

ON-BOARD SYSTEMS FOR TRAINS AND METHODS OF DETERMINING SAFE SPEEDS AND LOCATIONS OF TRAINS

TECHNICAL FIELD

5 The present disclosure relates to on-board systems for trains, methods of determining safe speeds for trains and methods of determining locations of trains. The methods and on-board systems may be used with all types of train, including but not limited to light rail trains, heavy rail trains, high speed trains, intercity trains, engineering trains, mass transit trains and underground trains. In some examples the methods and on-boards systems may be used to help with assisted driving, automated driving or manual driving of trains.

10 BACKGROUND

A traditional railway signalling system divides the railway into a plurality of sections known as blocks. A block circuit passes an electric current through the block enabling the presence of a train to be detected from the electrical properties of the block. This information may be passed to a central server of the railway signalling system which may control visual track side signals, 15 e.g. lights, to indicate to the driver whether they may proceed or must stop the train. In this way the movement of trains is controlled and in usual circumstances only one train is allowed on a block at a time.

In order to improve headway and allow closer spacing of trains Communications Based Train Control (CBTC) systems have been developed. CBTC systems comprise a plurality of trackside 20 devices for locating trains along the railway. The trackside devices may for example send Radio Frequency ID (RFID) signals which can be picked up by a train so that the train can be aware of its own position. Each train can then send its location information to a central server for monitoring and the central server can send instructions to the train either directly or via the trackside devices so as to maintain separation between trains.

25 Both traditional signalling systems and CBTC systems rely on a central server. Therefore there may be a significant disruption of service if the central server or communication between the central server and the trains fails. Further, while these systems can help to prevent collisions between trains, they cannot help prevent collisions between trains and pedestrians, cars, or other obstacles or with train buffers in areas such as train depots which are not usually covered 30 by traditional signalling or CBTC systems.

SUMMARY OF THE DISCLOSURE

The present disclosure proposes an on-board system for a train comprising a sensor system for detecting objects on the railway track ahead of the train. By detecting objects on the railway track, the sensor system may help to prevent collisions with obstacles such as other trains, vehicles, pedestrians and buffer stops etc. Further, the present disclosure proposes determining
5 a safe speed for the train based on a detection range of the sensing system. This may help to prevent the train from travelling too fast, such that it is unable to stop in time upon detecting an object.

Accordingly, a first aspect of the present disclosure provides a method of determining a safe speed for a train comprising:

10 determining a current location of the train on a railway;

determining a detection range of a sensor system of the train based on the current location of the train and a data store comprising information from which the detection range at a plurality of locations on the railway can be determined; and

determining a safe speed for the train based on the detection range.

15 In this way it may be ensured that the train travels at a safe speed, so as to prevent collision with other trains, without relying on communication with a remote server. Further, this approach can prevent collision not only with trains, but with other types of obstacle such as pedestrians, vehicles, buffer stops etc. In some examples the on-board system can operate independently without interfacing with existing or legacy signalling systems of a railway.

20 A second aspect of the disclosure provides an on-board system for a train comprising:

a sensor system for detecting objects on a railway track ahead of the train;

a locating system for determining a current location of the train;

a data store comprising information from which detection ranges of the sensor system at a plurality of locations on the railway can be determined; and

25 a speed determining module configured to:

receive a current location of the train from the locating system;

determine a detection range of the sensor system based on the current location of the train and the information in the data store; and

determine a safe speed for the train based on the determined detection range of the sensor system.

A third aspect of the present disclosure provides a method of determining a location of a train on a railway comprising:

5 receiving a video stream of an environment of the train from a camera mounted on the train;

receiving Light Detection and Ranging (LiDAR) data of an environment of the train generated by a LiDAR system mounted on the train;

10 generating a digital model of an environment of the train based on the video stream and the LiDAR data;

detecting a landmark in the digital model having identifying features which correspond with identifying features of a landmark having a known location in a digital map of the railway;

determining a speed of the train; and

15 determining a current location of the train based on the known location of the landmark, the speed of the train and the time elapsed since the landmark was detected.

A fourth aspect of the present disclosure provides an on-board system for a train comprising:

a camera to generate a video stream of an environment of the train,

a LiDAR system to generate LiDAR data of an environment of the train;

20 a digital map comprising identifying features and known locations of a plurality of landmarks of the railway;

a landmark detection module to detect a landmark in the video stream and the LiDAR data having features which match identifying features of a landmark in the digital map;

a speed determining apparatus to determine a speed of the train;

25 a location determining module to determine a current location of the train based on the known location of the detected landmark, the speed of the train and a time elapsed since the landmark was detected.

Further aspects of the present disclosure are provided in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples of the present disclosure will be explained with reference to the accompanying drawings, in which:-

5 Fig. 1 shows an example method of determining a safe speed for a train according to the present disclosure;

Fig. 2 shows an example of an on-board system for a train according to the present disclosure;

Fig. 3 shows an example of a detection range of a sensor system of a train according to the present disclosure;

10 Fig. 4 shows an example method of determining a safe speed for a train according to the present disclosure;

Fig. 5 shows examples of actions which may be taken based on a safe speed of a train according to the present disclosure;

Fig. 6 shows an example of an on-board system for train according to the present disclosure;

15 Fig. 7 shows an example method of determining a detection range according to characteristics of an upcoming portion of a railway according to the present disclosure;

Fig. 8A to 8E show examples of a curved section of railway track and determining a detection range in the curved section according to the present disclosure;

Fig. 9A to 9C show examples of a sloped section of railway track and determining a detection range in the sloped section according to the present disclosure;

20 Fig. 10 shows an example of a method of determining a location of a train according to the present disclosure;

Fig. 11 shows an example of an on-board system for a train according to the present disclosure; and

25 Figs. 12A to 12C show some examples of actual slopes and corresponding nominal slopes used for calculating a detection range.

DETAILED DESCRIPTION

Various examples of the disclosure are discussed below. While specific implementations are discussed, it should be understood that this is done for illustration purposes only. A person skilled in the relevant art will recognize that other components and configurations may be used without parting from the spirit and scope of the disclosure.

