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(71) Applicant: **JAGUAR LAND ROVER LIMITED**

[GB/GB]; Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB).

(72) Inventors: **BIRCH, Luke**; c/o Jaguar Land Rover, PatentsDepartment W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB). **BROWN, Sam**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB).**LAUSECKER, Dennis**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB). **MISTRY, Anesh**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB).**ALI, Syed Asad**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB). **KELLY, James**; c/o JaguarLand Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB). **BURDOCK, William**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB).Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB). **BURDOCK, William**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB).(74) Agent: **MUSGRAVE, Charlotte**; c/o Jaguar Land Rover, Patents Department W/1/073, Abbey Road, Whitley, Coventry Warwickshire CV3 4LF (GB).

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(54) Title: SLOPE COMPENSATION BY MOVING A VEHICLE CENTRE OF GRAVITY

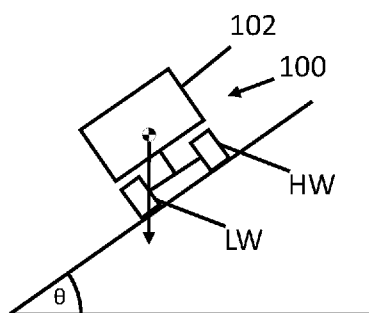


FIG. 6A

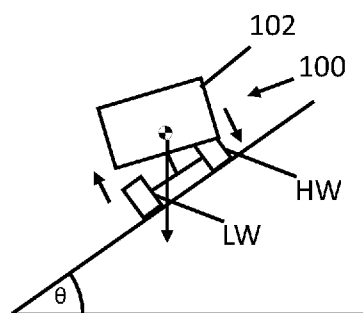


FIG. 6B

(57) Abstract: A control system (300) for controlling an active suspension system (104) of a vehicle (100), the vehicle comprising a vehicle body (102) supported by the active suspension system, the control system comprising one or more controller (301), wherein the control system is configured to: determine (1004) a vehicle attitude (X) comprising a vehicle roll angle; determine (1006) a vehicle body attitude (Y) of the vehicle body, comprising a vehicle body roll angle; and in dependence on the vehicle attitude changing (X0-X1), control (1008) the active suspension system to inhibit the vehicle body attitude from changing (Y0-Y1) in response to the change of vehicle attitude.



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SLOPE COMPENSATION BY MOVING A VEHICLE CENTRE OF GRAVITY

TECHNICAL FIELD

5 The present disclosure relates to slope compensation by moving a vehicle centre of gravity. In particular it relates to slope compensation by moving a vehicle centre of gravity using an active suspension system.

BACKGROUND

10 Driving on a longitudinal slope will modify the longitudinal pitch angle of a vehicle. Driving on a lateral slope (side-slope) will modify a roll angle of the vehicle. These changes in attitude of the vehicle (pitch and/or roll) can reduce comfort and visibility for vehicle occupants.

SUMMARY OF THE INVENTION

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According to an aspect of the invention there is provided a control system for controlling an active suspension system of a vehicle, the vehicle comprising a vehicle body supported by the active suspension system, the control system comprising one or more controller, wherein the control system is configured to:

20 determine a vehicle attitude comprising a vehicle roll angle;
determine a vehicle body attitude of the vehicle body, comprising a vehicle body roll angle; and
in dependence on the vehicle attitude changing, control the active suspension system to inhibit the vehicle body attitude from changing in response to the change of vehicle attitude.

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An advantage is that side slopes can be less uncomfortable for vehicle occupants and visibility can be improved.

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In some examples, the change of vehicle attitude is a first change of vehicle attitude below an attitude threshold, wherein the control system is configured to:

determine that a second change of the vehicle attitude is in excess of the attitude threshold; and
in dependence on determining that the second change is in excess of the attitude threshold, control the active suspension system to enable the vehicle body attitude to change in response to the second change of the vehicle attitude, at least partially without the inhibiting.

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In some examples, the control system is configured so that over a range of vehicle attitudes exceeding the attitude threshold, the vehicle body attitude is enabled to change in response to the first change of vehicle attitude as well as in response to a current change of vehicle attitude.

In some examples, the attitude threshold is configured to be exceeded by a value of vehicle roll angle having a value from the range approximately two degrees to approximately fifteen degrees.

In some examples, the control system is configured to:

determine that a third change of the vehicle attitude is in excess of a second attitude threshold; and

in dependence on determining that the third change is in excess of the second attitude threshold, control the active suspension system to enable the vehicle body attitude to linearly follow the third change of the vehicle attitude.

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In some examples, the second attitude threshold is configured to be exceeded by a value of vehicle roll angle from the range approximately 25 degrees to approximately 35 degrees.

In some examples, inhibiting the change of vehicle body attitude in response to increasing vehicle attitude is dependent on a ride height setting of the vehicle.

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In some examples, inhibiting the change of vehicle body attitude in response to increasing vehicle attitude is dependent on a weight indicator indicative of weight of the vehicle and/or indicative of weight distribution of the vehicle.

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In some examples, the weight indicator is dependent on weight-dependent feedback from the active suspension system.

In some examples, the control system is configured to:

determine that an indicator of vehicle speed is below a threshold; and

in dependence on determining that the indicator of vehicle speed is below the threshold, enable the control of the active suspension system.

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In some examples, the control of the active suspension system comprises hysteresis dependent on whether the change of vehicle attitude is an increase or a decrease.

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In some examples, inhibiting the change of vehicle body attitude in response to increasing vehicle attitude comprises controlling suspension actuators of a plurality of higher wheels of the vehicle so as to retract them towards the vehicle body and/or comprises controlling suspension actuators of a plurality of lower wheels of the vehicle so as to extend them away from the vehicle body.

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In some examples, inhibiting the change of vehicle body attitude in response to increasing vehicle attitude comprises controlling a suspension actuator so as to retract a higher wheel towards the vehicle body but not controlling a suspension actuator to extend a lower wheel away from the vehicle body.

In some examples, the control system is configured to smooth the rate of change of the vehicle body attitude in response to the change of vehicle attitude.

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In some examples, the control system is configured to cause output of driver feedback indicative that the active suspension system is being controlled in dependence on exceedance of the attitude threshold.

According to a further aspect of the invention there is provided a vehicle comprising the control system.

According to a further aspect of the invention there is provided a method of controlling an active suspension system of a vehicle, the vehicle comprising a vehicle body supported by the active suspension system, the method comprising:

- 5 determining a vehicle attitude comprising a vehicle roll angle;
 determining a vehicle body attitude of the vehicle body, comprising a vehicle body roll angle; and
 in dependence on the vehicle attitude changing, controlling the active suspension system to inhibit the vehicle body attitude from changing in response to the change of vehicle attitude.

- 10 According to a further aspect of the invention there is provided a control system for controlling an active suspension system of a vehicle, the vehicle comprising a vehicle body supported by the active suspension system, the control system comprising one or more controller, wherein the control system is configured to:

- determine a vehicle attitude comprising a vehicle roll angle;
 determine a vehicle body attitude of the vehicle body, comprising a vehicle body roll angle; and
15 control the active suspension system to control a rate at which the vehicle body attitude changes in response to changes of the vehicle attitude.

