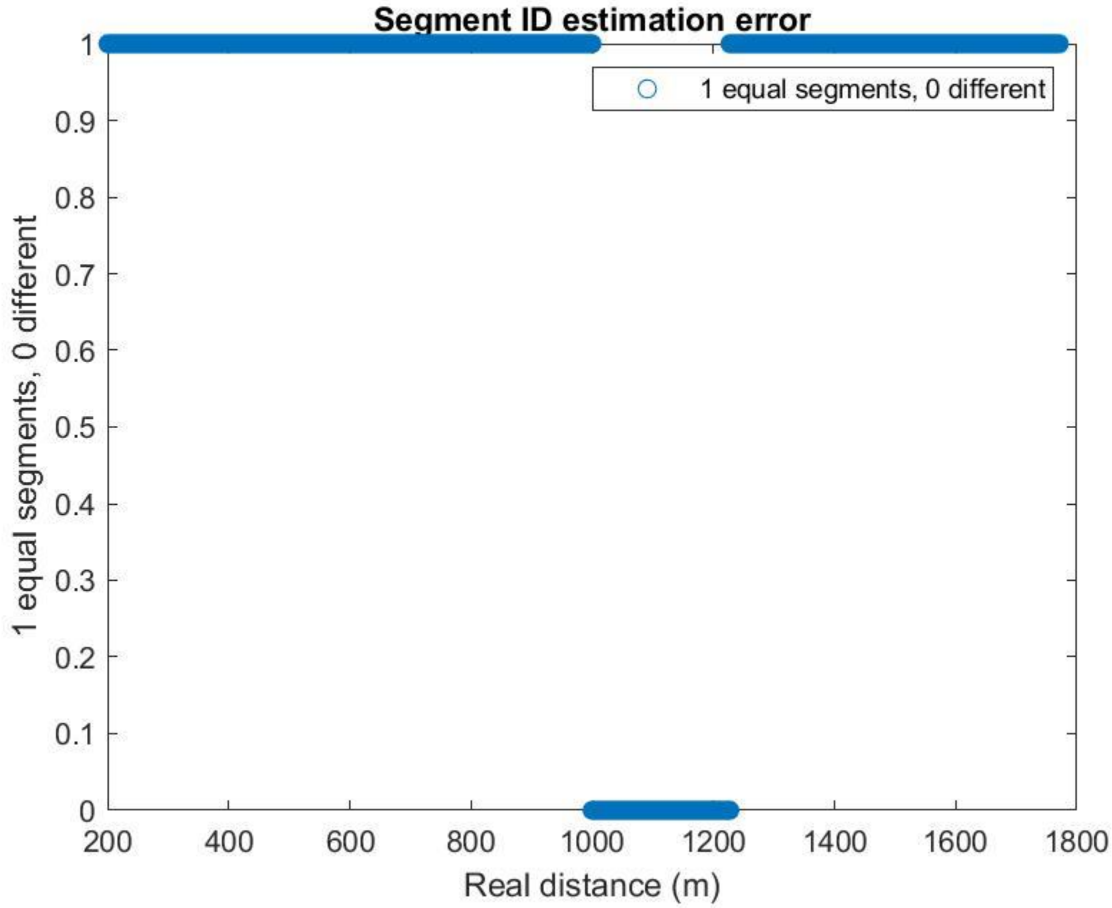

Figure 52 Segment determination illustration, 0 segment not located, 1 segment located

8.17.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value until 1000 meters which means that the error grows linearly with the travelled distance until it reaches the switch point. At this point in time, the figure shows zero error value due to the absence of segment determination not because is zero error value. Once the train is positioned there some perturbation to the distance calculation due to the IMU signal input that directly affects the positioning. Notice that if this test is compared to Test Case 23, it can be seen that the train is positioned earlier around 1200m. This is because in route 18 there is a curve that determines the position of the train whereas in route 17 the train is positioned by discarding any other possibility.

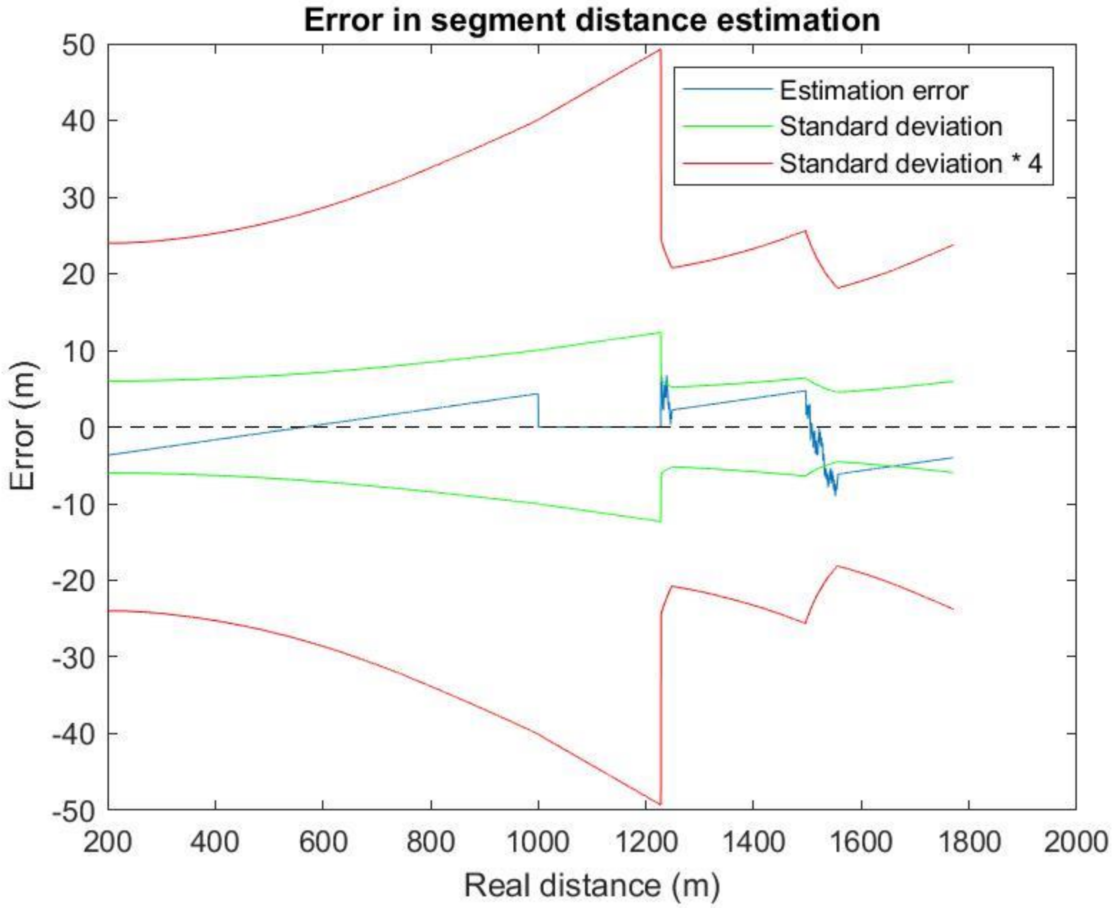

Figure 53 Segment distance error

8.17.2.3 Gyroscope Reading Detail

In the following illustration, the relation of the gyroscope reading versus the estimated position curvature is shown. In this test, the train is positioned just at the curve and it can be seen that due to the low speed the gyroscope measurement noise is much greater than the estimated curvature but still enough to determine train positioning.