- 5 The present disclosure proposes an on-board system for a train. An on-board system is a system which is to be installed on a train and which travels along with the train. The on-board system comprises a sensor system for detecting objects on the railway track ahead of the train. In some examples the sensor system may comprise a camera and a Laser Detection and Ranging (LiDAR) apparatus, while in other examples the sensor system may comprise other
10 types of sensors. If the sensor system detects an object on the railway track then the driver may be notified or a control system of the train activated to apply brakes, or otherwise adjust the speed of the train. If the sensor system does not detect an object on the railway track, then the speed of the train may be set to a safe speed.

- A safe speed is a speed at which the train is able to stop by braking before colliding with an
15 obstacle. The safe speed may be based on the detection range of the sensor system. For example, the safe speed may be set such that the braking distance of the train is within the detection range of the sensor system. The detection range of the sensor system is the range at which the sensor system can detect objects. The braking distance of the train is the distance the train will travel before coming to a stop after the on-board system determines that braking is
20 needed. The braking distance may, for example, be calculated based on a speed of the train, a braking deceleration of the train and a reaction time of the driver or a reaction time of an automatic braking system.

- The detection range may vary at different locations on the railway depending upon the characteristics of the railway track ahead of the train. Accordingly, in some examples the
25 detection range may be determined by referring to a digital map of the railway which includes geometric information of the railway, determining a current location of the train on the digital map and calculating the detection range based on the geometry of the railway tracks ahead of the train.

Fig. 1 shows an example method 100 of determining a safe speed for a train.

- 30 At block 110 a current location of the train on a railway is determined. For example, the current location may be determined from a Global Positioning System (GPS) signal, a position signal wirelessly received from trackside devices, or by recognising a landmark detected by the sensor system.

A block 120 a detection range of a sensor system of the train is determined based on the current location of the train and a data store comprising information from which the detection range at a plurality of locations on the railway can be determined. In one example the data store is a digital map of the railway including geometric information of the railway, such as track curvature and slope.

At block 130 a safe speed for the train is determined based on the detection range of the sensor system. For example, the safe speed may be set such that a braking distance of the train is within, i.e. equal to or less than, the detection range of the train.

In this way an appropriate safe speed can be determined for the train, taking into account the characteristics of the railway track ahead of the train and consequent detection range of the sensor system at the current location of the train. In some examples this determination of safe speed may be carried out autonomously by the on-board system without the input of external off-train devices or systems. In such examples, the system is not dependent upon a central signalling server or external communication network in order to determine the safe speed of the train.

Fig. 2 shows an example of an on-board system 200 for a train. The on-board system 200 may implement a method for determining a safe speed for a train, such as the method 100 described above with reference to Fig. 1.

The on-board system 200 comprises a sensor system 210 for detecting objects on a railway track ahead of the train, a locating system 220 for determining a current location of the train, a data store 230 and a speed determining module 240.

The sensor system 210 may, for example, include sensors such as a camera and a Laser Detecting and Ranging (LiDAR) apparatus, but is not limited thereto. In some examples the camera may be configured to generate a video stream comprising 2D images of an environment of the train and the LiDAR apparatus may be configured to generate a 3D point cloud of an environment of the train. The sensor system may be able to detect obstacles, such as other trains, pedestrians, vehicles or obstructions on the track ahead of the train. If an obstacle is detected an alert may generated for the driver of the train, or the speed of the train may be automatically adjusted, e.g. by activating a braking system of the train.

The locating system 220 is configured to determine a current location of the train on the railway. In one example the locating system 220 comprises logic to determine the current location of the train based on data from the sensor system 210. In other examples, the locating system 220

may comprise a Global Positioning System (GPS) or may wirelessly receive location signals from trackside devices.

The data store 230 stores information from which detection ranges of the sensor system at a plurality of locations on the railway can be determined. The data store may for example
5 comprise data stored on a non-transitory machine readable medium, such as a hard disk, solid state drive, read only memory or random access memory etc.

In one example the data store is a digital map comprising information relating to a geometry of the railway tracks including track slope and track curvature. The detection range may be calculated in real time based on the geometry of the railway tracks in one or more upcoming
10 sections of the railway along a route of the train ahead of the current location of the train. Calculating in real-time means calculating on demand. In this way the detection range may be calculated at frequent intervals, e.g. every second, as the train moves and the current location of the train changes. In another example the data store 230 includes a database or lookup table with detection ranges for a plurality of locations on the railway, such that real time calculation is
15 not needed, but this approach may require a large storage capacity for on the on-board system in order to store detection ranges for a large number of locations on the railway.

The speed determining module 240 is configured for determining a safe speed of the train. The speed determining module may comprise a module 242 to receive a current location of the train from the locating system, a module 244 to determine a detection range of the sensor system
20 based on the current location of the train and the information in the data store, and a module 246 to determine a safe speed for the train based on the determined detection range of the sensor system.

In one example the speed determining module 240 may be implemented by a processor, such as a central processing unit (CPU) or microprocessor, and a non-transitory storage medium,
25 such as a memory, hard disk or solid state drive etc., storing machine readable instructions which are executable by the processor. Thus it will be appreciated that the modules 242, 244 and 246 may be implemented as machine readable instructions which are executable by the processor.

Fig. 3 shows an example of a train 310 on a section of railway 300 travelling in a direction from the left to the right of the figure. An on-board system 320 including a sensor system 325 is
30 installed on the train. The on-board system may for example be as shown in Fig. 2 or other examples in this disclosure. The sensor system 325 may be directed towards a front of the train and may have a field of view 330 as shown in Fig. 3.

The sensor system 325 has a detection range 340, which is the maximum distance at which objects on the railway track can be detected and classified by the on-board system. Detecting and classifying means detecting the object and classifying the object as a particular object type, for example an obstacle such as another train, a pedestrian, a car, a depot buffer etc. and distinguishing such objects from other visual features such as the railway tracks. For instance, in some examples the detection range may be a value between 200m to 300m ahead of the train depending on the design of the sensor system. In the example of Fig. 3 the detection range is 240m ahead of the front of the train. An obstacle 370 lies 300m ahead of the front of the train and therefore is outside the detection range 340 of the sensing system 325. The braking distance of a train is the distance a train will travel if a decision is made to apply the brakes now.

