

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
20 April 2006 (20.04.2006)

PCT

(10) International Publication Number
WO 2006/042302 A1

(51) International Patent Classification⁷: **B60W 10/04**,
10/18, B60K 41/04, B62M 1/00, B62K 17/00, A61G 5/04,
B62M 23/02, B62D 37/00

(74) Agents: **SUNSTEIN, Bruce, D.** et al.; Bromberg & Sun-
stein LLP, 125 Summer Street, Boston, MA 02110-1618
(US).

(21) International Application Number:
PCT/US2005/036798

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN,
CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI,
GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE,
KG, KM, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY,
MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO,
NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK,
SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ,
VC, VN, YU, ZA, ZM, ZW.

(22) International Filing Date: 11 October 2005 (11.10.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/617,244 8 October 2004 (08.10.2004) US

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,
ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),
European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI,
FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT,
RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA,
GN, GQ, GW, ML, MR, NE, SN, TD, TG).

(71) Applicant (for all designated States except US): **DEKA
PRODUCTS LIMITED PARTNERSHIP** [US/US]; 340
Technology Center, Manchester, NH 03101-1108 (US).

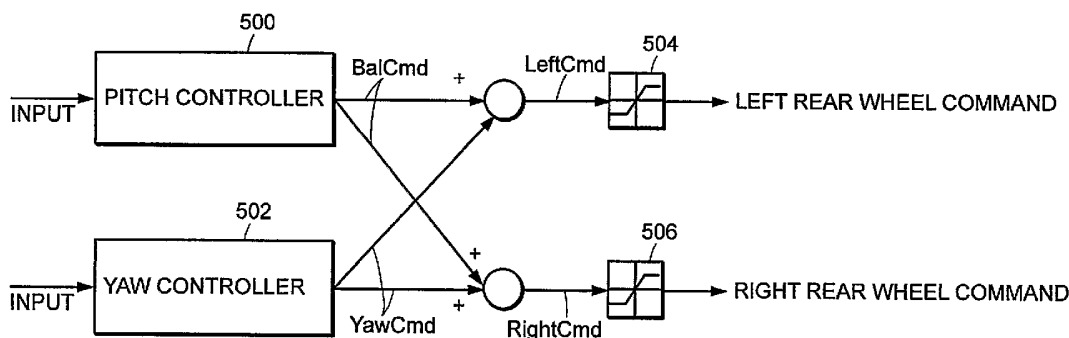
(72) Inventors; and

(75) Inventors/Applicants (for US only): **KAMEN, Dean**
[US/US]; 15 Westwind Drive, Bedford, NH 03110 (US).
AMBROGI, Robert, R. [US/US]; 34 Henry Avenue,
Melrose, MA 02176 (US). **BRECKENRIDGE, Cather-
ine, N.** [US/US]; 93 Kelley Street, Manchester, NH 03102
(US). **KERWIN, John, M.** [US/US]; 291 Ray Street,
Manchester, NH 03104 (US).

Published:
— with international search report

For two-letter codes and other abbreviations, refer to the "Guid-
ance Notes on Codes and Abbreviations" appearing at the begin-
ning of each regular issue of the PCT Gazette.

(54) Title: VEHICLE CONTROL BY PITCH MODULATION



(57) Abstract: A method for fore-aft stabilization of a vehicle for motion in a specified direction over an underlying surface. The vehicle has at least one forward wheel and at least one aft wheel, and the forward wheel is characterized by a force normal to the instantaneous direction of motion of the vehicle. A motor actuator drives each aft wheel, and a controller governs the motor actuator or motor actuators in such a manner as to dynamically stabilize the vehicle, according to a uniform control law, when the forward wheel is in contact with the underlying surface or not. A torque is applied to the aft wheel on the basis of vehicle pitch or the force on the forward wheel normal to the direction of motion. Additionally, a periodic rotational modulation may be applied to the aft wheel, and a stabilizing torque provided based on a detected response, either of vehicle pitch or of normal force on the front wheel. Left and right motor actuators may independently control left and right aft wheels to continue turns as governed by user steering, whether or not forward wheels are in contact with the ground.