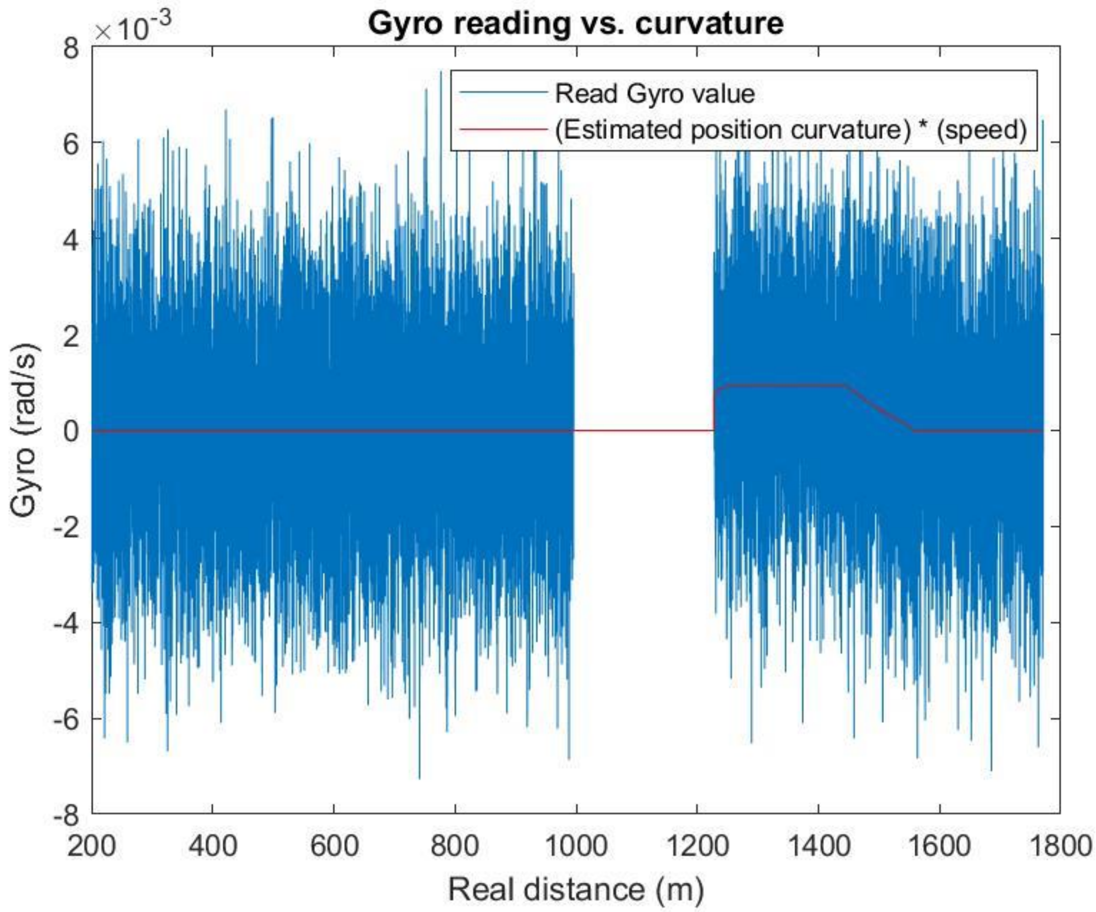

Figure 54 Vertical Gyroscope reading

8.17.2.4 Conclusion

The test is considered passed. The test show case the possibility of detecting the segment taken after a switch point.

8.18 Test Case 101

8.18.1 Test Definition

8.18.1.1 Description

The train is switched on Route 1 (Rt1) in a parallel track environment as shown in section 6.3.3. The train has valid position at the start off. The train starts moving at 70km/h from the start to the end at constant speed.

8.18.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 16 Error definition for test.

8.18.1.3 Expected result of the Test

The train position is valid from start to the end. The train is able to reduce the confidence interval because it passed a curve.

8.18.2 Test Results

8.18.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is always defined. This is because the train starts at a known position and there is not a switch in this test case. Notice that the single point of segment id at around 1000 meters refers to the one cycle difference that represents a 32ms difference between the simulation and the estimated position.

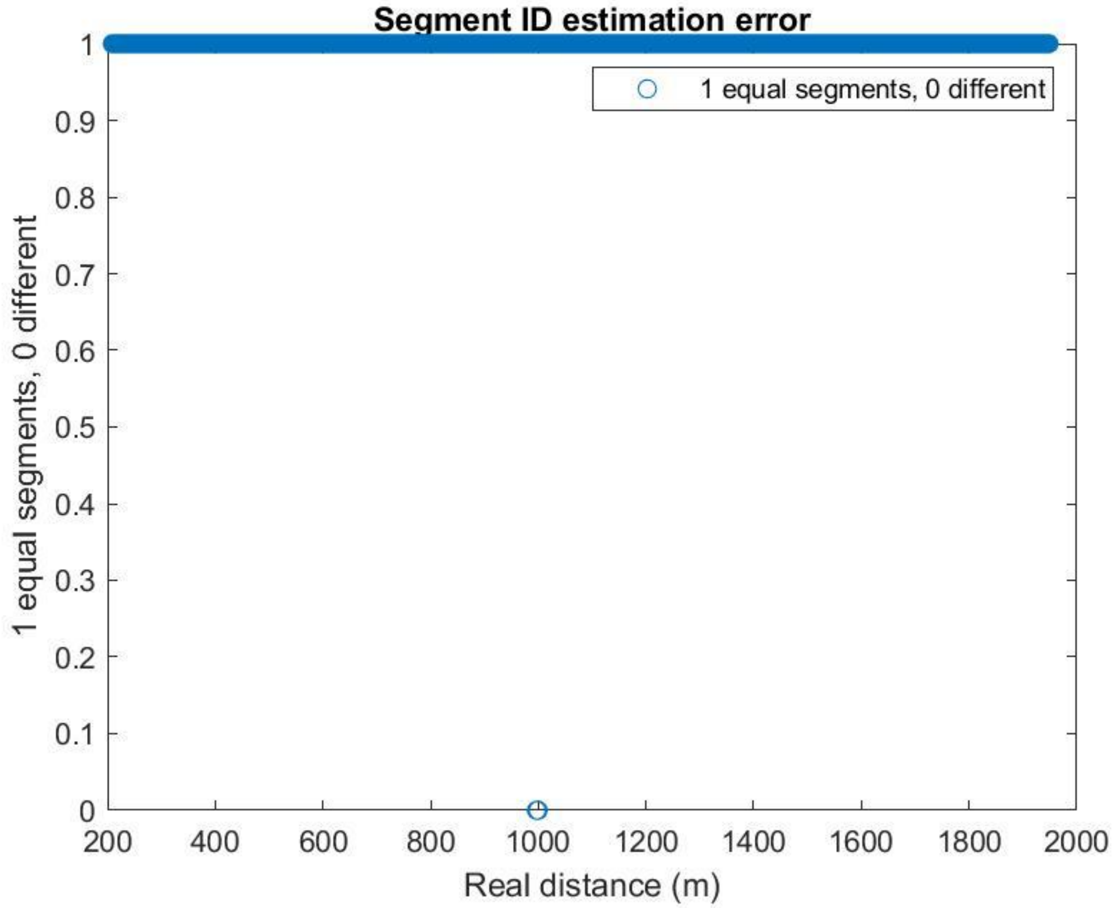

Figure 55 Segment determination illustration, 0 segment not located, 1 segment located

8.18.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value throughout the test and as there is no curve there is not a repositioning situation in the graph. Notice that due to the segment id single cycle discrepancy of the testing there is a peak at around 1000 meters but this does not represent repositioning.

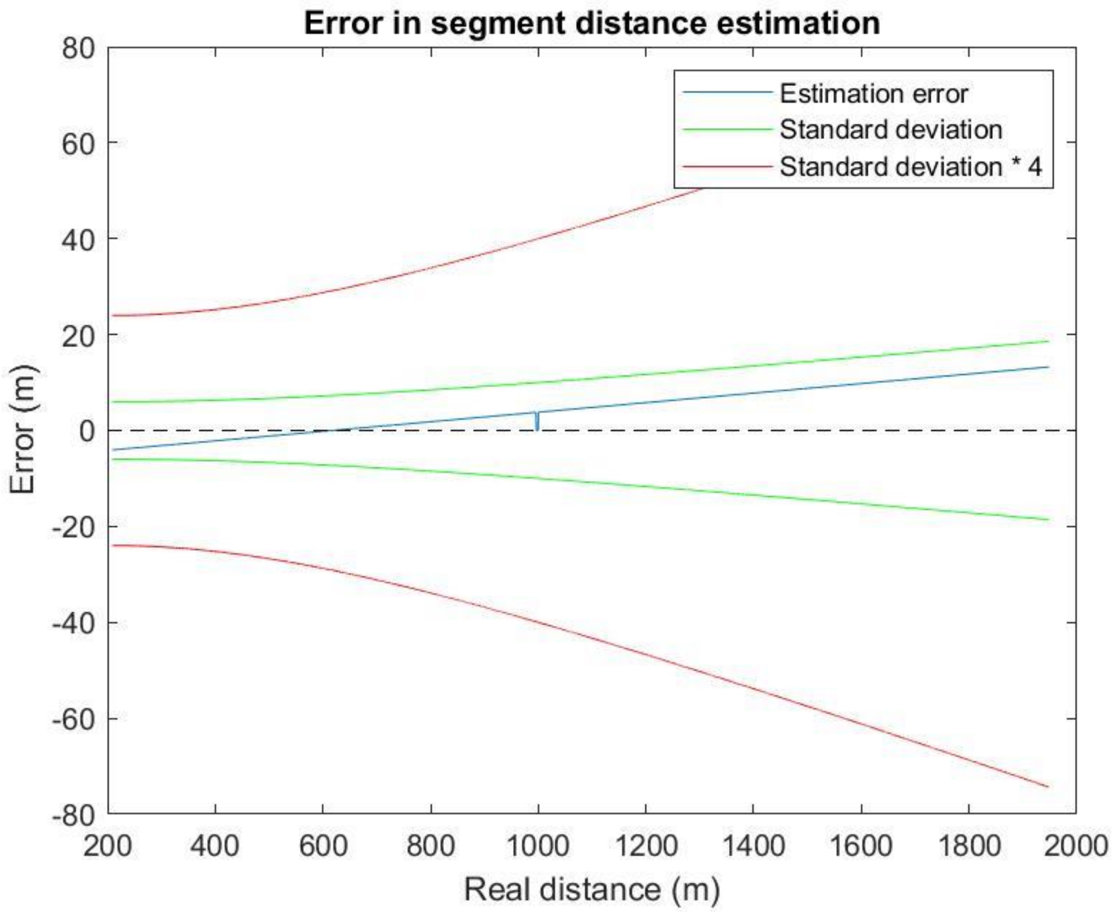

Figure 56 Segment distance error

8.18.2.3 Gyroscope Reading Detail

This behaviour can also be represented by the gyroscope values which as expected are noisy.