If the braking distance is greater than the detection range 340, e.g. greater than 240m in this example, then there is a risk that the train may detect the obstacle 370 too late. In that case the train may be unable to brake to a halt before it collides with the obstacle. For instance, if the braking distance is 260m, but the detection range is 240m, then the on-board system would detect the obstacle at 240m away, but be unable to stop the train until 260m, i.e. 20m past the position of the obstacle. On the other hand if the braking distance is within the detection range, e.g. 240m or less in this example, then the sensing system may detect the obstacle and the train may be stopped before a collision occurs. Fig. 3 shows a braking distance 360 that is within the detection range.

The braking distance of a train depends inter-alia on the speed of the train. Accordingly the safe speed of the train may be set such that a braking distance of the train is within the detection range of the sensor system. That is the braking range is less than or equal to the detection range. In this way the train will be able to brake to a halt after detecting an obstacle on the track and before colliding with the obstacle.

Fig 4 shows an example method 400 of setting a safe speed for the train based on the detection range, in such a way that a braking distance of the train is within the detection range of the sensor system. This method may, for example, be employed by block 130 of Fig. 1 or module 246 of Fig. 2.

At block 410 of Fig. 4, a detection range of the sensor system is determined. For example, this may be done as described above in block 120 of Fig. 1.

At block 420, a first speed at which a braking distance of the train is within the detection range is determined. For example a braking distance may be set at a value within the detection range and the maximum speed at which the train has that braking distance may be calculated.

At block 430 the first speed is set as the safe speed of the train.

- 5 The braking distance of the train may be calculated based on the speed of the train, the braking deceleration of the train and a reaction time. The reaction time may be a reaction time of the driver in the case that the driver is to activate the brakes or a reaction time of the on-board system if the on-board system is to automatically activate the brakes. In one example the braking distance may be calculated according to the formula:

10
$$D = v T + (v^2 / 2a) \quad (\text{Equation 1})$$

Where:

D = Braking distance,

- 15 v = speed of train,

T = reaction time, and

a = braking deceleration of the train

- 20 In one example the first speed may be a maximum speed of the train at which the braking distance is within the detection range. In that case the braking distance may be set as equal to the detection range and the maximum speed may be found by solving Equation 1 to find the speed.

- Once the safe speed has been determined, the safe speed may be used in various ways. In one example, the safe speed may be displayed to a driver of the train. For example, the safe speed
25 may be displayed on a display panel of the on-board system together with a current speed of the train. A driver of the train may take action accordingly.

- In some examples, as shown in the method 500 of Fig. 5, the on-board system may determine a current speed of the train at block 510 and compare the current speed of the train with the safe speed at block 520. At block 530, in response to determining that the current speed is greater
30 than the safe speed, an alert may be generated or the speed of the train may be automatically adjusted. For example a visual and/or audio alert may be notified to the driver through a display panel or speaker in a driver cabin of the train. In some implementations the on-board system may automatically adjust a current speed of the train, for example by activating a braking system of the train or reducing the engine speed etc.

Fig. 6 shows a further example of an on-board system 600 of a train according to the present disclosure. The on-board system 600 includes a main computer 620, a display 680, and a plurality of sensors including a camera 610, a LiDAR apparatus 612 and a speed sensor 614.

5 The camera 610 is configured to generate a video stream of an environment of the train and may for example generate a video stream comprising a plurality of 2D images. The LiDAR apparatus 612 is configured for generating LiDAR data of an environment of the train and is capable of determining a distance to objects. The LiDAR apparatus may for example generate a 3D point cloud of an environment of the train. The camera 610 and the LiDAR apparatus may be directed to the front of the train so that they can detect objects on the railway track in front of
10 the train. In some examples the camera 610 and/or the LiDAR apparatus may be rotatable so as to scan different areas in the environment of the train. The camera 610 and the LiDAR apparatus 612 may together form a sensor system for detecting objects in front of the train and may perform a similar function to that of the sensor system 210 of Fig. 2.

The speed sensor 614 is configured to determine a speed of the train. The speed sensor may
15 for example be an odometer, a gyroscopic device or a device for detecting a rotation speed of an axle of the train, or a radar or LiDAR device. In one example the speed sensor is a mm wavelength radar device. Radar or LiDAR speed sensing devices may be configured to use the Doppler effect to determine a speed of the train by transmitting radar or LiDAR waves, detecting radar or LiDAR waves reflected back to the train and determining a frequency shift between the
20 transmitted and reflected waves. A radar or LiDAR speed sensing device may be independent of the other systems of the train and thus is easy to implement on a wide variety of different types of train.

The main computer 620 may comprise a single computer or a plurality of computer systems. The main computer may include at least one processor 622 such as a central processing unit
25 (CPU) or microprocessor etc and a non-transitory machine readable storage medium 624 such as a hard drive, disk array, solid state drive, memory etc. The storage medium 624 may comprise modules of machine readable instructions which are executable by the processor 622 to perform any of the methods described in this disclosure.

The modules of machine readable instructions stored on the storage medium 624 may include a
30 visual analytics module 630, an integration module 632, an obstacle detection module 634, a location detection module 640, a speed determining module 650 and an action module 670. The storage medium 624 may also store a digital map of the railway 660. While these modules are shown in Fig. 6 as implemented on a single computer and residing on the same storage

medium, it is to be understood that in other examples the modules could be distributed between multiple computers and/or storage mediums of the on-board system.

5 The visual analytics module 630 is configured to detect objects in 2D images of the video stream from the camera 610. The visual analytics module may for example use machine learning to detect and classify objects. For example the visual analytics may be trained to recognise parts of the image which correspond to a railway track and detect any obstacles on the track. The visual analytics may be trained to classify obstacles by type such as another train, a depot buffer, a pedestrian, car or other foreign object etc.

10 The integration module 632 is configured to integrate data from the visual analytics module with 3D point cloud data from the LiDAR apparatus. For example the objects detected and classified by the visual analytics may be mapped to features in the point cloud data. In this way a distance to the detected objects can be determined as the point cloud includes information in 3 dimensions and is able to determine distance based on a time of flight of transmitted and received LiDAR pulses. The point cloud may also include information about finer features of the detected objects. By combining the visual analytics with the 3D point cloud the integration module can form a digital model of an environment of the train. The obstacle detection module 634 is configured to determine from the digital model if there is an obstacle on the track. The obstacle detection module 634 may be configured to determine the boundaries of a track area in front of the train and then detect obstacles within the track area while ignoring obstacles outside of the track area. The obstacle detection module may be configured to determine whether the obstacle may collide with the train based on a position of the obstacle, distance to the obstacle and speed and direction of travel of the obstacle if the obstacle is moving. If there is a risk of collision then the obstacle detection module may notify the action module 670 such that appropriate action may be taken, such as notifying the driver, generating an alert or automatically adjusting the speed of the train.