According to a further aspect of the invention there is provided a method of controlling an active suspension system of a vehicle, the vehicle comprising a vehicle body supported by the active suspension system, the method comprising:

- 20 determining a vehicle attitude comprising a vehicle roll angle;
 determining a vehicle body attitude of the vehicle body, comprising a vehicle body roll angle; and
 controlling the active suspension system to control a rate at which the vehicle body attitude changes in response to changes of the vehicle attitude.

- 25 According to a further aspect of the invention there is provided computer software that, when executed, is arranged to perform any one or more of the methods described herein. According to a further aspect of the invention there is provided a non-transitory computer readable medium comprising computer readable instructions that, when executed by a processor, cause performance of any one or more of the methods described herein.

- 30 The one or more controller may collectively comprise: at least one electronic processor having an electrical input for receiving information; and at least one electronic memory device electrically coupled to the at least one electronic processor and having instructions stored therein; and wherein the at least one electronic processor is configured to access the at least one memory device and execute the instructions thereon so as to cause the control system to cause performance of the method.

- 35 Within the scope of this application it is expressly intended that the various aspects, embodiments, examples and alternatives set out in the preceding paragraphs, in the claims and/or in the following description and drawings, and in particular the individual features thereof, may be taken independently or in any combination that falls within the scope of the appended claims. That is, all embodiments and/or features of any embodiment can be combined in any way and/or combination that falls within the scope of the appended claims, unless such features are incompatible. The applicant reserves the right to change

any originally filed claim or file any new claim accordingly, including the right to amend any originally filed claim to depend from and/or incorporate any feature of any other claim although not originally claimed in that manner.

BRIEF DESCRIPTION OF THE DRAWINGS

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One or more embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

FIG. 1 illustrates an example vehicle and a coordinate system;

FIG. 2 illustrates a vehicle on a side slope;

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FIG. 3 illustrates an example control system;

FIG. 4 illustrates an example of a non-transitory computer-readable storage medium;

FIG. 5 illustrates an example of an active suspension system of a vehicle;

FIGS. 6A, 6B illustrate an example of side slope compensation;

FIG. 7 illustrates an example of a vehicle speed-based entry condition;

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FIG. 8 illustrates an example smoothing function;

FIG. 9 illustrates an example relationship between vehicle attitude and vehicle body attitude; and

FIG. 10 illustrates an example method.

DETAILED DESCRIPTION

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FIG. 1 illustrates an example of a vehicle 100 in which embodiments of the invention can be implemented. In some, but not necessarily all examples, the vehicle 100 is a passenger vehicle, also referred to as a passenger car or as an automobile. In other examples, embodiments of the invention can be implemented for other applications, such as industrial or commercial vehicles. The vehicle 100 has a vehicle body 102 (sprung mass) supported by a suspension.

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FIG. 1 also illustrates a coordinate system. The x-axis is the longitudinal axis. A vehicle body rotation 'R' about the x-axis is vehicle body roll (relative to its axles, also known as vehicle roll-to-axle). The y-axis is the lateral axis. A vehicle body rotation 'P' about the y-axis is vehicle body pitch (relative to its axles, also known as vehicle pitch-to-axle). The z-axis is the vertical axis. A vehicle body rotation 'Y' about the z-axis is vehicle body yaw. A whole-vehicle rotation about the x-axis is vehicle roll (relative to a true horizontal horizon, also known as vehicle roll-to-horizontal angle). A whole-vehicle rotation about the y-axis is vehicle pitch (relative to true horizontal horizon, also known as pitch-to-horizontal angle).

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FIG. 2 schematically illustrates a vehicle 100 on a side-slope, without any compensation applied. The side slope has an angle θ relative to a horizontal horizon. The whole vehicle 100 including the vehicle body 102 is rolled to a vehicle roll angle approximately equal to θ relative to a true horizontal horizon. The term 'approximately' is used because for higher values of θ , the vehicle body roll angle may slightly exceed θ due to compression of the downhill suspension springs: this may or may not be fully compensated for in the methods described herein. A centre of gravity of the vehicle 100 extends towards the downhill wheel.

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Some types of vehicle 100 can accommodate side slopes of up to $\theta=40$ -45 degrees without rollover, in the right conditions. At least some examples of the present disclosure are concerned with lower values of θ when the side slope may start to be uncomfortable for vehicle occupants and/or reduce visibility, but within capabilities of the vehicle 100 for reasonable driving conditions.

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If the vehicle body 102 could be conditionally controlled so that the vehicle body attitude (vehicle body roll angle) increases slower than the vehicle attitude (vehicle roll angle of the whole vehicle = angle of slope), side slopes can be less uncomfortable for vehicle occupants and visibility can be improved.

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The vehicle body attitude can be controlled to have a vehicle body roll angle less than θ relative to the horizontal horizon, so that occupant comfort and visibility would be improved. Such conditional compensation is not available from self-levelling suspension systems. Self-levelling suspension systems are typically concerned with managing ride height at different corners of the vehicle to compensate for vehicle loading and lateral acceleration. Self-levelling suspension systems can compensate for the natural tendency of a vehicle to squat under heavy load. In other cases, such as on recreational vehicles, self-levelling suspension systems can, when the vehicle is parked on slightly uneven ground, compensate for that unevenness by adjusting air spring pressures to level the vehicle when parked up overnight.

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In at least some embodiments of the invention, the suspension of the vehicle 100 is an active suspension system able to reduce the vehicle body roll angle. An active suspension system 104 is a system to which energy can be supplied under the control of a control system 300 such as the one shown in FIG. 3, so as to independently vary the wheel-to-body distance at different wheels of the vehicle 100. By adding energy to increase wheel-to-body distance at the lower (downslope) side of the vehicle 100 relative to the higher (upslope) side of the vehicle 100, the centre of gravity of the vehicle 100 will be laterally moved further towards the centre of the vehicle body 102 (towards x-axis). This will provide a more level platform for vehicle occupants.

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The above concept is referred to herein as 'slope compensation', and can be employed to improve the driving experience on mild-to-moderate side slopes or diagonal slopes.

An active suspension system 104 and the control system 300 will first be described.

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The control system 300 of FIG. 3 comprises a controller 301. In other examples, the control system 300 may comprise a plurality of controllers on-board and/or off-board the vehicle 100. In some examples, a control system 300 or a controller 301 may be supplied as part of an active suspension system 104.

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The controller 301 of FIG. 3 includes at least one processor 304; and at least one memory device 306 electrically coupled to the electronic processor 304 and having instructions 308 (e.g. a computer program) stored therein, the at least one memory device 306 and the instructions 308 configured to, with the at least one processor 304, cause any one or more of the methods described herein to be performed. The processor 304 may have an interface 302 such as an electrical input/output I/O or electrical input for receiving information and interacting with external components such as the active suspension system 104.