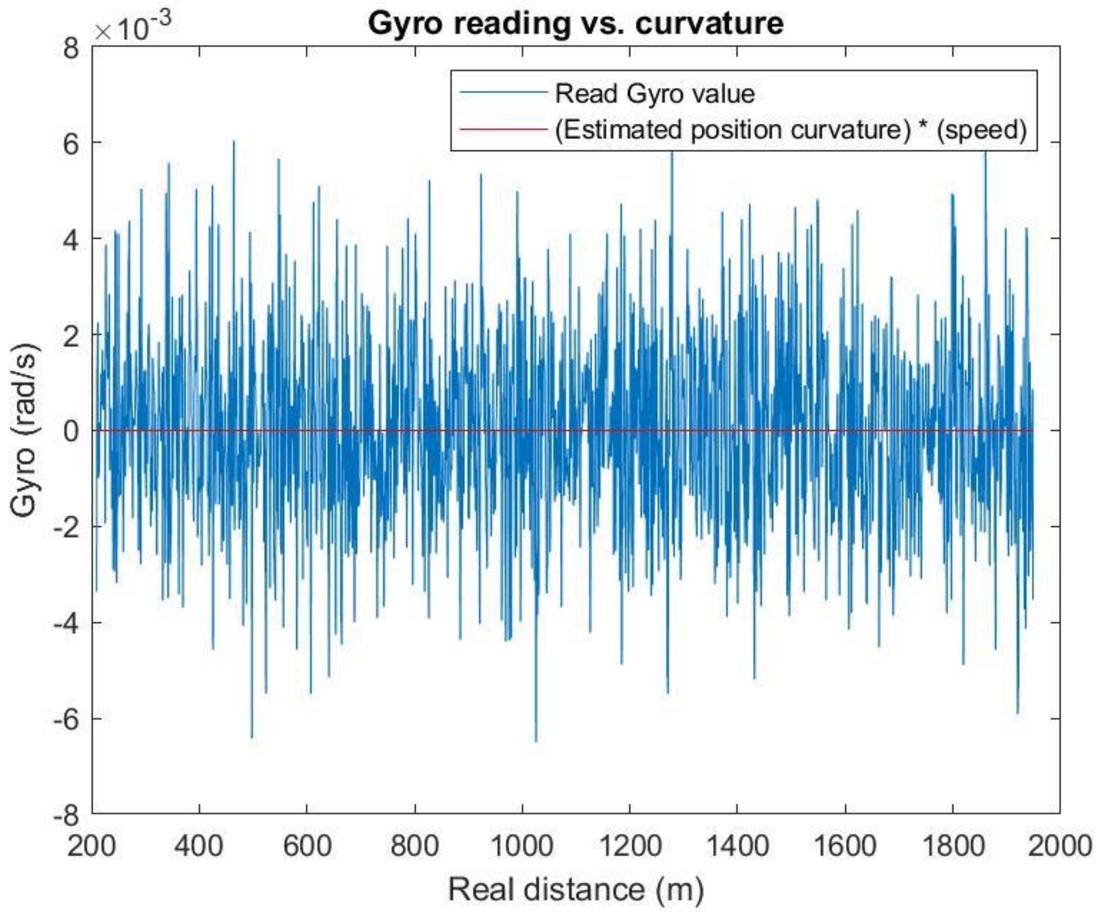

Figure 57 Gyroscope read value vs estimated curvature

8.18.2.4 Conclusion

The test is considered passed.

8.19 Test Case 102

8.19.1 Test Definition

8.19.1.1 Description

The train is switched on Route 2 (Rt2) in a parallel track environment as shown in section 6.3.3. The train has valid position at the start off. The train starts moving at 70km/h from the start to the end at constant speed.

8.19.1.2 Input Error Specification:

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}$, $\alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}$, $\alpha = 0$	No
Err_PVT	No	No	No

Table 17 Error definition for test.

8.19.1.3 Expected result of the Test

The train position is valid from start to the end. The train is able to reduce the confidence interval because it passed a curve.

8.19.2 Test Results

8.19.2.1 Segment determination

In the following illustration, it can be seen that the position's segment determination is always defined. This is because the train starts at a known position and there is not a switch in this test case. Notice that the single point of segment id at around 1000 meters refers to the one cycle difference that represents a 32ms difference between the simulation and the estimated position.

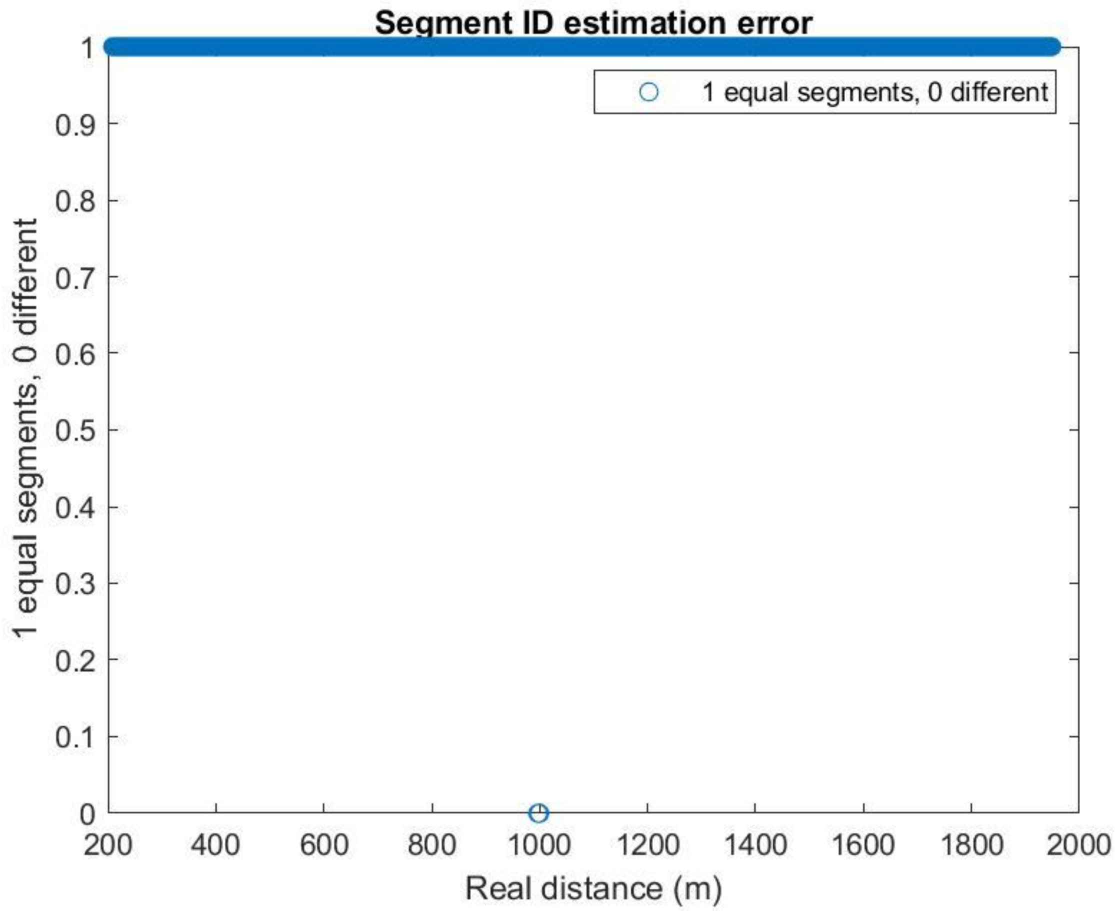

Figure 58 Segment determination illustration, 0 segment not located, 1 segment located

8.19.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value throughout the test and when the train starts the clothoid at 1200 meters the sensors start providing information which is reflected just before the end of the curve. So from 1200 to 1400 meters the windows to reposition the train occurs. As it can be seen, the standard deviation is reduced by a tenth almost.