25 The digital map 660 comprises information from which the detection range of the sensor system at a plurality of locations on the railway can be determined. For example, the digital map may include geometric data of the track including track slope, track curvature (e.g. radius of the curve), tunnel width and whether each section of track is straight, curved, level, upwardly inclined or downwardly inclined. The digital map may also include image data, data relating to the shape of the track, station-station distance, trackside infrastructure at specific location etc. The digital map may also include information relating to landmarks, such as stations or other trackside infrastructure including identifying features and the known locations of the landmarks.

By way of non-limiting example, the digital map may include one or more of the following:

- a) image data of the landmarks
- b) point cloud data of the landmarks
- c) information relating to stations
 - station map
- 5 d) information relating to turnouts
 - length of each section
 - location of turnouts
 - type of turnouts
- e) track section information
 - 10 - straight track (length of straight section)
 - curved track (radius of curve, locations of entrance to curved track section and exit to curved track section)
 - sloped track (whether slope concave or convex, gradient of slope, locations of entrance and exit to sloped track section, junctions between sections of different
 - 15 gradients and/or characteristics of a nominal slope approximating the actual slope)
 - whether each section of track is open or a tunnel

The location detection module 640 is configured to determine a location of the train. In some examples the location detection module may determine the location based on receiving a GPS

20 signal or a wireless location signal from a trackside device. In other examples the location detection module may be configured to match the digital model of the environment of the train generated by the integration module 632 with a location on the digital map. For example, the location detection module may determine a location of the train based on identifying a location on the digital map having features which match features detected by the camera and LiDAR

25 apparatus. For example, the location detection module 640 may determine a location of the train by comparing landmarks in a digital map with landmarks detected by the camera and LiDAR apparatus. Further examples of such an approach using landmarks to determine a location of the train are described in Figs. 10 and 11.

The speed determining module 650 is configured to determine a speed for the train. The speed

30 determining module 650 includes a module 652 to receive a current location of the train from the location detection module 640, a module 654 to determine a detection range of the sensor system at the current location of the train and a module 656 to determine a safe speed for the train based on the detection range. The modules 650, 652, 654 and 656 may perform the same functions as the modules 240, 242, 244 and 246 in Fig. 2 and may perform the method of Fig. 1

35 in order to determine the safe speed for the train.

The on-board system includes a display 680 which may display information about the train and the train environment to assist the driver. The display may be part of a user interface through which the driver may control the train. The display may display a current speed of the train and a safe speed for the train as determined by the speed determining module. The display may
5 further display and/or highlight obstacles detected by the obstacle detection module. For instance, the display may highlight a buffer stop, train or pedestrian, when the respective obstacle is detected by the obstacle detection module 634.

The action module 670 is configured to determine whether action needs to be taken based on the output of the speed determining module 650 and/or the object detection module 634. The
10 action module 670 may compare the safe speed determined by the speed determining module 650 with the current speed of the train determined by the speed sensor 614. The action module 670 may generate an alert or automatically adjust a current speed of the train if the current speed is greater than the safe speed. In some examples, the action module 670 may generate an alert or automatically adjust a current speed of the train if an obstacle, such as other trains,
15 vehicles, pedestrians and buffer stops etc. is detected ahead of the train.

For example the alert may be displayed on a display 680 or user interface of the on-board system. The alert may indicate that the speed of the train should be decreased. Instead of generating an alert, or if an alert is not acted on within a certain period of time, the action module may automatically adjust the speed of the train by sending instructions to a control
20 system of the train to brake the train or adjust an engine speed of the train.

The obstacle detection module 634 may notify the action module 670 of a collision risk such that the action module may take any of the actions described above and/or cause the detected obstacle to be displayed on the display 680.

The on-board system may further include a communication interface 690 for communicating
25 wirelessly with a remote computer at a control centre of the railway, or for sending communications to other trains on the railway. The communication interface may, for example, send information such as a position of the train, speed or status of the train and/or alerts over a telecommunication network such as a 3G, 4G or 5G network.

As discussed above, the detection range is determined based on features of the track ahead of
30 the train. For example, determining the detection range of the train may comprise performing a calculation in real time based on the geometry of the railway tracks on upcoming sections of the railway along a route of the train ahead of the current location of the train. The geometry of the railway tracks may be found by referring to the digital map. The railway track may be divided

into sections, each section being either straight, curved or inclined. One, two or more upcoming sections may be considered when determining the detection range. The upcoming sections may be defined as sections within a predetermined length of railway track ahead of the current location of the train. The predetermined length may be a length equal to the maximum detection range when the track ahead is straight and level, e.g. 240m. As the track ahead of the train may depend upon the route of the train in the case of junctions or turnouts, the digital map may store a route of the train so that the upcoming sections can be determined.

The detection range will depend upon whether the track ahead is straight or curved, level or sloped. When the upcoming sections include only straight sections, the detection range will be longer than if the upcoming sections include curved or sloped sections. Accordingly, the calculation of the detection range may comprise determining from the digital map whether the upcoming sections of the railway include straight, curved, level, upwardly inclined or downwardly inclined sections.

Fig. 7 shows an example method 700 for determining a detection range of the sensor system.

At block 710 it is determined whether the upcoming sections include a curved or sloped section.

At block 720 in response to determining that the upcoming sections do not include a curved or sloped section, the detection range is set to a first predetermined distance X. X is the maximum detection range of the sensor system. In one example X may be set to 240m.

At block 730 in response to determining the upcoming sections includes a curved section, the detection range is calculated based, at least in part, on a radius of the curved section. If the curved section is in a tunnel rather than open, then the detection range may depend upon a width of the tunnel as well the radius of the curve.