WO 2006/042302 A1

Vehicle Control by Pitch Modulation

Technical Field

The present invention pertains to methods for actively maintaining stability and control of the motion of a vehicle equipped with one or more forward wheels and one or more aft wheels, whereby balanced operation may be enabled in case the front wheels lose, or are removed from, contact with the ground.

Background of the Invention

Human transport devices serve to move a person over a surface and may take many different forms. For example, a human transport device, as the term is used herein, may include, but is not limited to, wheelchairs, motorized carts, all-terrain vehicles, bicycles, motorcycles, cars, hovercrafts, and the like. Some types of human transport may include stabilization mechanisms to help ensure that the device does not fall over and injure the user of the transport device.

A typical four-wheeled wheelchair contacts the ground with all four wheels. If the center of gravity of the combination of the wheelchair and the user remains over the area between the wheels, the wheelchair should not tip over. If the center of gravity is located above and outside of the ground contacting members of the transport device, the transport device may become unstable and tip over.

Referring now to FIG. 1A, a typical wheelchair **100** is shown. The wheelchair **100** and the user **102** define a frame. The frame has a center of gravity **104** located at a position vertically disposed above the surface **106**. The term "surface" as it is used herein refers to any surface upon which a human transport device may sit or locomote. Examples of a surface include flat ground, an inclined plane such as a ramp, a gravel covered street, and may include a curb which vertically connects two substantially parallel surfaces vertically displaced from one another (e.g., a street curb).

The surface **106** may be at an incline as compared to the horizontal axis **108** (which is a line in the plane transverse to the local vertical). The angle by which the surface **106** is offset from the horizontal axis **108** is called the surface pitch and will be represented by an angle denoted as θ_s .

The front wheel **112** and the rear wheel **110** of the wheelchair **100** are separated

by a distance **d**. The distance **d** between the two wheels may be measured as a linear (e.g., straight line) distance. The wheels **110** and **112** typically have opposing counterparts (not shown) on the other side of the wheelchair. The opposing counterparts may each share an axis with wheels **110** and **112**, respectively. The area covered by the polygon which connects the points where these four wheels touch the ground (or the outside portions of the ground contacting parts, when the ground contacting part may cover more than a point) provides an area over which the center of gravity **104** may be located while the wheelchair remains stable. This area may be referred to as the footprint of the device. The footprint of a device, as the term is used herein, is defined by the projection of the area between the wheels as projected onto the horizontal plane. If the center of gravity is above this location, the transport device should remain stable.

If the center of gravity **104** is vertically displaced above the surface **106** and outside the footprint (i.e., the projection of area between the wheels **110** and **112** onto the horizontal plane), wheelchair **100** may tip over. This could happen, for example, when the wheelchair is on a surface that has a steep incline, or, alternatively, if the user ‘pops a wheelie’ in order to surmount a curb, for example. When on a steep incline, the center of gravity **104** may shift back and cause the wheelchair **100** to flip over backwards. This is shown in FIG. 1B where the center of gravity **104** is located at a position that is outside the footprint of the wheelchair **100**. The center of gravity **104** is shown including a gravity acceleration vector (**g**) which linearly translates the center of gravity **104** in a downward direction. The wheelchair **100** may rotate about an axis of the rear wheel **110** until the wheelchair **100** contacts the surface being traversed.

User **102** may help to return the center of gravity **104** to a location that is above the area between the wheels **110** and **112** by leaning forward in the wheelchair **100**. Given this limited control of the location of the center of gravity **104**, it is clear that human transport devices such as wheelchairs may encounter great difficulties when traversing uneven surfaces such as a curb or steps.