FIG. 4 illustrates a non-transitory computer-readable storage medium 400 comprising the instructions 308 (computer software).

5 FIG. 5 illustrates an example implementation of the active suspension system 104.

The active suspension system 104 comprises front left active suspension 106 for a front left wheel FL, front right active suspension 116 for a front right wheel FR, rear left active suspension 108 for a rear left wheel RL, and rear right active suspension 118 for a rear right wheel RR. The active suspension for each wheel (e.g. quarter/corner) of the vehicle 100 may
10 be individually controllable.

FIG. 5 also shows a torque source 103 such as an internal combustion engine or electric machine, for driving at least some of the vehicle wheels.

15 The active suspension for each corner of the vehicle 100 comprises an actuator 502.

The actuator 502 may be a hydraulic actuator such as a hydraulic fluid-filled chamber containing a piston. One end of the actuator 502 is coupled to a vehicle wheel and the other end is coupled to the vehicle body 102. A spring 504 (e.g. coil or pneumatic) may be in equilibrium and acting in parallel with the actuator 502.
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When the vehicle suspension is undisturbed, the piston of the hydraulic actuator 502 sits at a particular neutral position in the chamber.

The piston can move in either direction inside the chamber, e.g. due to a road disturbance compressing the actuator 502. The
25 piston can displace fluid out of the chamber into a hydraulic circuit (not shown). The fluid imparts a restoring force against movement of the piston. Energy can be added to and/or extracted from the actuator 502 by pumping fluid and/or controlling valves to regulate fluid pressure to either side of the piston.

Therefore, a control system 300 can dynamically control restoring force against the displaced piston. This force is equivalent
30 to spring force of a coil spring against displacement. Dynamic control enables the force-displacement relationship to be changed to adapt to a driving scenario. Energy can be added or removed quickly, e.g. within tens of milliseconds. In order to control spring force, the control system 300 may output a force request that is dependent on sensed wheel travel (wheel-to-body displacement/articulation).

35 Dynamic damping characteristics of the actuator 502 can be modified by controlling a fluid valve at a constriction, which regulates the rate at which fluid is transferred in and out of the actuator 502 by movement of the piston.

Further, energy can be added to or removed from the actuator 502 in order to extend or retract the actuator 502. In FIG. 5 this enables the wheel-to-body distance to be changed independently at different ends and/or at different corners of the vehicle 100.

- 5 The above example refers to a hydraulic actuator 502, and in other embodiments the actuator may be an electromagnetic actuator or a pneumatic actuator, or the like.

The above example refers to a fully active suspension system. It would be appreciated that in other examples, the methods described herein can be performed by a different type of active suspension system such as an active roll control system.

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In FIG. 5 but not necessarily all examples, the spring 504 comprises an active spring such as a pneumatic spring, enabling control of ride height. The control system 300 may be configured to pump gas (e.g. air) in or out of the pneumatic spring 504 to control ride height. An air-levelling function of the control system 300 seeks to maintain a set ride height irrespective of vehicle load and achieves this by modifying the volume of air and therefore air pressure to maintain the set ride height.

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Energy can be added to or removed from the active spring 504 in order to increase or decrease the volume of the active spring 504. Increasing the volume can lift the vehicle body 102 in the z-axis. In FIG. 5 this enables the wheel-to-body distance to be changed independently at different ends and/or at different corners of the vehicle 100.

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Additionally, or alternatively, the spring 504 comprises a passive spring (e.g. coil) or is omitted entirely.

Control of the active suspension system 104 relies on one or more sensors. Wheel travel may be sensed by a wheel-to-body displacement sensor 514 (suspension displacement-based sensor), for example. The wheel-to-body displacement sensor 514 is placed somewhere on the active suspension and can sense the position of the wheel along an arc defined by suspension geometry. An example of a wheel-to-body displacement sensor 514 is a rotary potentiometer attached to a lever, wherein one end of the lever is coupled to the vehicle body 102, and the other end is coupled to a suspension link.

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In some examples, the control system 300 more accurately determines the wheel travel and/or its associated derivatives by fusing information from the wheel-to-body displacement sensor 514 with information from hub accelerometers.

30

Pressure in the pneumatic spring 504 is weight-dependent feedback that can indicate weight onto the wheel, by indicating how much pressure is required to get the vehicle body 102 up to a required ride height (depends on weight).

35

In at least some examples the control system 300 is configured to control the active suspension system 104 by transmitting a force request to the active suspension or to a low-level controller thereof. The force request may be an arbitrated force request based on requests from various requestors and information from various sensors.

FIG. 5 illustrates additional optional features that may interact with the control system 300 to influence force request calculation. These include any one or more of:

- A wheel speed sensor 512 for each wheel. In an example implementation, the wheel speed sensor 512 is part of an antilock braking system (ABS).
- A hub-mounted accelerometer 516 for each wheel, coupled to the unsprung mass of the vehicle 100.
- A human-machine interface (HMI) 520. This refers to any of the various input devices and input/output devices available to the driver such as touchscreens, displays, hardware switches/sliders/selectors or the like.
- At least one vehicle body accelerometer 522 coupled to the vehicle body 102 (sprung mass). A particular example includes a 3DOF or 6DOF inertial measurement unit (IMU). A unit may comprise an accelerometer or a multi-axis set of accelerometers.

FIG. 6A shows the vehicle 100 and the side slope of FIG. 2, with a lower (downslope) wheel LW and a higher (upslope) wheel HW highlighted. The lower wheel could be the left wheels FL, RL and the higher wheel could be the right wheels FR, RR, or vice versa.

FIG. 6B shows the vehicle 100 after the active suspension system has been controlled to compensate for the side slope. In this example, but not necessarily all examples the higher wheel/wheels HW has been retracted towards the vehicle body 102 while concurrently the lower wheel/wheels LW has been extended away from the vehicle body 102.

In another embodiment the higher wheels HW are retracted without extending the lower wheels LW, or only the lower wheels LW are extended without retracting the higher wheels HW. However, the illustrated approach enables a greater amount of slope compensation.

As a result of the slope compensation, the centre of gravity of the vehicle 100 has moved inboard and away from a predetermined attitude limit of the vehicle 100. The predetermined attitude limit could be an angle limit inherent to the vehicle design and specified by a manufacturer. The predetermined attitude limit varies between vehicles depending on their mass distributions, but may be somewhere between 35 degrees and 45 degrees of vehicle roll angle for an ideal surface. Note that the predetermined attitude limit is a vehicle characteristic, and does not necessarily feature in the calculations of the control system 300.

The amount of compensation is referred to as a 'compensation angle', which is a target angle of the vehicle body 102. The target compensation angle is reached by controlling the active suspension system 104 to inhibit (prevent or slow) the rolling motion of the vehicle body 102 in response to a change of vehicle roll angle, to prevent or slow deviation of the vehicle body roll angle relative to the horizontal horizon. The illustrated compensation angle can compensate for all of the vehicle roll angle to maintain a horizontal attitude, and/or can partially compensate for higher vehicle roll angles depending on the capabilities of the active suspension system 104.