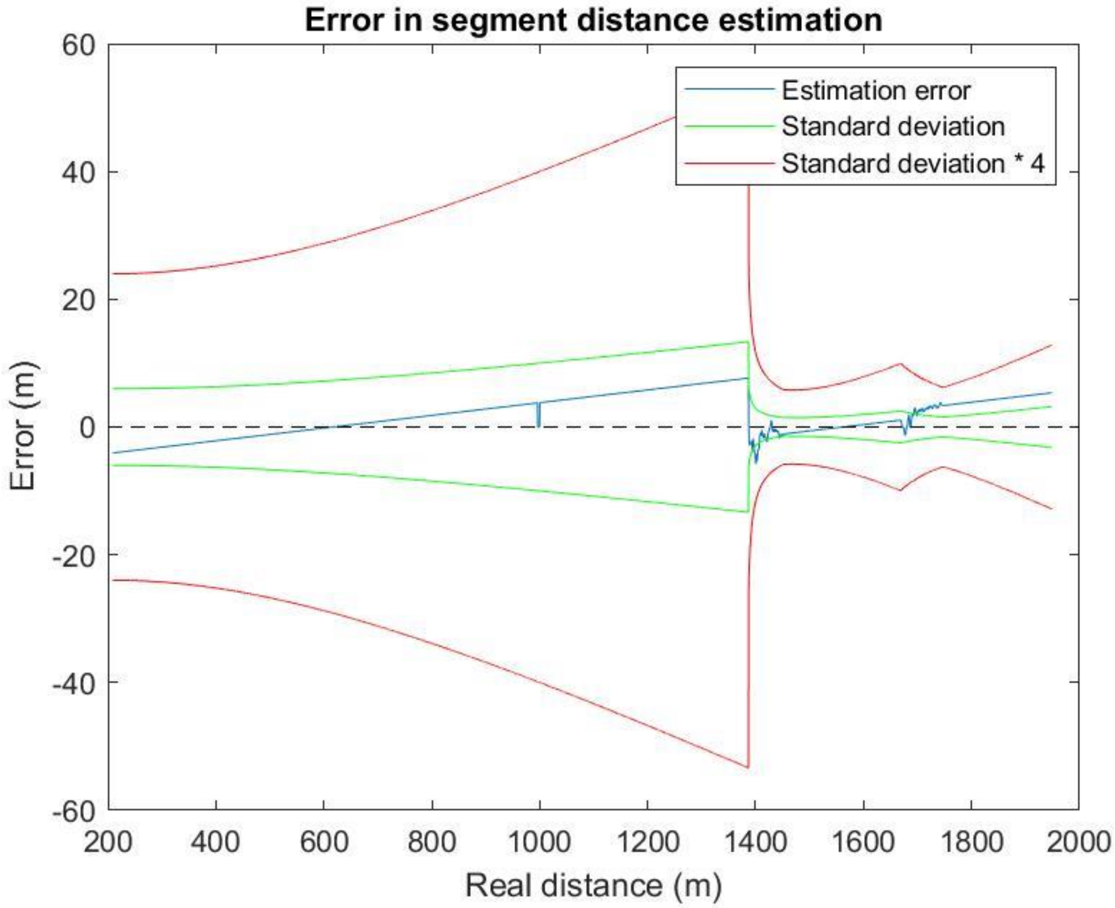

Figure 59 Segment distance error

8.19.2.3 Gyroscope Reading Detail

This behaviour can also be represented by the gyroscope values that show how the system is able to find out within the gyroscope signal the theoretical curvature that if matched with the digital map it enables the algorithm to obtain the repositioning.

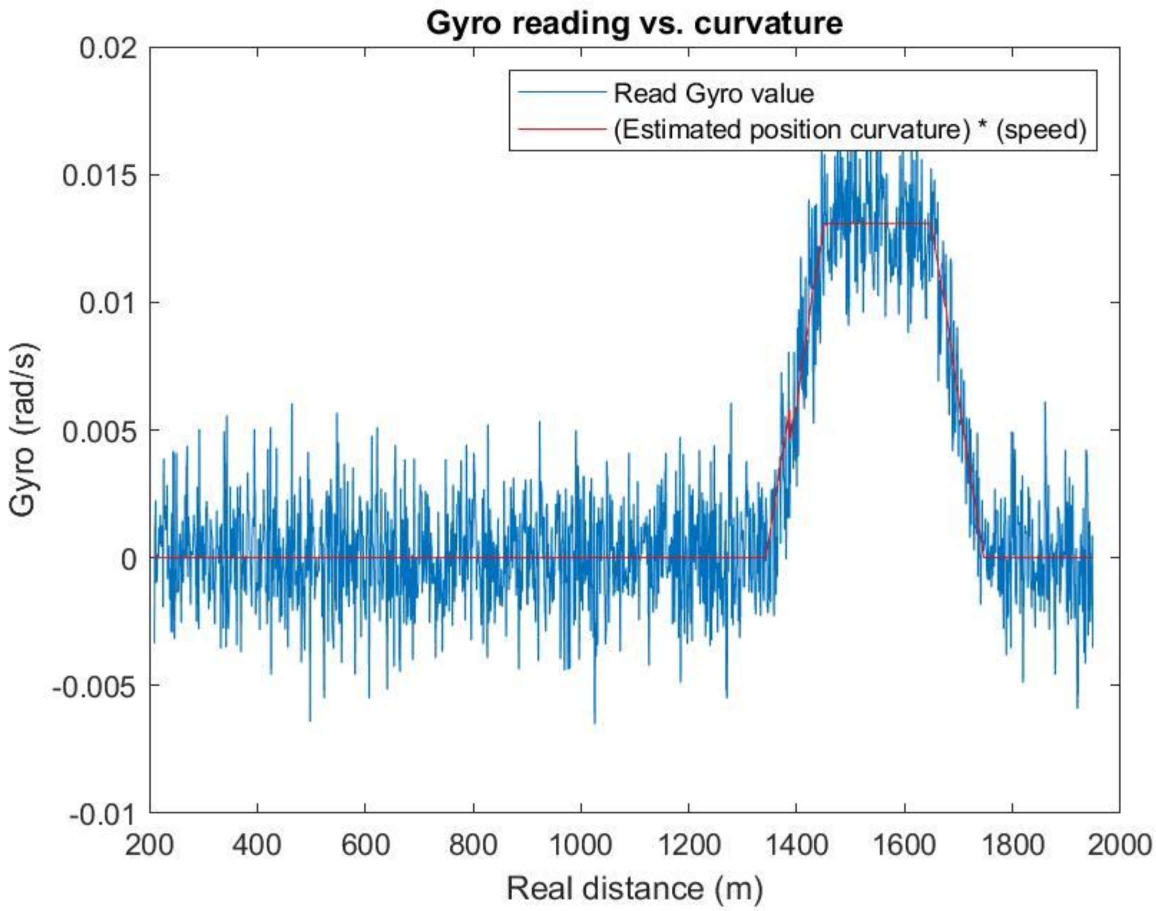

Figure 60 Gyroscope read value vs estimated curvature

8.19.2.4 Conclusion

The test is considered passed.

8.20 Test Case 103

8.20.1 Test Definition

8.20.1.1 Description

Test Case equal to Test Case 102 but 5km/h speed value.

8.20.1.2 Input Error Specification:

Test Case equal to Test Case 102.

8.20.1.3 Expected result of the Test

The train position is valid from start to the end. The train is able to reduce the confidence interval because it passed a curve.

8.20.2 Test Results

8.20.2.1 Segment determination

As shown in all 10x tests the segment determination is always known.

8.20.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value throughout the test and when the train starts the clothoid at 1200 meters the sensors start providing information which is reflected just before the end of the curve. So from 1200 to 1400 meters the windows to reposition the train occurs. As it can be seen, the standard deviation is reduced by a tenth almost.

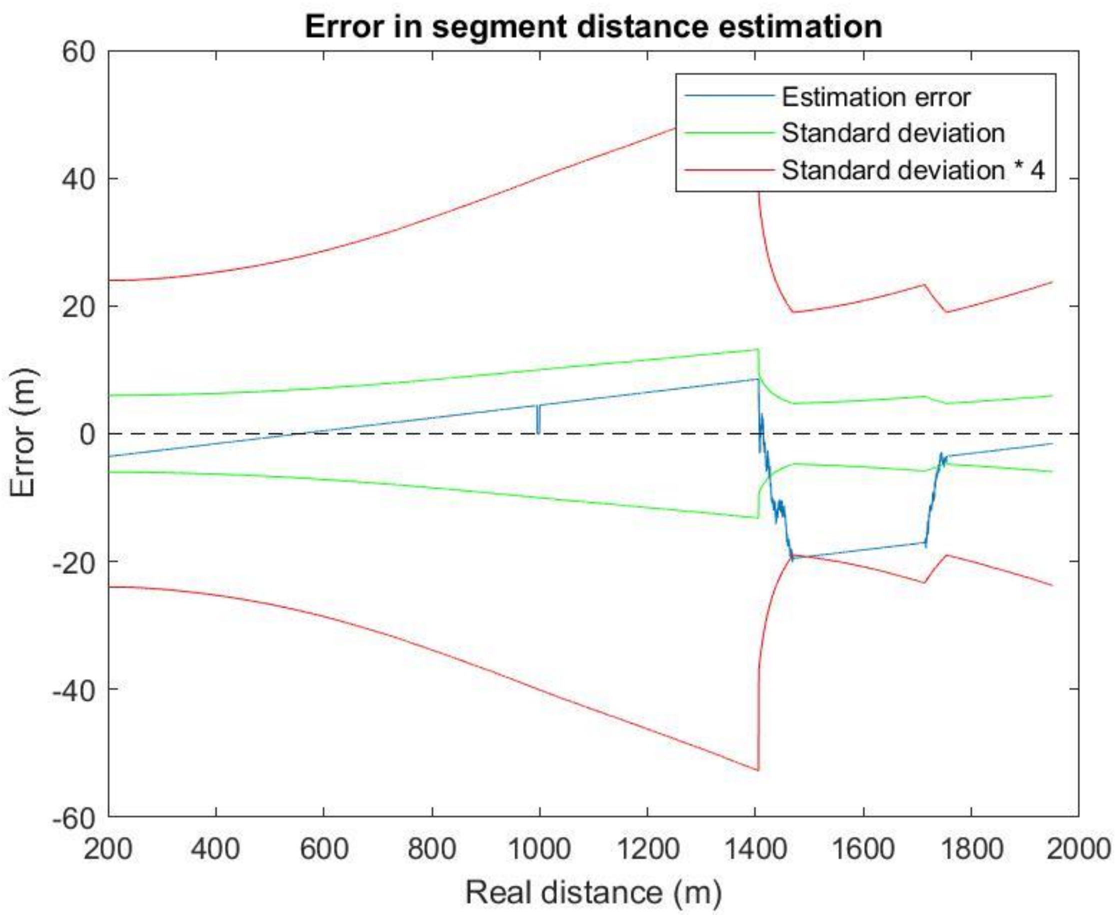

Figure 61 Segment distance error

8.20.2.3 Gyroscope Reading Detail

This behaviour can also be represented by the gyroscope values that show how the system is able to find out within the gyroscope signal the theoretical curvature that if matched with the digital map it enables the algorithm to obtain the repositioning.