At block 740 in response to determining the upcoming sections include a sloped section, the detection range is calculated based, at least in part, on a gradient of the sloped section. If the sloped section is in a tunnel rather than open, then the detection range may depend upon a height of the tunnel as well the gradient of the sloped section.

In some cases two or more consecutive track sections (e.g. curved-straight-curved) may be considered to allow smoothing of the detection range profile, such that the detection range does not change abruptly when the train enters or exits a curved or sloped section of the railway track. Otherwise, if the detection range changed abruptly, e.g. from 240m to 150m on entering a curved section or from 150m to 240m on exiting a curved section then the safe speed would

also change abruptly which may lead to sudden braking, or sudden acceleration, of the train which may be undesirable.

Accordingly, calculating the detection range may include smoothing the variation of detection range so that the detection range decreases gradually from the first predetermined distance X to a second predetermined distance Y and gradually increases from the second predetermined distance Y to the first predetermined distance X, where X is a detection range for a flat, straight section of the railway track and Y is a minimum detection range in relation to a curved or sloped section of the railway track.

Examples of ways in which the detection range may be calculated for different sections of track will now be described.

Straight Track Section

When the section ahead is straight, e.g. as shown in Fig. 3, the detection range will not be limited by the track, but rather by the inherent detection capabilities of the sensor system. The detection range is thus X which is the maximum distance at which the sensor system can reliably detect obstacles on the railway track and may be determined by testing the system. In order to prioritize safety, a conservative value for X may be chosen. As the value X depends upon the characteristics of the train, it may be set as a first predetermined distance stored in the on-board system. The value of X may be determined by testing of the on-board system on a train and railway track. The value X may be set and stored in the on-board system as part of the on-board system set-up and calibration. In one example X is a value between 200m and 300m. In one example X is equal to 240m.

Curved Track Section

Fig. 8A shows an example of a train T on a portion of railway 800. The upcoming sections of railway in front of the train including a straight section 810 and a curved section 820. Location A is at a point prior to the entrance 815 to the curved section, location B is inside the curved section and location C is at an exit to the curved section. When the train is on the straight section of track 810 and a distance of X or more ahead of the curved section 820, then the detection range will be equal to X. When the train is less than X away from the curved section then the detection range will be less than X as it will be curtailed by the curved section.

Fig 8B shows an example where the train T is in the curved section 820 of the tunnel, e.g. at a position such as location B in Fig. 8A. It can be seen that the field of view 830 of the sensor system of the train is curtailed by the curvature of the tunnel. Accordingly, the detection range of

the sensor system is reduced and the sensor system is not able to detect an obstacle, such as second train T2, which is less than X meters away, as the second train T2 is out of the field of view of the sensor system.

Fig. 8C shows the curved section 820 of the railway tunnel, which has a radius of R and a tunnel width of DI. Assuming the train is the middle of the track and the radius of curvature is measured from an origin O at the center of curvature to an inner edge of the curved section, the train is at a distance R-DI/2 from the origin O. Accordingly a detection range at location B inside the curved track section may be calculated according to the formula:

$$detection\ range = Y = 2 * \sqrt{\left(R - \frac{DI}{2}\right)^2 - (R - DI)^2} \quad (\text{Equation 2})$$

where:

- R is the radius of the curved track section
- DI is the width of the tunnel

The value Y may be considered to be a minimum value for detection range in the curved section. For example it applies at the entrance 815 to the curved section and may apply at a location B in the middle of the curved section as shown in Fig. 8C.

Fig. 8D shows the situation where the train is at location A on the straight section 810, but approaching the entrance 815 to the curved section 820. In this case the detection range Y' at location A depends on both the distance DS of the train from the entrance 815 to the curved section and the minimum detection range Y in the curved section.

Accordingly the detection range Y' at location A approaching the entrance to the curved section may be calculated according to the formula:

$$detection\ range = Y' = DS + \frac{Y}{2} = DS + \sqrt{\left(R - \frac{DI}{2}\right)^2 - (R - DI)^2} \quad (\text{Equation 3})$$

where:

- DS is the distance between the train and the entrance of the curved section;

- R is the radius of the curved section;
- DI is the width of the tunnel

A similar calculation may be applied when the train is inside the curved section, but approaching the exit to the curved section (e.g. past the halfway point).

- 5 With the calculation method above, the detection range profile can be visualized as shown in Fig. 8E. It can be seen that the detection range gradually decreases from X to Y at locations approaching the start of the curved section and gradually increases from Y to X at locations approaching the end of the curved section; where Y is a minimum detection range for the curved section.
- 10 To conclude, when the train is approaching a curved section, given that maximum detection range of the sensor system is X, when the distance between the train and the entrance of the curved section is larger than $\sim Y/2$, the detection range is set to X. When the distance between the train and the entrance of the curved section is less than $X \sim Y/2$, the detection range varies based on Equation 3 above. This calculation method may also be applied to the situation where
- 15 there are consecutive curved track sections.

The above calculations presume the curved section of track is in a tunnel of width DI. If the curved track is in an outdoor section, then the detection range will in theory be longer, as there would be no line-of-sight blockage of the sensor system by the tunnel walls. However, taking a conservative approach, the above equations may be used for an outdoor section of track too.

- 20 For instance, the outdoor section of track may be assigned a nominal tunnel width based on the width of the track or assigned a nominal tunnel width which is the same as a tunnel width for sections of the railway which have tunnels. This approach is safe, as it will determine a detection range on outdoor sections which is the same, or less than, the actual detection range for the outdoor sections.

25 Convex Slope Track Section

- When determining the detection range the relevant consideration is not the absolute slope or gradient, but rather whether a gradient of the current section of track is different from the gradient of the subsequent section of track. When the gradient changes between sections of track this curtails the detection range as the floor of the track (and also the ceiling if in a tunnel)
- 30 may cut off the field of view of the sensor system. In this respect there are two types of slope: a convex slope and a concave slope. Thus the on-board system may first determine whether the

upcoming sloped section is a convex slope or a concave slope and then determine a detection range for the sloped section.