In some examples the compensation angle is capable of being at least 2 degrees (upper limit) depending on the capability of the active suspension system 104. In some examples the compensation angle is capable of being up to 15 degrees depending on the capability of the active suspension system 104. In an example use case the compensation angle is approximately 8 degrees.

In some examples the maximum compensation angle is dependent on information from wheel-to-body displacement sensors 514, and configured to leave a margin for wheel-to-body displacement before an end of suspension travel is reached.

When calculating the compensation angle, the control system 300 can determine the vehicle attitude (e.g. vehicle roll angle) relative to a reference (e.g. horizontal horizon) to determine the angle of the slope that the vehicle 100 is on. An example sensing approach comprises determining the vehicle body roll angle from the IMU 522, and then compensating for the difference between vehicle body roll angle and vehicle roll angle using measurements from the wheel-to-body displacement sensors 514 and/ hub-mounted accelerometers 516. Derivatives such as roll rate can also be calculated to compensate for dynamic effects.

The control system 300 can further determine the vehicle body attitude (e.g. vehicle body roll angle) relative to a reference (e.g. horizontal horizon) to determine the angle of the vehicle body 102. An example sensing approach comprises determining the vehicle body roll angle from the IMU 522.

In at least some examples the slope compensation is performed at least if the side slope angle θ as indicated by the vehicle roll angle is nonzero, or exceeds an initial attitude threshold having a value greater than zero (e.g. <5 degrees).

In some examples, the target compensation angle is processed into lower-level commands governing an amount of extension and/or retraction required at each wheel / each group of wheels LW/HW.

In some, but not necessarily all examples, when the lower-level commands are calculated the control system 300 may be configured to move the position of a roll centre of the vehicle 100 leftwards or rightwards relative to its natural roll centre position, by controlling the ratio of extension of the lower wheels LW to the retraction of the higher wheels HW.

In an example use case, the position of the roll centre can be controlled for passenger comfort and/or for driver comfort. The control system 300 can receive occupancy information from an occupancy sensor (e.g. seatbelt sensor; seat weight sensor; cabin-facing camera etc.) to determine a target position of the roll centre. The roll centre can be moved towards an occupied passenger seat for improved passenger comfort. The roll centre can alternatively be moved towards a driver's seat for improved driver comfort. In some examples, the roll centre can be initially moved towards a passenger seat but then automatically moved towards the driver's seat as the vehicle roll angle increases (increasing slope).

FIG. 7 is a graph schematically illustrating how the control system 300 could be configured to activate slope compensation. In this example the slope compensation is enabled at low vehicle speeds and disabled at higher vehicle speeds. This ensures that the active suspension system 104 is working within its bandwidth to provide an instant response, and can ensure that the compensation is not implemented when travelling at highway speeds on superelevated roads.

FIG. 7 illustrates a y-axis comprising a maximum compensation angle ('Max [o]') and an x-axis comprising an indicator of vehicle speed (e.g. average wheel speeds). The maximum compensation angle refers to the maximum amount of vehicle body attitude that is allowed to be subtracted, towards a zero attitude (horizontal horizon). The control system 300 can monitor

how much vehicle body attitude has been subtracted using information from wheel-to-body displacement sensors 514 and/or feedback from the IMU 522.

As illustrated, the maximum compensation angle is initially zero when vehicle speed is above a vehicle speed threshold. Then, when vehicle speed falls below the vehicle speed threshold, the maximum angle rises above zero. The vehicle speed threshold can have a value selected from the range approximately 5 m/s to approximately 12 m/s.

In FIG. 7, but not necessarily all examples the maximum compensation angle increases in dependence on decreasing vehicle speed, for vehicle speeds below the vehicle speed threshold. The maximum compensation angle may have a maximum value when vehicle speed is zero. In FIG. 7, but not necessarily all examples the increase of the maximum compensation angle is nonlinear, steepening as vehicle speed gets lower. The maximum compensation angle could follow an inverse-S curve.

If vehicle speed subsequently rises, slope compensation could be reduced using the same or a similar curve to that shown in FIG. 7. Some hysteresis could be implemented by having different thresholds and/or different curves, to slow the vehicle's response to fast fluctuations of vehicle speed.

The functionality of FIG. 7 could be implemented as a map in the control system 300. It would be appreciated that the maximum compensation angle could vary with vehicle speed in a manner different from that shown in FIG. 7. For example, the control could be binary.

In at least some examples the slope compensation is configured to provide comfort to vehicle occupants, because requesting actuator extension/retraction at the maximum responsiveness could cause a jerk. Accordingly, the graph of FIG. 8 illustrates examples of how smoothing could be implemented to control a rate of change of the vehicle body attitude in response to the change of vehicle attitude for an increasing slope. This can be regarded as a roll rate limitation.

The y-axis of FIG. 8 illustrates a permitted vehicle roll rate (y-axis) relative to increasing vehicle roll rate (x-axis). Additionally, or alternatively, the function of FIG. 8 can be applied to vehicle roll acceleration.

As illustrated in FIG. 8, the permitted vehicle roll rate may be saturated at a predetermined comfort value, by restricting the force request to slow the response of the actuator 502. The functionality of FIG. 8 could be implemented as a map in the control system 300, providing a saturation function.

FIG. 9 is a graph illustrating an example of a variable relationship between measured vehicle attitude and requested vehicle body attitude, to control the rate at which the vehicle body attitude changes in response to changes of vehicle attitude. The y-axis comprises the vehicle body attitude Y (e.g. vehicle body roll angle) and the x-axis comprises the vehicle attitude X (e.g. vehicle roll angle).

In FIG. 9, but not necessarily all examples, the initial vehicle attitude threshold X_0 for enabling slope compensation is set to $X_0=0$. Therefore, slope compensation is not limited to steep slopes.

In FIG. 9, but not necessarily all examples, slope compensation can be performed for a change of vehicle attitudes between the initial attitude threshold X0 of vehicle attitude, and a first attitude threshold X1 of the vehicle attitude. The first attitude threshold X1 can have a value selected from the range approximately two degrees to approximately fifteen degrees. In a use case X1 is equal to approximately 8 degrees. The first attitude threshold can optionally vary in dependence on various factors described later.

Within this 'comfort' range X0 to X1, the control system 300 controls the active suspension system 104 to inhibit (prevent or impede) the vehicle body attitude from changing (naturally changing) in response to the change of vehicle attitude. The resulting slope compensation can be as described in relation to FIG. 6B, although FIG. 6B exaggerates the steepness of the slope.

In some examples, the term 'inhibit' refers to holding the vehicle body attitude at a different, more horizontal target angle than the current vehicle attitude of the unsprung mass of the vehicle, without enabling the vehicle body attitude to catch up to the vehicle attitude. In other words, if the vehicle attitude remains at a constant value X1, the target vehicle body attitude (target compensation angle) will be continuously maintained.