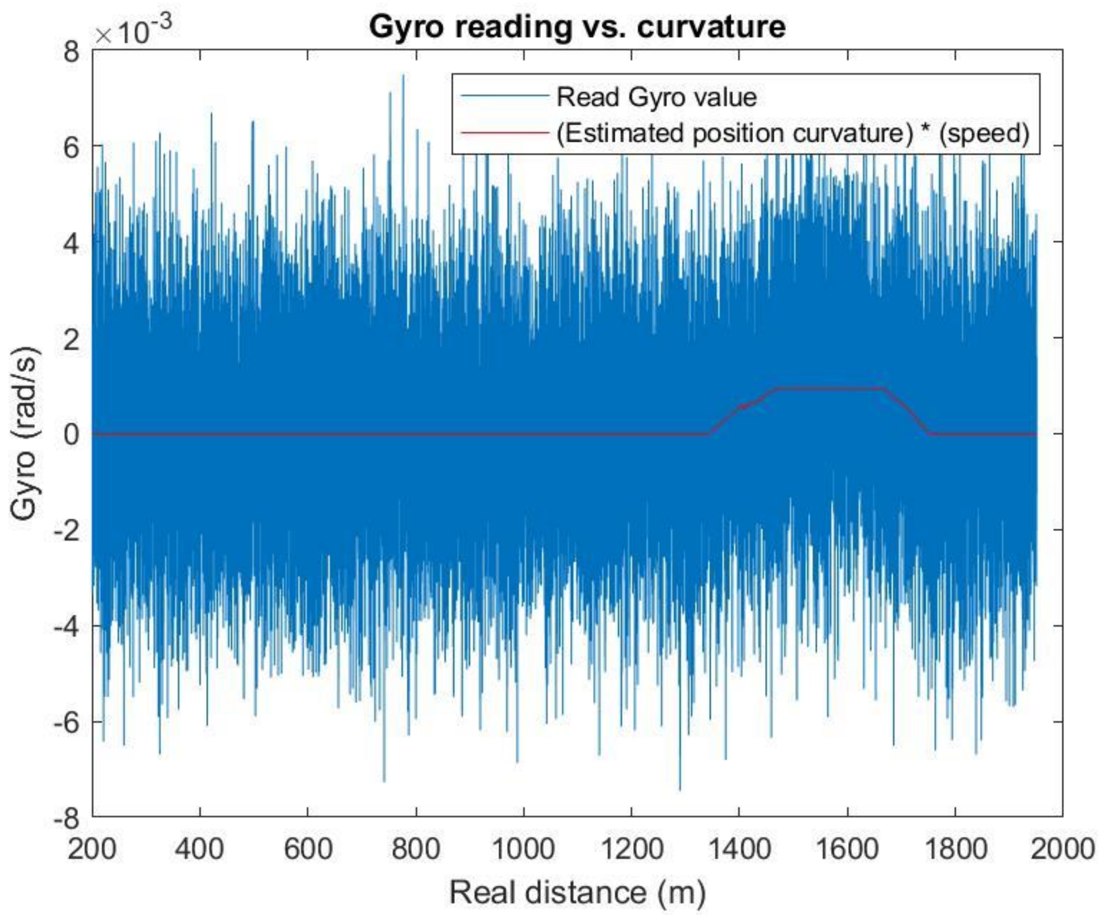

Figure 62 Gyroscope read value vs estimated curvature

8.20.2.4 Conclusion

The test is considered passed.

8.21 Test Case 104

8.21.1 Test Definition

8.21.1.1 Description

Test Case equal to Test Case 102.

8.21.1.2 Input Error Specification:

Gyroscope noise is 10 times greater than Test Case 102

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.02\}, \alpha = 0$	No
Err_PVT	No	No	No

8.21.1.3 Expected result of the Test

The train position is valid from start to the end. The train is able to reduce the confidence interval because it passed a curve.

8.21.2 Test Results

8.21.2.1 Segment determination

As shown in all 10x tests the segment determination is always known.

8.21.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value throughout the test and when the train starts the clothoid at 1200 meters the sensors start providing information which is reflected just before the end of the curve. So from 1200 to 1400 meters the windows to reposition the train occurs but this time the impact of this repositioning is negligible.

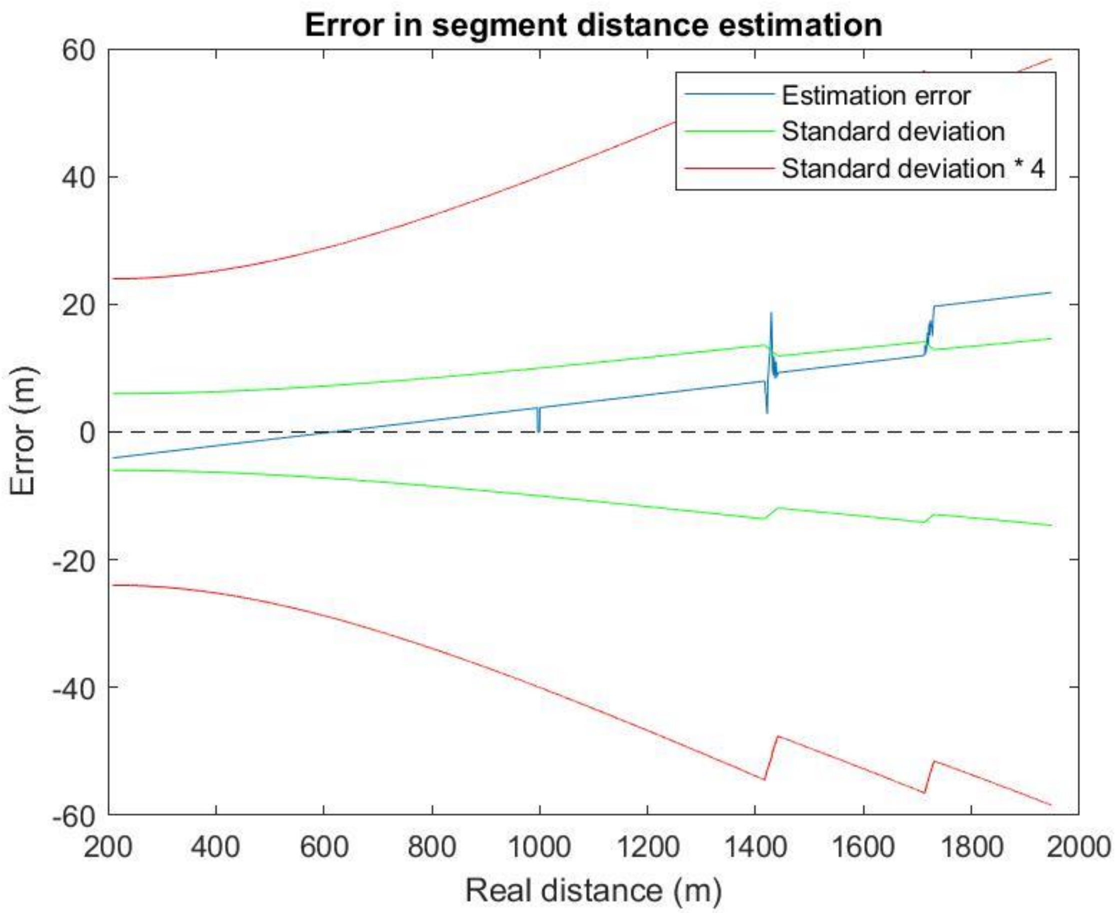

Figure 63 Segment distance error

8.21.2.3 Gyroscope Reading Detail

This behaviour can also be represented by the gyroscope values that show how the system is NOT able to accurately reposition itself.