Some vehicles, by virtue of their weight distribution or typical modes of operation are prone to fore-aft instability and end-over-end (“endo”) rollovers. In operation of an all-terrain vehicle (ATV), for example, it is not always possible or desirable to maintain all wheels of the vehicle in contact with the underlying surface at all times. Yet, it is desirable to preclude loss of control of the vehicle or end-over-end roll-over. ATVs may benefit from stabilization in one or more of the fore-aft or left-right planes, especially under conditions in which fewer than a stable complement of wheels are in contact with

the ground. Vehicles of this sort may be more efficiently and safely operated employing control modes supplementary to those described in the prior art.

Summary of the Invention

In accordance with preferred embodiments of the present invention, a method is provided for fore-aft stabilization of a vehicle for motion in a specified direction over an underlying surface, where the vehicle having a plurality of driven wheels including a forward wheel and an aft wheel, and with the forward wheel characterized by a force normal to the instantaneous direction of motion of the vehicle. The method has the step of applying a torque to the aft wheel based on the force on the forward wheel normal to the direction of motion and/or the instantaneously sensed tilt of the vehicle.

In accordance with other embodiments of the invention, the method may have additional steps of applying a periodic torque to at least one of the wheels for inducing a small pitch modulation, detecting pitch variation of the vehicle in response to the applied periodic torque, and applying a stabilizing torque to the aft wheel on the basis, at least, of any detected pitch variation in response to the applied periodic torque.

In accordance with yet further embodiments of the invention, an apparatus is provided for pitch stabilization of the motion of a vehicle having at least one forward wheel and at least one aft wheel. The apparatus has a sensor for sensing a force on the forward wheel normal to an instantaneous direction of motion of the vehicle, a motor actuator for driving the aft wheel, and a controller for applying a torque to the aft wheel on the basis of a control law based at least on the normal force on the forward wheel.

In accordance with another aspect of the present invention, a stabilized vehicle is provided that has at least one forward wheel and at least one aft wheel. Additionally, the vehicle has a sensor for sensing a force on the forward wheel normal to an instantaneous direction of motion of the vehicle, and/or an instantaneous pitch of the vehicle and/or a function of the instantaneous pitch. The vehicle also has a motor actuator for driving the aft wheel, and a controller for applying a torque to the aft wheel on the basis of a control law based at least on the normal force on the forward wheel. The vehicle may include a pedal-driven bicycle, a motorcycle, or a wheelchair.

In accordance with yet further embodiments of the present invention, there is provided a vehicle with a plurality of wheels, including at least one forward wheel and at least one aft wheel. A motor actuator drives each aft wheel, and a controller governs the motor actuator or motor actuators in such a manner as to dynamically stabilize the vehicle

when the forward wheel is not in contact with the underlying surface. More particularly, a left aft actuator drives a left aft wheel independently of the right aft wheel, thus the controller can govern differential rotation of the left and right aft wheels for controlling yaw of the vehicle whether a forward wheel is in contact with the ground, or not.

In accordance with further embodiments of the invention, the controller is such as to govern the motor actuator according to a control law independent of whether the forward wheel is in contact with the underlying surface. The vehicle may further have a user input device for providing a throttle output signal, and a pitch sensor for providing a pitch signal. The controller may then govern the motor actuator according to a control law based at least upon the throttle output signal or the pitch signal or a pitch rate signal. More particularly, the controller may govern the motor actuator according to a control law based at least upon the pitch signal when the vehicle pitch angle exceeds a specified value.

In accordance with a further embodiment of the invention, there is provided a vehicle that includes a first fore-wheel coupled to a first pivot point by a first strut and a second fore-wheel coupled to the first pivot point by a second strut. The vehicle of this embodiment also includes at least one aft-wheel coupled to the first pivot point. In this embodiment, the first and second struts are spaced apart from one another and are arranged and configured to cause the vehicle to vary its direction of motion by causing the first fore-wheel and the second fore-wheel to both pivot about at least their respective vertical axis.