In the specific example of FIG. 9, but not necessarily all examples, the vehicle body attitude Y1 at vehicle attitude X1 is substantially the same as the original vehicle body attitude Y0 at vehicle attitude X0. Therefore, the slope increase has been fully compensated. Therefore, the value of X1 should be within the earlier-defined upper limits of travel of the active suspension system 104 to enable the full compensation.

In FIG. 9, but not necessarily all examples, when the vehicle attitude exceeds the attitude threshold X1 but is less than a second attitude threshold X2, the behaviour may change. The control system 300 controls the active suspension system 104 to enable the vehicle body attitude to change in response to the vehicle attitude, with less or no additional slope compensation.

Above X1, the vehicle body attitude starts to increase to follow increasing vehicle attitude, as shown by the rising line in FIG. 9. The transition through X1 could be smoothed (transitional curve) in order to make the threshold imperceptible. In other words, the slope compensation can be reduced in a non-binary manner as the vehicle attitude passes through X1.

The second attitude threshold X2 can have a value selected from the range approximately 25 degrees to approximately 35 degrees, representing a point at which the slope becomes very steep. The second attitude threshold can optionally vary in dependence on various factors described later.

In the specific example of FIG. 9, but not necessarily all examples, the vehicle body attitude Y2 at the second attitude threshold X2 is the same value that it would have been if slope compensation had never been performed. In order to achieve this, the vehicle body attitude firstly needs to change in response to the current vehicle attitude and secondly needs to change in response to the original change in vehicle attitude from X0 to X1, to undo (unwind) all of the original slope compensation. Remember that until the original slope compensation has been unwound, the vehicle body attitude will remain a few degrees

more horizontal than the vehicle attitude. The vehicle occupants may perceive this unwinding behaviour as the vehicle body rolling slightly faster than the increasing slope angle ($>1:1$ relationship), which can act as a haptic notification that the slope is getting quite steep. Therefore, the region X1-X2 can be regarded as a 'haptic notification' region.

5 The resulting curve between X1 and X2 is characterized by the ratio vehicle body attitude:vehicle attitude being initially slightly less than 1:1 (partial slope compensation performed), and then becoming slightly greater than 1:1 (no slope compensation with unwinding of previous slope compensation), before ending up equal to 1:1 at X2. These characteristics can be captured by a slight S-shaped curve function as illustrated, or a similar function.

10 Since FIG. 9 is a continuous function with a variable and at least partially nonlinear ratio, all of the above-defined thresholds X0, X1, X2 can be regarded as points along the continuous function shown in FIG. 9, rather than as distinct staircase/bang-bang thresholds.

15 The functionality of FIG. 9 could be implemented as a map in the control system 300. In other embodiments, at least some of the functionality of FIG. 9 is binary rather than variable, and/or the logic could be applied to other variables.

Although not shown in FIG. 9, in some examples the slope compensation can depend on other monitored variables that affect the amount of available slope compensation that can be performed. For example, the slope compensation may depend on a ride height setting of the vehicle 100 (detected/target ride height), and/or a weight indicator indicative of weight of the vehicle
20 100 and/or a tyre pressure. The weight indicator could indicate total weight of the vehicle 100 or could indicate a weight distribution of the vehicle 100 to different corners of the vehicle 100. The weight distribution and/or vehicle weight could be indicated by active spring pressures, for example. The ride height setting and/or weight indicator may affect either the whole relationship (e.g. function of FIG. 9) or just parts thereof such as a threshold (e.g. X1, X2).

25 In some examples:
low tyre pressure of at least one tyre (e.g. below threshold) can reduce X1;
high weight on at least one wheel (e.g. above threshold) can reduce X2; and
a high ride height setpoint (e.g. above threshold) can reduce X1 and/or X2.

30 FIG. 10 is a flowchart illustrating an example control method 1000 for slope compensation, implemented by the control system 300. The method could compensate for lateral slopes or diagonal slopes comprising a combination of a lateral slope and a longitudinal slope. A longitudinal slope can be compensated for by extending downhill actuators 502 and/or retracting uphill actuators 502.

35 The method 1000 starts at operation 1002 in which the method 1000 is enabled. Enabling the method 1000 may optionally require that one or more inhibit conditions are not active, such as the feature being disabled by the driver via an HMI 522, or the vehicle 100 not being in a specific operating mode.

At operation 1004 the vehicle attitude is determined as described earlier. At operation 1006 the vehicle body attitude is determined as described earlier.

At operation 1008 the method 1000 proceeds to implementing the slope compensation. In an example the method controls the rate at which vehicle body attitude changes in response to vehicle attitude changes. Examples are already described in relation to FIGS. 6A-9.

In addition to implementing slope compensation, the control system 300 may concurrently cause output of driver feedback 1010 indicative that the active suspension system 104 is being controlled to provide slope compensation. The output may sent to an HMI 520. The output may be audible and/or visual. The driver feedback could be in the form of displaying a graphical representation of the vehicle 100 and a graphical representation of the slope angle and/or of the horizontal horizon. The slope angle correction may be graphically represented as the vehicle body representation being more horizontal than the slope and wheels of the vehicle.

In some examples the driver can manually cancel slope compensation using an HMI 520, or configure slope compensation such as one or more of the control parameters described herein (e.g. X1).

For purposes of this disclosure, it is to be understood that the controller(s) described herein can each comprise a control unit or computational device having one or more electronic processors. A vehicle and/or a system thereof may comprise a single control unit or electronic controller or alternatively different functions of the controller(s) may be embodied in, or hosted in, different control units or controllers. A set of instructions could be provided which, when executed, cause said controller(s) or control unit(s) to implement the control techniques described herein (including the described method(s)). The set of instructions may be embedded in one or more electronic processors, or alternatively, the set of instructions could be provided as software to be executed by one or more electronic processor(s). For example, a first controller may be implemented in software run on one or more electronic processors, and one or more other controller may also be implemented in software run on one or more electronic processors, optionally the same one or more processors as the first controller. It will be appreciated, however, that other arrangements are also useful, and therefore, the present disclosure is not intended to be limited to any particular arrangement. In any event, the set of instructions described above may be embedded in a computer-readable storage medium (e.g., a non-transitory computer-readable storage medium) that may comprise any mechanism for storing information in a form readable by a machine or electronic processors/computational device, including, without limitation: a magnetic storage medium (e.g., floppy diskette); optical storage medium (e.g., CD-ROM); magneto optical storage medium; read only memory (ROM); random access memory (RAM); erasable programmable memory (e.g., EPROM and EEPROM); flash memory; or electrical or other types of medium for storing such information/instructions.

It will be appreciated that various changes and modifications can be made to the present invention without departing from the scope of the present application.

The blocks illustrated in FIG. 10 may represent steps in a method and/or sections of code in the computer program 308. The illustration of a particular order to the blocks does not necessarily imply that there is a required or preferred order for the blocks and the order and arrangement of the block may be varied. Furthermore, it may be possible for some steps to be omitted.