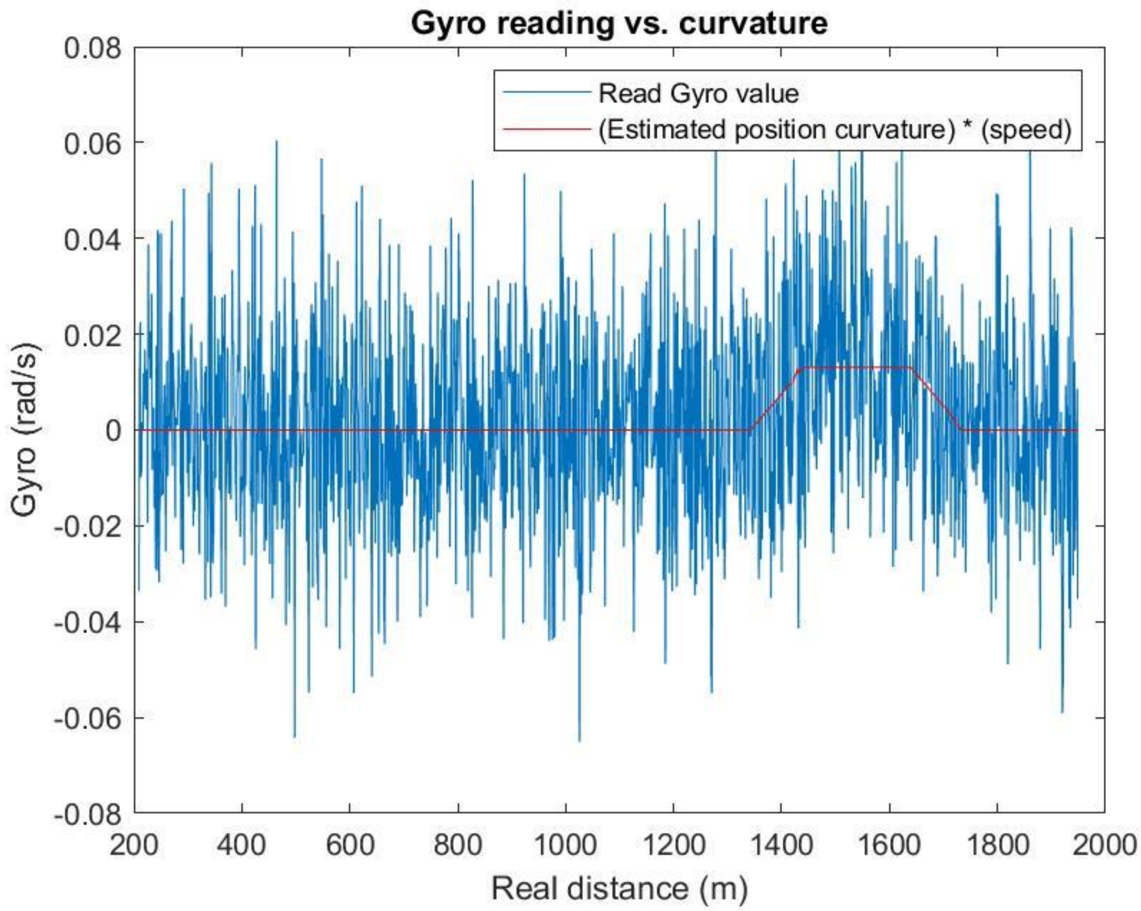

Figure 64 Gyroscope read value vs estimated curvature

8.21.2.4 Conclusion

The test is considered NOT passed.

8.22 Test Case 105

8.22.1 Test Definition

8.22.1.1 Description

Test Case equal to Test Case 102.

8.22.1.2 Input Error Specification:

Accelerometer noise is 10 times greater than Test Case 102.Test Case 102

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.4\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.002\}, \alpha = 0$	No
Err_PVT	No	No	No

8.22.1.3 Expected result of the Test

The train position is valid from start to the end. The train is able to reduce the confidence interval because it passed a curve.

8.22.2 Test Results

8.22.2.1 Segment determination

As shown in all 101 to 106 tests the segment determination is always known.

8.22.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value throughout the test and when the train starts the clothoid at 1200 meters the sensors start providing information which is reflected just before the end of the curve. So from 1200 to 1400 meters the train position is adjusted but the estimation values are noisier due to the speed value variance.

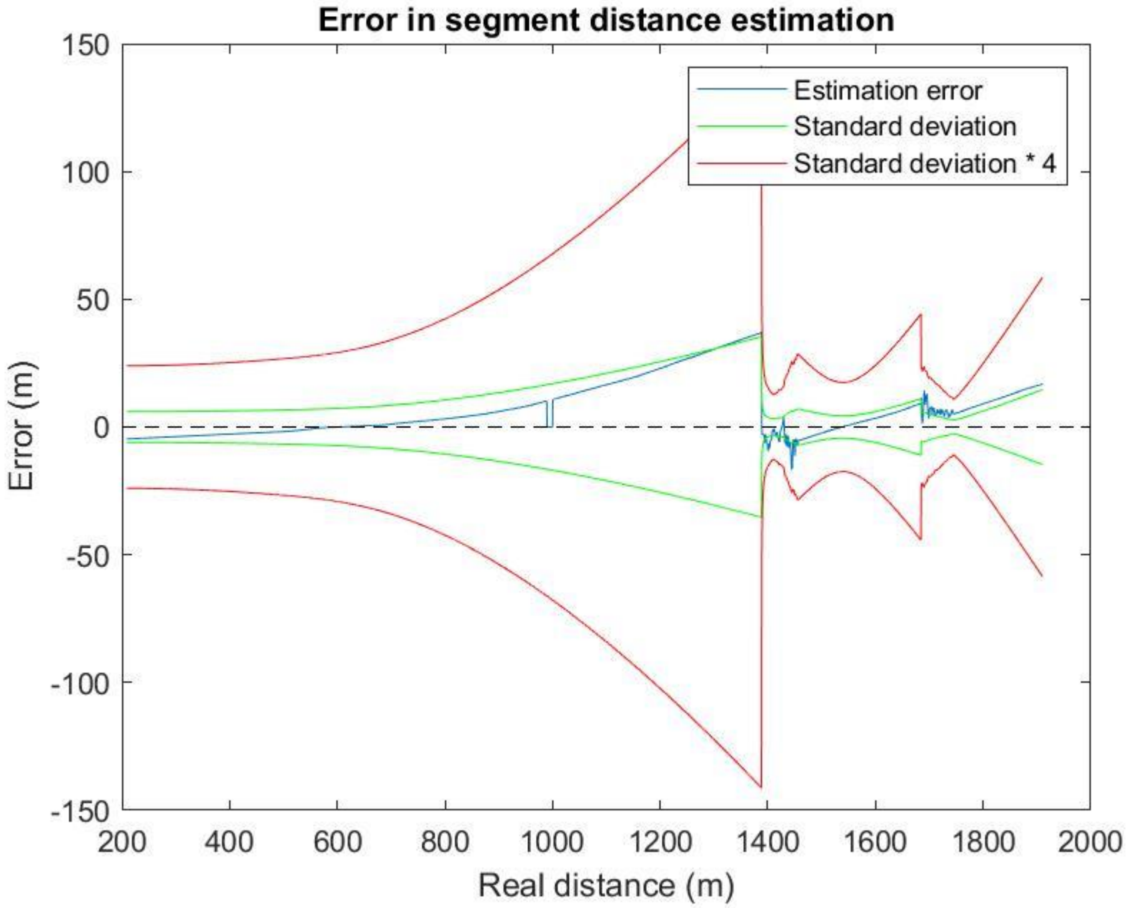

Figure 65 Segment distance error

8.22.2.3 Speed Reading Detail

In the following graph the detail according to the speed estimation is shown. The illustration shows how the speed estimation deviates with the accelerometer values leading to a poor performance.