In accordance with a further embodiment of the invention, there is provided a vehicle that includes a central pivot. The vehicle also includes a first fore-wheel coupled to the central pivot point by a first strut, the first strut being arranged and configured to rotate about the central pivot during operation and a second fore-wheel coupled to the central pivot by a second strut, the second strut being arranged and configured to rotate about the central pivot during operation. The vehicle of this embodiment also includes at least one aft-wheel coupled to the central pivot by a connecting member arranged configured to retain a fixed orientation with respect to the central pivot.

In accordance with a further embodiment of the invention, there is provided a vehicle that includes a plurality of wheels, including at least one forward wheel and at least two aft wheels. The vehicle of this embodiment also includes at least one motor actuator that drives each aft wheel and at least one yaw controller. The vehicle of this embodiment also includes a controller that controls the at least one motor actuator such

that a direction imparted on the at least one forward wheel by the yaw controller is replicated by differential rotation of the at least two aft wheels.

In accordance with a further embodiment of the invention, there is provided a vehicle that includes a plurality of wheels, including at least one forward wheel and at least two aft wheels. The vehicle of this embodiment also includes at least one motor actuator that drives each aft wheel and at least one yaw controller. The vehicle of this embodiment may also include a throttle and a controller that, when all of the plurality of wheels is in contact with a surface being traversed, causes the vehicle to accelerate when the throttle is rotated and that, when the at least one forward wheel is not in contact with a surface being traversed, causes an offset from a pitch limit to be adjusted when the throttle is rotated.

Brief Description of the Drawings

The invention will be more readily understood by reference to the following description, taken with the accompanying drawings, in which:

FIGS. **1A** and **1B** are schematic side views of a prior art personal vehicle of the type in which an embodiment of the invention may be advantageously employed;

FIG. **2** is a diagram of typical components of a personal vehicle of the type in which an embodiment of the invention may be advantageously employed indicating the variables used in the description of specific embodiments of the present invention;

FIG. **3** is a block diagram depicting the coupling of pitch and yaw controller outputs for generation of wheel amplifier commands;

FIG. **4A** is a block diagram showing the constitutive inputs of a pitch command in accordance with an embodiment of the present invention;

FIG. **4B** is a block diagram showing the constitutive inputs of a pitch command with a unilateral limit in accordance with an embodiment of the present invention;

FIG. **5A** is a block diagram showing the constitutive inputs of a yaw command in accordance with embodiments of the present invention;

FIGS. **5B** and **5C** are block diagrams of different embodiments of a yaw controller in accordance with embodiments of the present invention;

FIG. **6** is a side view of an all-terrain vehicle capable of balancing operation in accordance with one embodiment of the present invention;

FIG. **7** is a perspective view from above of the embodiment of the invention of Fig. 6;

FIG. 8 is a further side view of the all-terrain vehicle of Fig. 6 showing operation by a standing user;

FIG. 9 is yet a further side view of the all-terrain vehicle of Fig. 6 showing operation by a seated user;

FIG. 10 shows the coupling of the handlebar to the upper pushrods for steering of the front wheels in accordance with a preferred embodiment of the invention; and

FIG. 11 shows the coupling of the lower pushrods to steer the forward wheels, in accordance with the embodiment of Fig. 10.

Detailed Description of Specific Embodiments

Definitions:

A vehicle may be said to act as "balancing" if it is capable of operation on one or more wheels but would be unable to stand on those wheels alone, but for operation of a control loop governing operation of the wheels. A balancing vehicle, when operated in a balancing mode, lacks static stability but is dynamically balanced. The wheels, or other ground-contacting elements, that provide contact between such a vehicle and the ground or other underlying surface, and minimally support the transporter with respect to tipping during routine operation, are referred to herein as "primary wheels." "Stability" as used in this description and in any appended claims refers to the mechanical condition of an operating position with respect to which the system will naturally return if the system is perturbed away from the operating position in any respect. The term "system" refers to all mass caused to move due to motion of the wheels with respect to the surface over which the vehicle is moving, and thus includes both the vehicle and the rider.