5 Although embodiments of the present invention have been described in the preceding paragraphs with reference to various examples, it should be appreciated that modifications to the examples given can be made without departing from the scope of the invention as claimed.

Features described in the preceding description may be used in combinations other than the combinations explicitly described.

10

Although functions have been described with reference to certain features, those functions may be performable by other features whether described or not.

15 Although features have been described with reference to certain embodiments, those features may also be present in other embodiments whether described or not.

20 Whilst endeavoring in the foregoing specification to draw attention to those features of the invention believed to be of particular importance it should be understood that the Applicant reserves the right to claim protection in respect of any patentable feature or combination of features hereinbefore referred to and/or shown in the drawings whether or not particular emphasis has been placed thereon.

CLAIMS

1. A control system for controlling an active suspension system of a vehicle, the vehicle comprising a vehicle body supported by the active suspension system, the control system comprising one or more controller, wherein the control system is configured to:

determine a vehicle attitude comprising a vehicle roll angle;

determine a vehicle body attitude of the vehicle body, comprising a vehicle body roll angle; and

in dependence on the vehicle attitude changing, control the active suspension system to inhibit the vehicle body attitude from changing in response to the change of vehicle attitude.

2. The control system of claim 1, wherein the change of vehicle attitude is a first change of vehicle attitude below an attitude threshold, wherein the control system is configured to:

determine that a second change of the vehicle attitude is in excess of the attitude threshold; and

in dependence on determining that the second change is in excess of the attitude threshold, control the active suspension system to enable the vehicle body attitude to change in response to the second change of the vehicle attitude, at least partially without the inhibiting; and optionally

wherein the control system is configured so that over a range of vehicle attitudes exceeding the attitude threshold, the vehicle body attitude is enabled to change in response to the first change of vehicle attitude as well as in response to a current change of vehicle attitude.

3. The control system of claim 2, wherein the attitude threshold is configured to be exceeded by a value of vehicle roll angle having a value from the range approximately two degrees to approximately fifteen degrees.

4. The control system of any one of claims 2 to 3, configured to:

determine that a third change of the vehicle attitude is in excess of a second attitude threshold; and

in dependence on determining that the third change is in excess of the second attitude threshold, control the active suspension system to enable the vehicle body attitude to linearly follow the third change of the vehicle attitude; and optionally wherein the second attitude threshold is configured to be exceeded by a value of vehicle roll angle from the range approximately 25 degrees to approximately 35 degrees.

5. The control system of any preceding claim, wherein inhibiting the change of vehicle body attitude in response to increasing vehicle attitude is dependent on a ride height setting of the vehicle.

6. The control system of any preceding claim, wherein inhibiting the change of vehicle body attitude in response to increasing vehicle attitude is dependent on a weight indicator indicative of weight of the vehicle and/or indicative of weight distribution of the vehicle and optionally wherein the weight indicator is dependent on weight-dependent feedback from the active suspension system.

7. The control system of any preceding claim, configured to:

determine that an indicator of vehicle speed is below a threshold; and
in dependence on determining that the indicator of vehicle speed is below the threshold, enable the control of the active suspension system.

- 5 8. The control system of any preceding claim, wherein the control of the active suspension system comprises hysteresis dependent on whether the change of vehicle attitude is an increase or a decrease.
9. The control system of any preceding claim, wherein inhibiting the change of vehicle body attitude in response to increasing vehicle attitude comprises controlling suspension actuators of a plurality of higher wheels of the vehicle so as to retract them towards the vehicle body and/or comprises controlling suspension actuators of a plurality of lower wheels of the vehicle so as to extend them away from the vehicle body.
- 10 10. The control system of any preceding claim, wherein inhibiting the change of vehicle body attitude in response to increasing vehicle attitude comprises controlling a suspension actuator so as to retract a higher wheel towards the vehicle body but not controlling a suspension actuator to extend a lower wheel away from the vehicle body.
- 15 11. A vehicle comprising the control system of any preceding claim.
12. A method of controlling an active suspension system of a vehicle, the vehicle comprising a vehicle body supported by the active suspension system, the method comprising:
- 20 determining a vehicle attitude comprising a vehicle roll angle;
 determining a vehicle body attitude of the vehicle body, comprising a vehicle body roll angle; and
 in dependence on the vehicle attitude changing, controlling the active suspension system to inhibit the vehicle body attitude from changing in response to the change of vehicle attitude.
- 25 13. Computer software that, when executed, is arranged to perform a method according to claim 12.