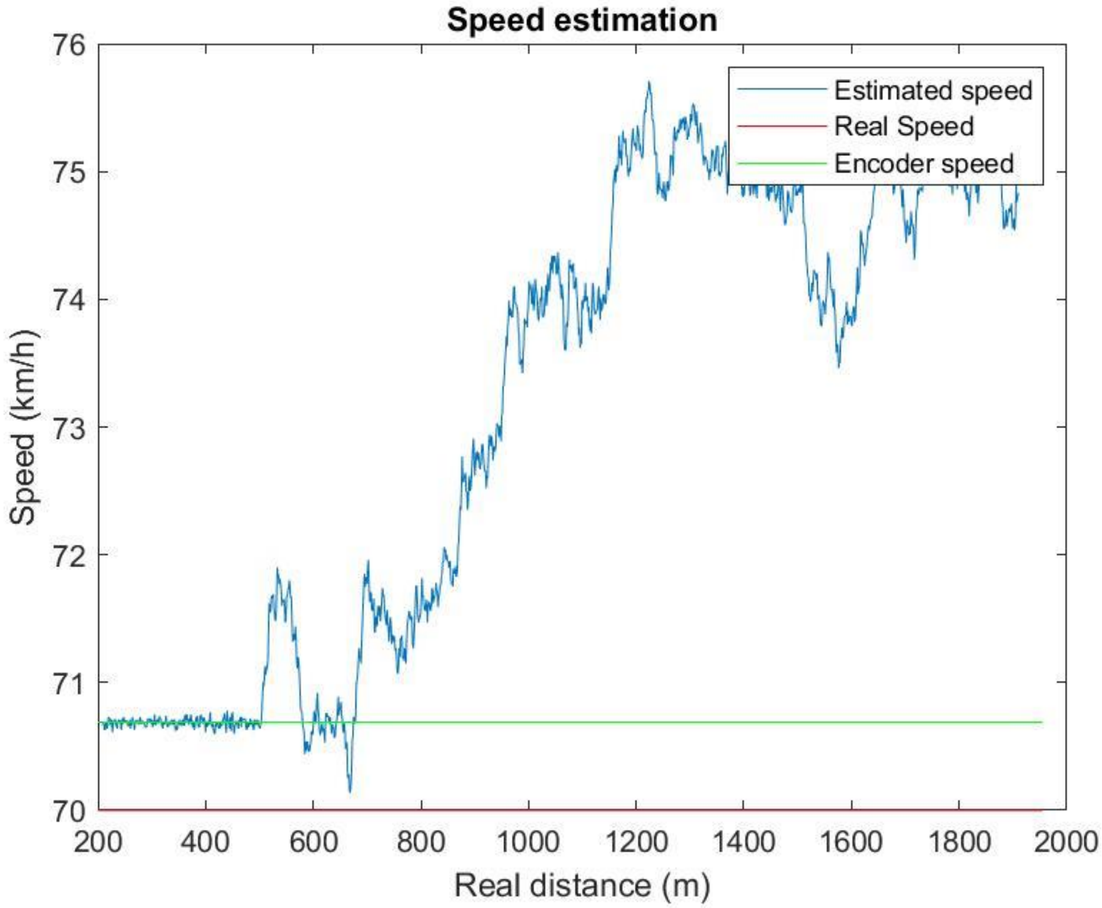

Figure 66 Speed estimation

8.22.2.4 Conclusion

Regardless of the low accelerometer input the test is considered passed as it resets the train position.

8.23 Test Case 106

8.23.1 Test Definition

8.23.1.1 Description

Test Case equal to Test Case 103.

8.23.1.2 Input Error Specification:

Test Case equal to Test Case 103 but gyroscope inputs has 10 times greater error.

	Offset Error	Noise Error	Noise Proportional Error
Err_WAS	1%	No	No
Err_Acc	No	$\omega_k\{STD = 0.04\}, \alpha = 0$	No
Err_Gyr	No	$\omega_k\{STD = 0.02\}, \alpha = 0$	No
Err_PVT	No	No	No

Table 18 Error definition for test.

8.23.1.3 Expected result of the Test

The train position is valid from start to the end. The train is able to reduce the confidence interval because it passed a curve.

8.23.2 Test Results

8.23.2.1 Segment determination

As shown in all 10x tests the segment determination is always known.

8.23.2.2 Distance Error

In the following illustration, the distance error within the segment is represented. The train knows its segment value throughout the test and when the train starts the clothoid at 1200 meters the sensors start providing information but since the error value of the gyroscope is large with respect to the radius curvature and speed value then the algorithm does not find a matching and there is not a repositioning of the travelled distance.

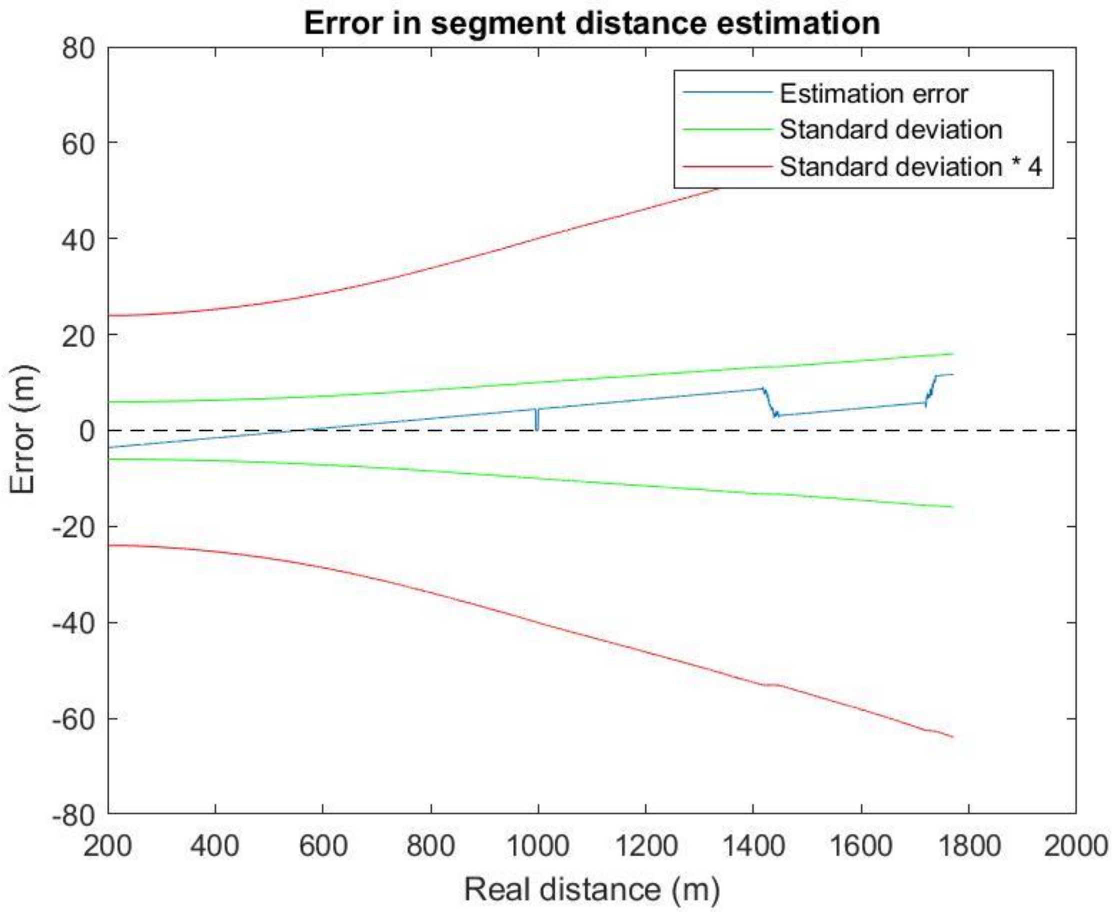

Figure 67 Segment distance error

8.23.2.3 Gyroscope Reading Detail

This behaviour can also be represented by the gyroscope values where it can be seen that the noise of the gyroscope is greater than the estimated curvature value.

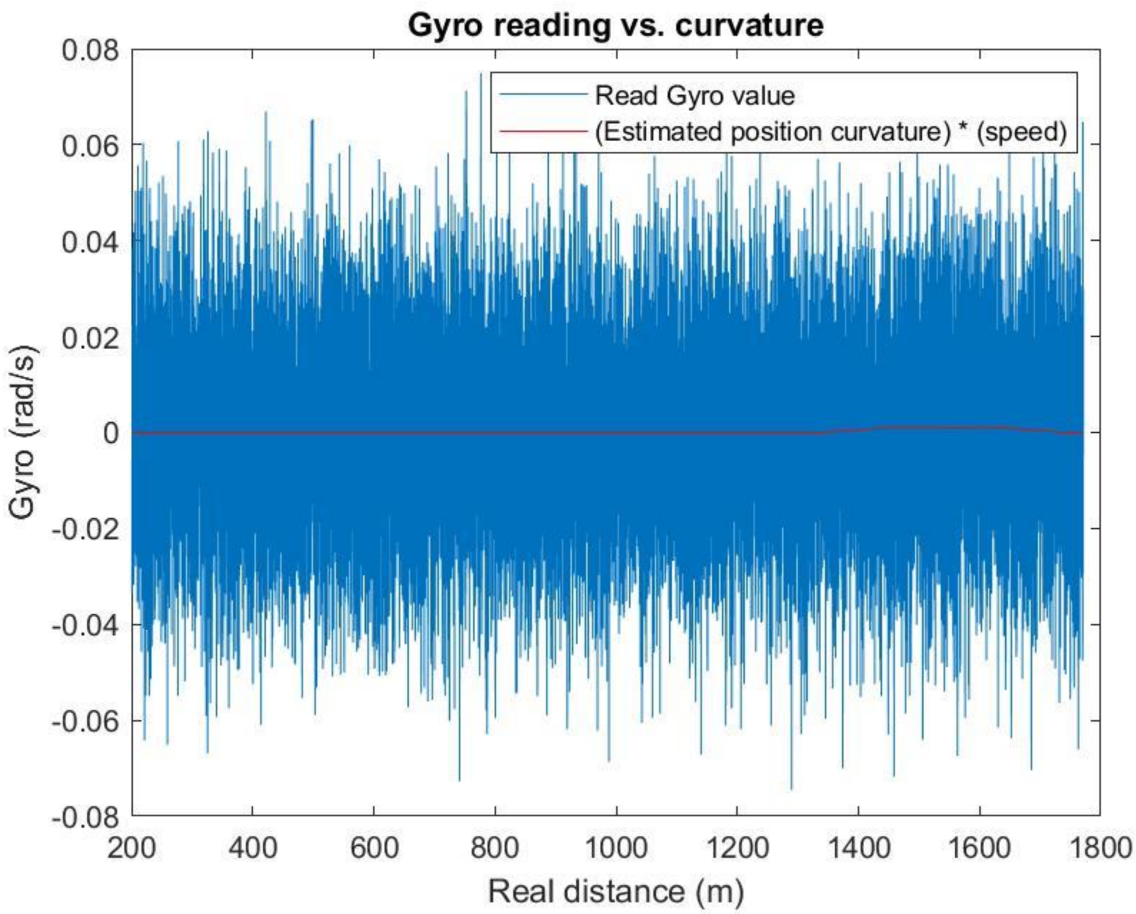

Figure 68 Gyroscope read value vs estimated curvature

8.23.2.4 Conclusion

The test is considered Not passed.