The term "lean" is often used with respect to a system balanced on a single point of a perfectly rigid member. In that case, the point (or line) of contact between the member and the underlying surface has zero theoretical width. In that case, furthermore, lean may refer to a quantity that expresses the orientation with respect to the vertical (i.e., an imaginary line passing through the center of the earth) of a line from the center of gravity (CG) of the system through the theoretical line of ground contact of the wheel. Recognizing that the tire of an actual wheel is not perfectly rigid, the term "lean" is used herein in the common sense of a theoretical limit of a rigid ground-contacting member.

Operation in Accordance with Embodiments of the Invention:

One embodiment of a stabilized vehicle in accordance with the present invention is depicted in Fig. 2 and designated generally by numeral **10**. User **8**, as shown in Fig. 2, is seated position on user support **12** of vehicle **10**, though it is to be understood that user **8** may be supported otherwise than by sitting on a seat, and may, for example, within the scope of the present invention, be standing on a user support in the form of a platform.

Aft wheels **21** (of which only one is visible in the side-view of Fig. 2) are coaxial about an axis defined as the **Y** axis. Each of rear wheels **21** is driven by a motor actuator (not shown) disposed within a power base **24** such that steering may be effectuated through differential torque applied to respective rear wheels **21**. Compensating, by differential actuation of the rear wheels for the increased rotational travel of the outer wheel on a turn may be referred to herein as an "active differential." Rider **8** may be supported on vehicle **10** in various body positions, thereby controlling the position of the center of mass of the vehicle, as governed by the distribution of weight of the load, namely the user. For example, user **8** may be seated, as shown in Fig. 2, on seat **12**, with his feet resting on footrest **26**.

The embodiment shown of vehicle **10**, additionally, has two forward wheels **13** (of which one is visible in the side view of Fig. 2), typically in contact with the ground during ordinary operation. Forward wheel **13** and one or more other forward wheels may be mounted on a common axle or otherwise, and pivoting of any of the forward wheels is within the scope of the present invention. Personal vehicles designed for enhanced maneuverability and safety may also include one or more clusters of wheels, with the cluster and the wheels in each cluster capable of being motor-driven independently of each other. Such vehicles are described in U.S. Patent nos. 5,701,965, 5,971,091, 6,302,230, 6,311,794, and 6,553,271, all of which patents are incorporated herein by reference.

Controller **30** provides for stability of the vehicle by continuously sensing the orientation of the vehicle and the commanded velocity, as described in detail below, determining the corrective action to maintain stability, and commanding the wheel motors to make any necessary corrective action.

In accordance with preferred embodiments of the present invention, the same control law is applied whether or not forward wheels of the vehicle are in contact with the ground.

Steering or other control may be provided by means of a user input device **18**,

which may be a joystick, handlebars or by any other user input mechanisms. A variety of steering devices which are further examples of user input mechanisms that may be employed within the scope of the present invention are described in U.S. Patents nos. 6,581,714 and 6,789,640, which are incorporated herein by reference.

A sensor unit **28** is provided as part of power base **24** for providing one or more sensor signals to controller **30**. Sensor unit **28** may provide a measure of pitch rate and/or pitch of the vehicle, and may employ inertial sensing of the type described in detail in US Patent no. 6,332,103, which is incorporated herein by reference. Alternatively, or additionally, sensor unit **28** may include a force sensor for measuring the force (designated by arrow **32**) normal to the underlying surface that is exerted on the underlying surface by wheel **13** (and, reciprocally, on the wheel by the underlying surface). Force sensors, such as those based on piezoresistors, are well-known in the art, and any kind of force sensor is within the scope of the present invention.

A simplified control algorithm for achieving balance in the embodiment of the invention according to Fig. 2 is now described. The control algorithm is described for the case of a single driven wheel, as may be employed for stabilization of an in-line bicycle or motorcycle. The generalization to the case of multiple driven wheels is discussed in detail below.