Fig. 9A shows an example of a length of track 900 including a level section of track 910 followed by a sloped section 920 which forms a convex slope. The solid lines show the ceiling and floor of the tunnel. It can be seen that the sloped section 920 in this example includes a first portion 920A and a second portion 920B which have different gradients. However, for the purpose of modeling these may be converted to a nominal slope profile, shown in dashed lines, which includes a level portion 921A and an inclined or declined portion 921B. The nominal slope profile thus includes two portions: a first portion 921A which is flat and a second portion 921B corresponding to the last part, or steepest gradient, of the slope. A point 925 is defined as a junction between the first portion and second portion of the nominal slope profile and referred to hereinafter as the junction of the sloped section. The diagram shows the train in four possible positions T1, T2, T3 and T4. The sensing system may have a viewing range covering a range of angles, e.g. 20 degrees either side of the horizontal. The dotted and dashed lines show the longest line of sight of the sensing system within the viewing range.

The train at position T1 is a first distance Z before the junction 925, while the train in the second position T2 is a second distance W before the junction 925. The train in position T3 is a third distance T after the junction 925. The detection range is at a minimum at locations between Z meters and W meters ahead of the junction 925 of the sloped section, i.e. between the positions T1 and T2 shown in Fig. 9A, due to the line of sight of the sensor system being cut off by the slope. In the following discussion the junction of the sloped section 925 is taken to have co-ordinates of 0, so e.g. a distance Z before the junction 925 has co-ordinates of -Z.

Accordingly the detection range may be set to a minimum value Y at locations between a first distance (-Z) and a second distance (-W) ahead of the junction of the sloped section. At locations prior to -Z and after -W the detection range may be gradually increased to the maximum value X.

The values Z, W and T may be calculated based on characteristics of the sloped section. In one example the values Z, W and T may be calculated according to the formulas

$$Z \approx 4.5 / \text{relativeSlope}$$

$$T \approx 0.6 * \left(\frac{DH}{\text{relativeSlope}} - \frac{H}{\text{relativeSlope}} \right)$$

$$W \approx 0.6 * \left(\frac{DH}{relativeSlope} - \frac{HC}{relativeSlope} \right)$$

(Equation 4)

where:

- 5 - Z, W and T depend on the steepness or gradient of the slope. The greater the steepness, the smaller Z, W and T will be and vice versa.
- H is the height of the train relative to the rail track
- HC is the height of the sensors of the sensor system relative to the rail track
- DH is the height of the tunnel
- 10 - relativeSlope is a variable which depends on the characteristics of the slope, such as the gradient or steepness of the slope.

The value relativeSlope may be unique to each sloped track section and may be determined based on on-site testing of the detection range at the slope.

- 15 In one example, the detection range may be calculated depending on the location of the train relative to the junction 925 of the sloped section, according to the three scenarios below:

Scenario 1:

- if the distance of the train from the junction of the slope is between -X+T and -Z, the detection range will gradually decrease from X to Z+T, and is given by the formula:

$$detection\ range = 1 * x + T \quad (\text{Equation 5})$$

- 20 Where:

- x is the distance of the train away from the junction of the sloped section and $-X+T \leq x \leq -Z$

Scenario 2:

- if the distance of the train to the junction of the slope is between $-Z$ and $-W$, then the detection range is given by the formula:

$$\text{detection range} = Z + T \quad (\text{Equation 6})$$

This is the minimum value of detection range for the slope referred to above and may be represented by the variable Y . Thus, in this example, the minimum value Y of detection range for the convex slope is equal to $Z+T$.

Scenario 3:

- if the distance of the train is beyond the position $-W$ (i.e. less than W before the slope or on the slope), the detection range is not limited by the slope track section, but rather is subject to the next track section. If there are no factors limiting the line of sight on the next track section then the theoretical detection range will be X . However, for smoothing purposes and to avoid abrupt changes, the detection range beyond $(-W)$ may be gradually increased from $Z+T$ to X . For smoothing purposes the rate of increase may be limited to a certain value, e.g. not more than 22 meters per second. In some cases the detection range may increase to a value less than X if there are limitations to the detection range due to the characteristics of the next track section such as further slopes or curves.

A visual example of the profile of the detection range at locations approaching and in the convex sloped section are shown in Fig. 9B. It can be seen that the detection range decreases from X to $Z+T$ as the train travels from a distance $X-T$ ahead of the junction of the sloped section to a distance Z ahead of the junction of the sloped section. The detection range then remains at $Z+T$ until the train reaches a distance of W ahead of the junction of the sloped section. After passing the distance W ahead of the junction of the sloped section the detection range gradually increases back to X or to a value determined by the characteristics of the next track section ahead of the current sloped section.

While Figs. 9A and 9B show an upwardly inclined convex slope, the same approach and equations may be used for a downwardly inclined convex slope.

Concave Track Section

Fig. 9C shows an example of an inclined section of track 930 followed by a level section of track 940 which forms a concave slope 901. The solid lines show the ceiling and floor of the tunnel. It can be seen that the sloped section 930 in this example includes a first portion 930A and a

second portion 930B which have different gradients. However, for the purpose of modeling these may be converted to the nominal profile shown in the dotted lines with a level portion 931B and an inclined or declined portion 931A. A junction 935 is defined as the joining point between these two portions. A train is shown at a first position T1 and a later second position T2, with the dotted and dashed lines indicating a line of sight of the sensor system of the train in each position. It will be appreciated that the detection range is less in position T1 than it is in position T2.

The joining point or junction 935, between the first and second portion of the nominal slope profile, is considered to have co-ordinates of 0 in the following discussion. The on-board system may define a first distance Z and a second distance W ahead of the junction. At locations between -Z and -W the detection range will have a minimum value Y. At locations prior to -Z and after -W the detection range may gradually increase to X which is the detection range for a level, straight section of track.

The first distance Z and the second distance W may be defined as follows:

$$Z \approx 4.5 / \text{relativeSlope}$$

$$W \approx 0.6 * \left(\frac{DH}{\text{relativeSlope}} - \frac{HC}{\text{relativeSlope}} \right)$$

(Equation 7)

where:

- Z, W depends on the gradient or steepness of the slope. The greater the steepness, the smaller the Z and W and vice versa.
- H, is the height of the train
- HC is the height of the sensors of the sensor system relative to the rail track
- DH is the height of the tunnel
- relativeSlope is a variable which depends on the characteristics of the slope, such as the gradient or steepness of the slope.