9 Conclusion

In this document the results of a laboratory environment are presented. The laboratory environment has been extended from its previous definition on [1] and the algorithm is tested under a variety of scenarios. Although the number of potential scenarios that could be executed is very extensive, in this document the most representative ones for the algorithm in [6] are presented. In addition, the tests have also shown the limitations and boundaries of the proposed algorithm in terms of relationship between curve radius, speed and IMU performance types. The tests are carried out in a controlled environment where the number of possible parallel lines and switch points are controlled, which is an advantage at the time of defining the influence of each sensor on the performance. Notice that although the overall purpose is to find the requirements that guarantee the performance of a positioning system, the understanding of each sensor at each time is considered an important knowledge. As such the following set of conclusions can be extracted.

- With an IMU’s vertical gyroscope with an STD noise lower or equal to 0.002 STD, all curves between 1500 m and 200 m can be detected, when the speed is greater than 5km/h.
    - Notice a curve detection can contribute to both, track discrimination and track repositioning.
- With an IMU’s accelerometer with an STD noise greater than 0.04 STD, the usage of its values as part of the speed calculation functionality may lead to erroneous estimation. Although test cases such as 12, show that it is possible to perform track discrimination with such accelerometers, it can be understood that the overall safe assumption is to avoid such sensors.
- GNSS PVT information error, as used by the algorithm, it has shown its impact on the initial error position estimation. However, if the IMU error estimation for both accelerometers and gyroscopes, is correctly parametrised in the algorithm it has been shown that track discrimination and train position repositioning is possible.

It is also worth stressing that the algorithm tested in this document requires a digital map with the radius curvature profile associated with absolute positions and the gradient profile associated with absolute positions. The former allows the track discrimination and repositioning whereas the second allows to adjust the offset values related to accelerometer data.

10 References

[1] X2R2-TSK3.13-D-CAI-001-04-VandV Test Specifications, Verification and Validation compliant Testing Environment definition for Stand Alone Fail-Safe Train Positioning, Version 04.

[2] X2R2-TSK3.9-D-CAI-001-06_STREAM2 Fail Safe Train Positioining- SRS, System Requirement Specification, Version 06.

[3] ERA, Report ERTMS Longer Term Perspective, 18/12/2015.

[4] X2R2-TSK3.10-D-CAI-001-02 – Architecture Specification for Stand-Alone Fail Safe Train Positioning, Version 03

[5] STARS project. D5.1 - State of the art of EGNSS projects for the rail application, STR-WP5-D-IFS-033 (IFSTTAR – 21/03/17)

[6] X2R2-TSK311-D-CAI-001-05_-_Tech_ Solution_ for_Stand_Alone_Fail-Safe_Train_Positioning

Appendix A: Representation Description

10.1 Representation of a line:

A line represent the center of the track, where the standard loading gauge for ETCS is 1.435meters. The line is a topological representation and does not include the curvature representation.

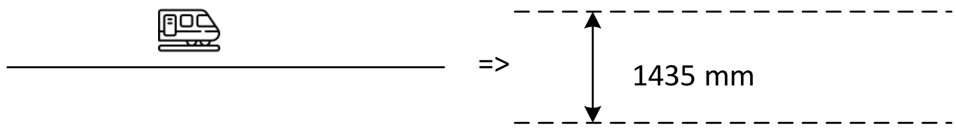

Figure 69 Track representation, centre of the track and track lines

The track to track distance or centre to centre distance varies from 3.5 meters to 4.8 meters depending on the application. So assume the following:

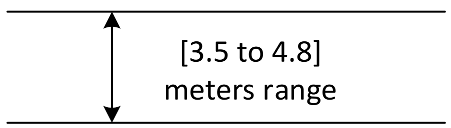

Figure 70 Track representation, distance between track centres.

10.2 Curvature representation

The following is the representation of a topological line with the curvature representation where notice that left handed curves are represented as positive curves.

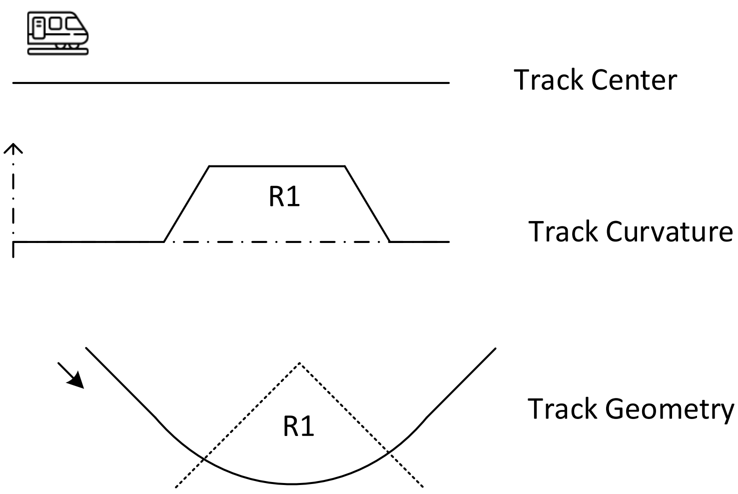

Figure 71 Track representation with curvature values

10.3 Parallel track representation with different curvature radius

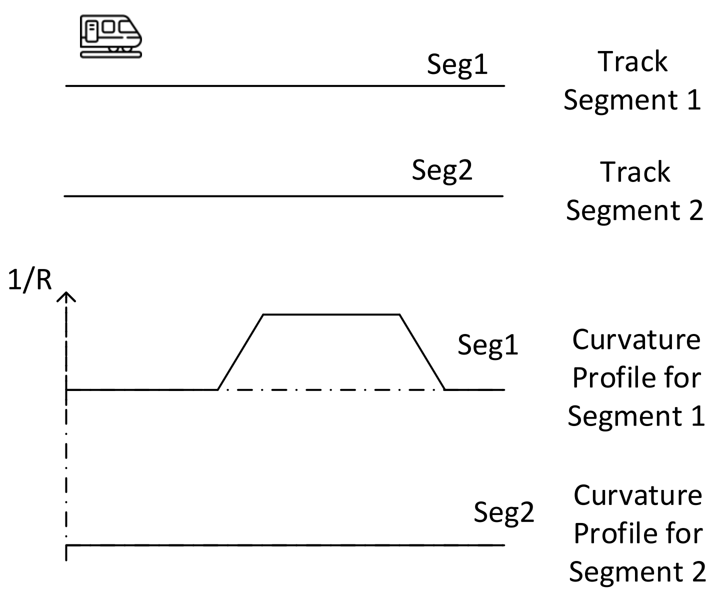

Figure 72 Parallel track representation with different curvature values

10.4 Parallel track representation with equal curvature radius

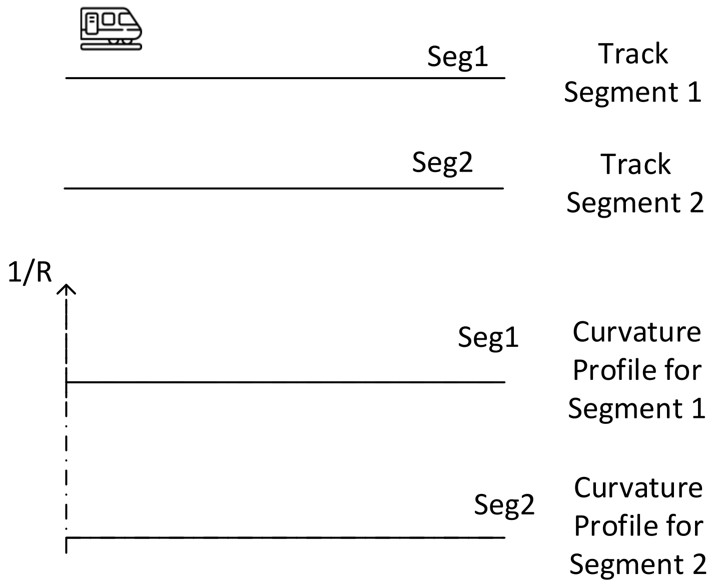

Figure 73 Parallel track representation with equal curvature values

10.5 Switch Point

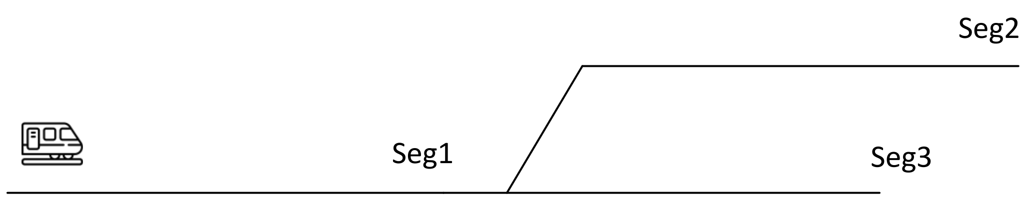

Figure 74 Parallel track representation with different curvature values