1/4

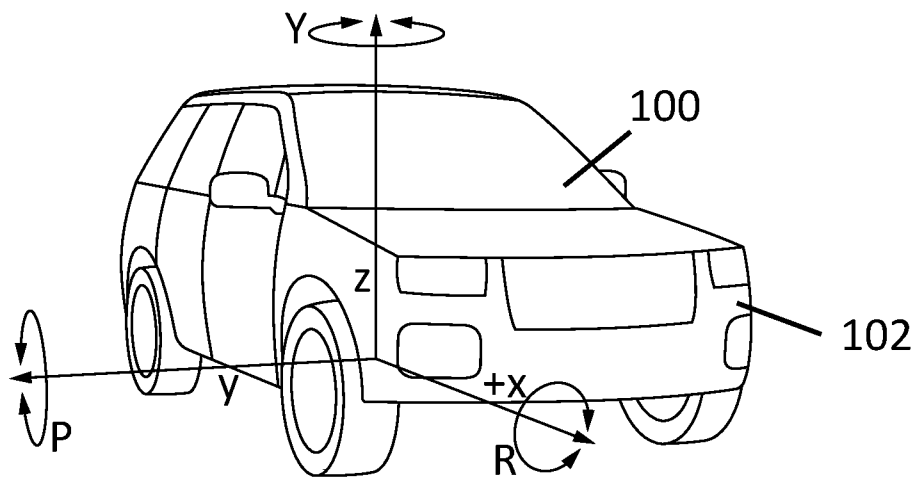


FIG. 1

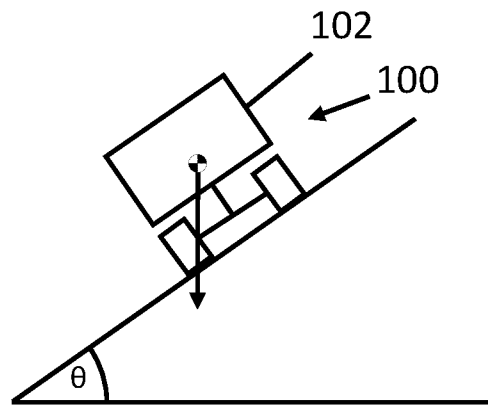


FIG. 2

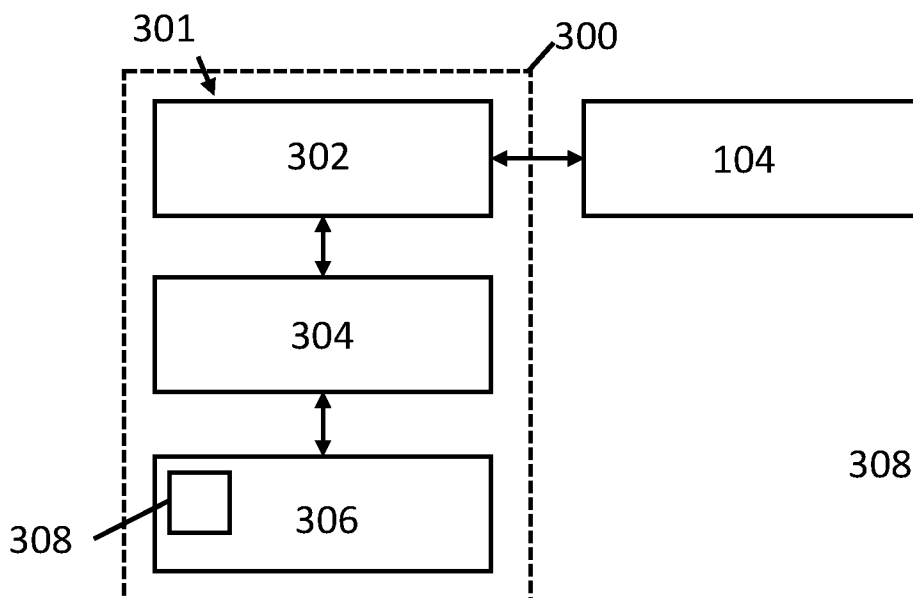


FIG. 3

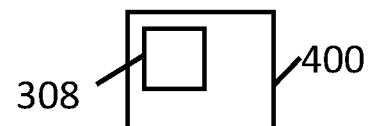


FIG. 4

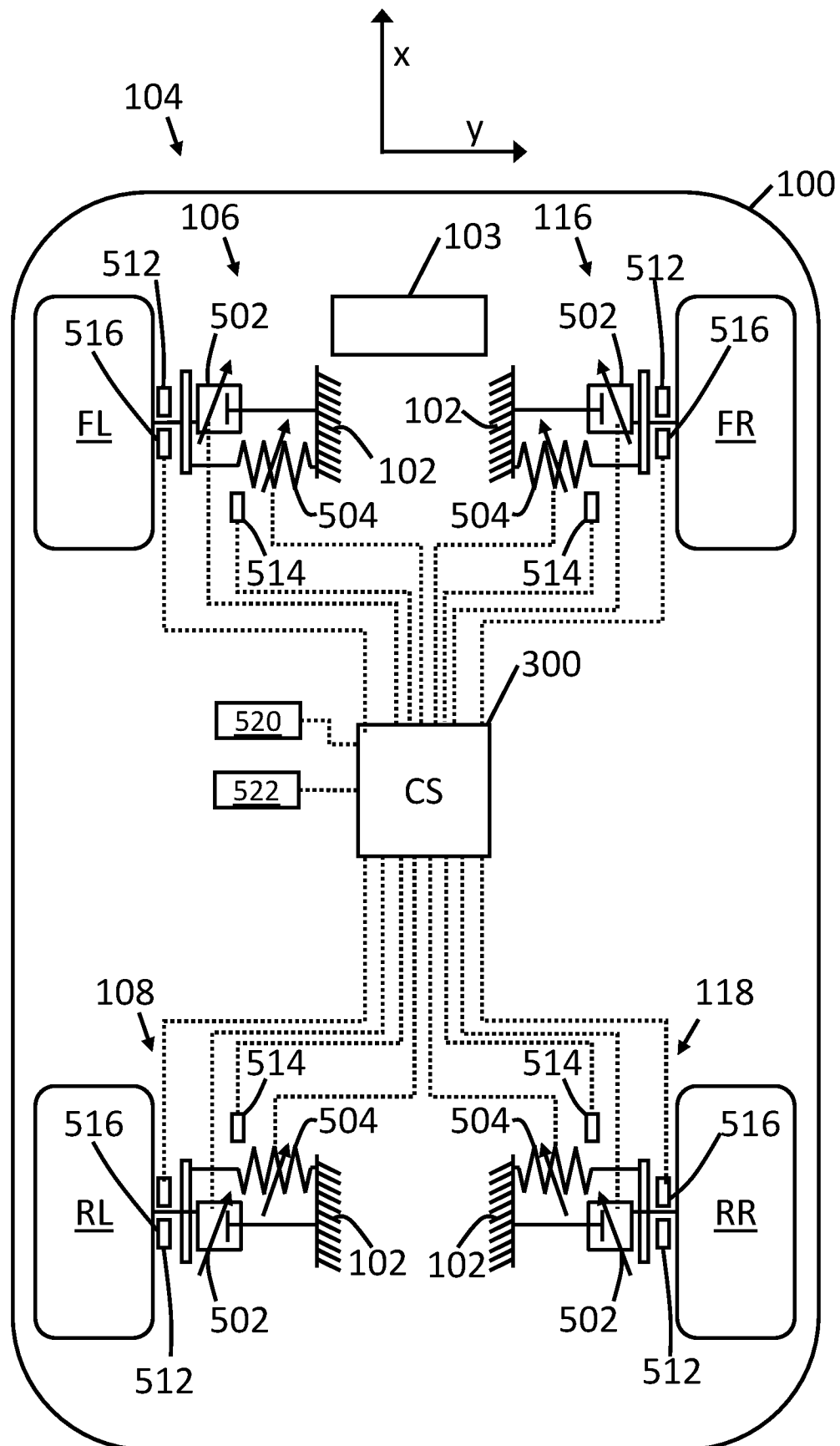


FIG. 5

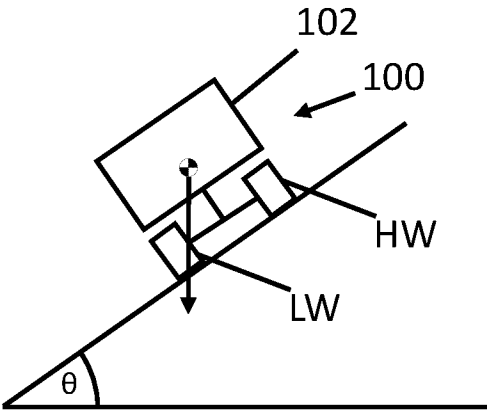


FIG. 6A

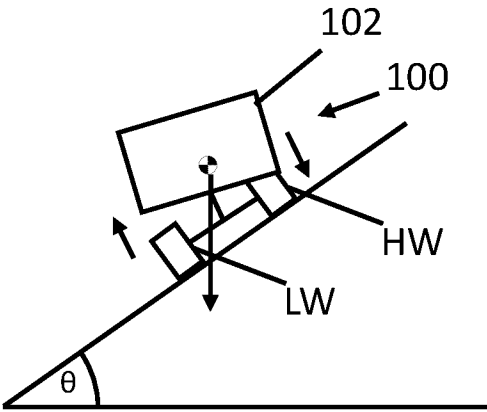


FIG. 6B

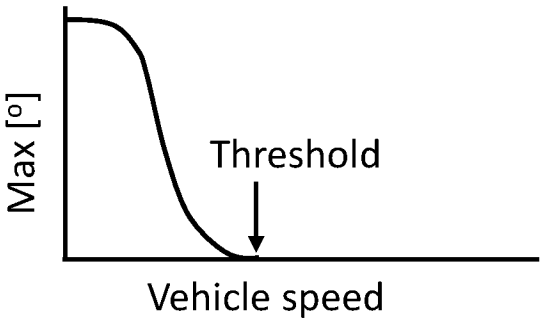


FIG. 7

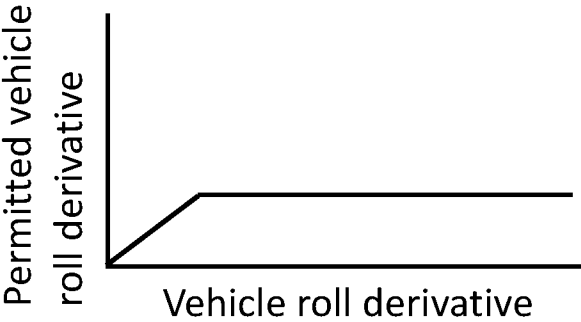


FIG. 8

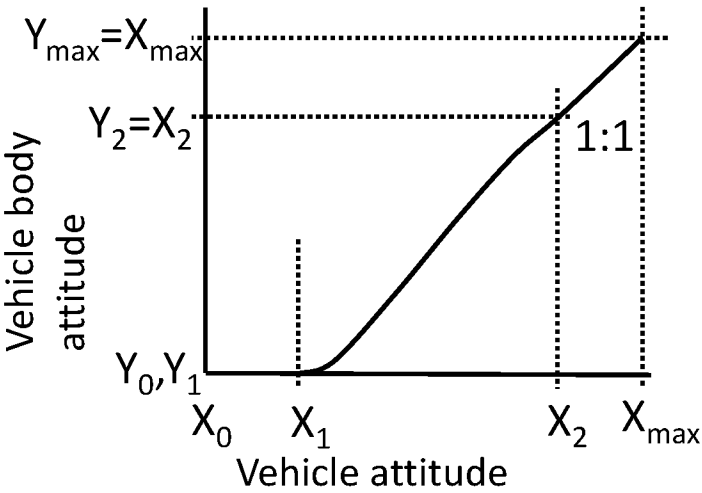


FIG. 9

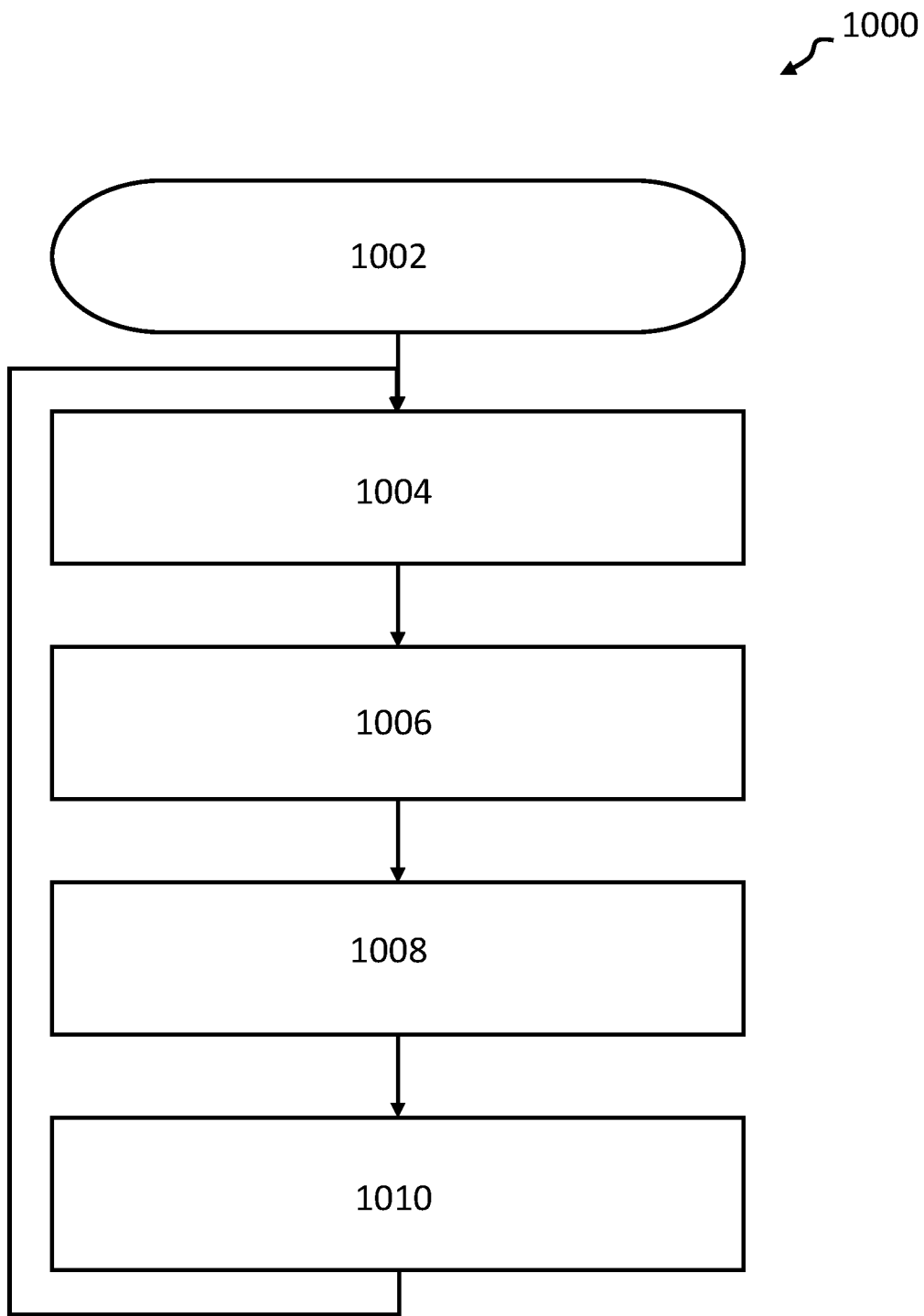


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2021/083063

A. CLASSIFICATION OF SUBJECT MATTER**INV. B60G17/0165****ADD.**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B60G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2019/078640 A1 (AWANO KOICHIRO [JP]) 14 March 2019 (2019-03-14) abstract figures 1, 3 paragraphs [0030] - [0034], [0043] - [0045], [0050] - [0051], [0055] -----	1, 8, 11-13
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Further documents are listed in the continuation of Box C.



See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

2 March 2022

Date of mailing of the international search report

18/03/2022

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2

NL - 2280 HV Rijswijk

Tel. (+31-70) 340-2040,

Fax: (+31-70) 340-3016

Authorized officer

Schmidt, Nico

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2021/083063

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
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