The value relativeSlope may be unique to each sloped track section and may be determined based on on-site testing of the detection range at the slope.

In one example, the detection range may be calculated depending on the location of the train relative to the junction 935, according to the three scenarios below.

Scenario 1:

- 5 - if the train is at the range $(-X, -Z)$, the detection range will decrease gradually from X to Z,

$$\text{detection range} = 1 * x$$

where:

x is the distance of the train away from the joining point

$$-X \leq x \leq -Z$$

10 Scenario 2:

- if the distance of the train is at the range $(-Z, -W)$,

$$\text{detection range} = Z$$

This is the minimum value of detection range for the slope referred to above and may be represented by the variable Y. Thus, in this example, the minimum value Y of detection range for the concave slope is equal to Z.

15

Scenario 3:

- 20 - if the distance of the train is at the range beyond $(-W)$, the detection range is not limited by this slope track section, but rather is subject to the next track section. If there are no factors limiting the line of sight on the next track section then the theoretical detection range will be X. However, for smoothing purposes and to avoid abrupt changes, the detection range beyond $(-W)$ may be gradually increased from Z to X. For smoothing purposes the rate of increase may be limited to a certain value, e.g. not more than 22 meters per second. In some cases the detection range may increase to a value less than X if there are limitations to the detection range due to the characteristics of the next track
- 25 section such as further slopes or curves.

While Fig. 9C shows an upwardly inclined concave slope, the same approach and equations may be used for a downwardly inclined concave slope.

While Figs 9A to 9C show one example of a convex slope and one example of a concave slope, the same approach may be applied to other convex or concave slopes having different profiles. In general, the actual slope profile may be converted to a nominal slope profile comprising two portions: a first portion having a gradient corresponding to a gradient of the first part of the slope and the second portion having a gradient corresponding to a gradient of the last part of the slope. For instance, Figs. 12A, 12B and 12C show examples of actual slopes 1200 in solid lines and corresponding nominal slopes comprising a first portion 1210 and second portion 1220 in dashed lines. The above described calculations for detection range can be applied by calculating T, W and Z based on the gradient of the second portion 1220 of the slope and the position of the junction 1215 between the first portion and the second portion of the nominal slope.

The above calculations presume the sloped section of track is in a tunnel of height DH. If the sloped track is in an outdoor section then the detection range will in theory be longer as there would be no line-of-sight blockage by the tunnel ceiling or floor. However, taking a conservative approach, the above equations may be used for an outdoor section of track too. For instance the outdoor section of track may be assigned a nominal tunnel height for instance using the same tunnel height as for a section of the railway which has a tunnel. This approach is safe, as it will determine a detection range on outdoor sections which is the same or less than the actual detection range for the outdoor sections.

20 Setting Safe Speed based on Detected Obstacle

When sensor system of the on-board system of a train detects an obstacle (e.g. pedestrian or another train) on the track ahead of the train, the distance between the object and train can be obtained by the sensor system, e.g. by using LiDAR. In this case the action module 670 may generate an alert to the driver of the train or take automatic action to adjust the speed of the train. In some examples the on-board system may determine a new safe speed for the train based on the detected obstacle. Thus the safe speed may be determined based on the detection range derived from the digital map or data store when no obstacle is detected and based on the detected obstacle when an obstacle is detected ahead of the train on the railway track.

30 One approach for determining a new speed for the train in light of the detected obstacle is to redefine the detection range as the distance of the obstacle from the train. In that case the new speed can be determined using the method of Fig. 4 and the adjusted detection range.

Detecting Location of Train based on Sensor System

In some examples the locating system may include a GPS receiver to receive GPS location signals. However, GPS signals cannot be received in tunnels and underground portions of a railway. In other examples the locating system may include a wireless device such as a RFID reader to receive location signals from trackside devices. However, it can be expensive to install
5 trackside devices along the whole length of a railway. Further, even if trackside devices are already installed, the on-board system would still need to be adapted to be compatible with such trackside devices, which may differ from railway to railway.

Accordingly, one aspect of the present disclosure proposes determining the current location of the train based on information from the sensor system. For example a landmark detected by the
10 camera and LiDAR apparatus may be matched with a landmark having a known location and the current location is determined based on the known location of the landmark, a speed of the train and a period of time elapsed since the landmark was detected. In this way the on-board system is not reliant on external systems such as GPS or trackside devices to determine a location of the train. This approach can work underground and in tunnels and does not require
15 expensive installation of trackside devices.

Fig. 10 shows a method 1000 of determining a location of a train on a railway.

At block 1010 a video stream of an environment of the train is generated by a camera mounted on the train.

At block 1020 Light Detection and Ranging (LiDAR) data of an environment of the train is
20 generated by a LiDAR system mounted on the train.

At block 1030 a digital model of an environment of the train is generated based on the video stream and the LiDAR data.

At block 1040 a landmark is detected in the digital model, which landmark has identifying features corresponding with identifying features of a landmark having a known location in a
25 digital map of the railway.

The landmark may for example be a specific station or arrangement of trackside infrastructure. Each landmark has unique identifying features, such as the arrangement and shape of various trackside infrastructure, the length of the station platforms, size and shape of buildings or other infrastructure near the platforms etc. Images, LiDAR data and/or identifying features of the
30 landmark as well as the location of the landmark may be stored in the digital map such that the landmark can be recognised by the on-board system using machine learning.

At block 1050 a speed of the train is determined.

For example, the speed of the train may be determined by using an odometer, gyroscopic device or a radar or LiDAR speed sensor. If a radar or LiDAR speed sensor is used this may be independent of existing control systems of the train which may simplify installation of the on-board system. This makes the on-board system highly adaptable and easier to migrate to different types of train.

At block 1060 a current location of the train is determined based on the known location of the landmark, the speed of the train and the time elapsed since the landmark was detected.

The known location of the landmark may be stored in the digital map. Thus at the point in time when the landmark is detected it may be ascertained that the train is close to the known location of the landmark. In some examples the location of the train may be further refined based on the LiDAR data indicating a distance of the train from the landmark. If the train continues to move after the landmark has been detected, the location can be updated based on the speed of the train as determined in block 1050 and the time elapsed since the landmark was detected.

The method may further comprise detecting a second landmark in the digital model and performing a location calibration in response to detecting the second landmark. In this way the location can be corrected based on detecting a second landmark at a later time after detecting the first landmark.

In some examples the location calibration may comprise detecting a difference between the determined current location and a known location of the second landmark and adjusting the determining of a current location to correct for this difference.

For example the location calibration may comprise re-setting the current location to the known location of the second landmark (which may be stored in the digital map). In this way the location of the train may be re-set each time a landmark is passed so that cumulative errors are not introduced into the location calculation.

Generating the digital model of the environment of the train in block 1030 may comprise combining information from a visual analytics system which detects objects in 2D images of the video stream with information on objects from a 3D point cloud generated based on the LiDAR data.

Fig. 11 shows an example of an on-board system 1100 for carrying out the method of Fig. 10.

The on-board system comprises a camera 1110 to generate a video stream of an environment of the train and a LiDAR apparatus 1120 to generate LiDAR data of an environment of the train.

The video stream may comprise a plurality of 2D images and the LiDAR data may comprise a 3D point cloud. The on-board system may include a visual analytics system which uses machine learning to detect objects in 2D images of the video stream and may be configured to combine the visual analytics with information on objects from the 3D point cloud generated by the LiDAR data to form a digital model of the environment of the train.

The on-board system further comprises a digital map 1130 comprising identifying features 1132A of a plurality of landmarks 1132 of the railway and known locations 1132B of the plurality of landmarks. The landmarks may for example be specific stations or specific arrangements of trackside infrastructure. Each landmark has unique identifying features, such as the arrangement and shape of various trackside infrastructure, the length of the station platforms, size and shape of buildings or other infrastructure near the platforms etc. Images, LiDAR data and/or identifying features of the landmark as well as the location of the landmark may be stored in the digital map such that the landmark can be recognised by the on-board system using machine learning. The digital map may have any of the features of digital maps and data stores described in this disclosure.

The on-board system further comprises a landmark detection module 1140 configured to detect a landmark in the video stream and the LiDAR data having features which match identifying features of a landmark in the digital map. The landmark detection module may use machine learning to detect 1142 landmarks in the data from the camera and the LiDAR and match 1144 the detected with landmarks in the digital map. The landmark detection module may then determine 1146 the location of the landmark from the digital map.

The on-board system further comprises a speed determining apparatus 1150 to determine a speed of the train. For example, the speed determining apparatus may be an odometer, gyroscopic device or a radar or LiDAR speed sensor.

The on-board system further comprises a location determining module 1160 to determine a current location of the train based on the known location of the detected landmark, the speed of the train and a time elapsed since the landmark was detected. The speed determining module may for example carry out the processes described above in relation to block 1060 of Fig. 10.

The on-board system may comprise one or more non-transitory machine readable storage mediums such as a hard drives, solid state drives, disk arrays, read only memory or random

access memory etc. and one or more processors such as central processing units (CPUs), microprocessors etc. The digital map may be stored on the non-transitory machine readable storage medium. The modules 1140 and 1160 may be implemented as machine readable instructions stored on the non-transitory machine readable storage medium and executable by
5 the one or more processors of the on-board system.

The on-board system of Fig. 11 may have any of the features of the on-board systems described above in relations to Figs. 1-9 and may be configured to perform any of the methods described herein including those described with reference to Figs. 1-10.

Thus the on-board systems and methods described herein may easily be modified for use with a
10 variety of different trains and railways. This is especially the case where the speed sensor is a LiDAR or radar sensor and not tied to existing train systems. In some examples, the on-board system may be independent of any existing signalling or monitoring systems of the train or railway. When introducing the on-board system to a new railway system, a digital map of the new railway may be installed on the on-board system. When introducing the on-board system to
15 a new train, certain parameters such as braking deceleration, may be set by testing the train or based on the train manufacturer's or railway operator's stated values.

In some examples, the on-board system may provide a display panel for a driver of the train to notify the driver of the determined safe speed of the train, alert the driver to any detected obstacles and/or generate an alert in case the speed of the train needs to be adjusted. In such
20 cases the on-board system need not be interfaced with control systems of the train. In other examples, the on-board system may be interfaced with a control system of the train to facilitate automatic braking and/or automatic driving of the train. In still other examples, the on-board system may provide both a display for the driver and also be interfaced with control systems of the train, so the train may be driven in manual mode, assisted and/or automatic driving mode
25 depending on the situation or choice of the driver.

In the examples above some instances of the present technology have been presented as including individual functional blocks including functional blocks comprising devices, device components, blocks or routines in a method embodied in software, or combinations of hardware and software.

30 Methods according to the above-described examples can be implemented using computer-executable instructions that are stored or otherwise available from computer readable media. Such instructions can comprise, for example, instructions and data which cause or otherwise configure a general purpose computer, special purpose computer, or special purpose

processing device to perform a certain function or group of functions. Portions of computer resources used can be accessible over a network. The computer executable instructions may be, for example, binaries, intermediate format instructions such as assembly language, firmware, or source code. Examples of computer-readable media that may be used to store
5 instructions, information used, and/or information created during methods according to described examples include magnetic or optical disks, flash memory, Universal Serial Bus (USB) devices provided with non-volatile memory, networked storage devices, and so on.

Devices implementing methods according to these disclosures can comprise hardware, firmware and/or software, and can take any of a variety of form factors. Typical examples of
10 such form factors include laptops, smart phones, small form factor personal computers, personal digital assistants, and so on. Functionality described herein also can be embodied in peripherals or add-in cards. Such functionality can also be implemented on a circuit board among different chips or different processes executing in a single device, by way of further example.

15 The instructions, media for conveying such instructions, computing resources for executing them, and other structures for supporting such computing resources are means for providing the functions described in these disclosures.

Although a variety of examples and other information was used to explain aspects within the scope of the appended claims, no limitation of the claims should be implied based on particular
20 features or arrangements in such examples, as one of ordinary skill would be able to use these examples to derive a wide variety of implementations. Further and although some subject matter may have been described in language specific to examples of structural features and/or method steps, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to these described features or acts. For example, such functionality can
25 be distributed differently or performed in components other than those identified herein. Rather, the above embodiments are described by way of example only and many variations are possible without departing from the scope of the disclosure as defined in the appended claims.