To achieve dynamic control to insure stability of the system, the wheel torque **T** in this embodiment is governed by the following simplified control equation:

$$T = K_1(\theta) \cdot (\theta - \theta_0) + K_2 \cdot \dot{\theta} + K_3 \cdot (v - v_{\text{command}}) + K_4 \cdot \int (v - v_{\text{command}}) dt + A \cdot f(\omega t) ,$$

(Eqn. 1)

where:

- T denotes a torque applied to a ground-contacting element about its axis of rotation;
- $K_1(\theta)$ is a gain function that may depend, as discussed below, on the instantaneous value of lean θ ;
- θ is a quantity corresponding to the lean of the entire system about the ground contact region beneath the common axis Y of the rear wheels, with θ_0 representing the magnitude of a system pitch offset, all as discussed in detail below;
- v identifies the fore-aft velocity along the surface, with v_{command} representing the magnitude of a user input such as a throttle constituted by user input (e.g., joystick) **18**;
- a dot over a character denotes a variable differentiated with respect to time; and

- a subscripted variable denotes a specified offset that may be input into the system as described below; and
- K_1 , K_2 , K_3 and K_4 are gain functions or coefficients that may be configured, either in design of the system or in real-time, on the basis of a current operating mode and operating conditions as well as preferences of a user. The gain coefficients may be of a positive, negative, or zero magnitude. The gains K_1 , K_2 , K_3 and K_4 are dependent upon the physical parameters of the system and other effects such as gravity. The simplified control algorithm of Eqn. 1 maintains balance of the vehicle in the presence of changes to the system's center of mass due to body motion of the rider or features of the underlying terrain.

The final term of Eqn. (1) allows for application of a periodic driving component, of period $2\pi/\omega$, and amplitude A (which may be zero, in the case of no applied modulation), to the torque applied to the driven wheel. The periodic function $f(\omega t)$ may be a sinusoidal function, for example.

It should be noted that the amplifier control may be configured to control motor current (in which case torque T is commanded) or, alternatively, the voltage applied to the motor may be controlled, in which case the commanded parameter is velocity.

The effect of θ_0 in the above control equation (Eqn. 1) is to produce a specified offset θ_0 from the non-pitched position, $\theta = 0$. Adjustment of θ_0 will adjust the vehicle's offset from a non-pitched position. In some embodiments, pitch offset may be adjusted by the user. Alternatively, θ_0 can be set by the control system of the vehicle as a method of limiting the speed and/or the performance of the vehicle. In a preferred embodiment of the invention, a backward tilting limit is imposed, with the gain function K_1 substantially zero until the tilting limit is approached. Thus, the rider is free to lean the vehicle backward by shifting his weight, and thus the center-of-mass of the vehicle system, backward, until the tilt limit is approached. Then, K_1 assumes a non-zero value, and a term appears in control equation (1) that tends to counteract further backward leaning of the vehicle.

The magnitude of K_3 determines the gain of the user input, and may advantageously be a non-linear function, providing, for example, greater sensitivity near zero velocity. The K_2 term provides for control based on the instantaneous pitch rate, $\dot{\theta}$, of the vehicle, as measured by a pitch rate sensor or by differentiation of a measured pitch.

The response of a normal force **32** measured by sensor **28** in response to the applied pitch modulation $A_f(\omega t)$, may be used, in accordance with embodiments of the invention, to counteract further backward leaning of the vehicle and maintain contact of the forward wheel with the ground, or, alternatively, impose a limit on rearward tilt.

In order to accommodate two wheels instead of the one-wheel system that has been described with respect to Eqn. 1, separate motors may be provided for left and right wheels of the vehicle and the torque desired from the left motor and the torque to be applied by the right motor can be governed in the general manner described above. Additionally, tracking both the left wheel motion and the right wheel motion permits adjustments to be made to prevent unwanted turning of the vehicle and to account for performance variations between the two drive motors.

In accordance with preferred embodiments of the invention, differential drive of the two rear wheels tracks turns according to the same yaw input as applied, via mechanical linkages, to the front wheels. This operation is described below, with reference to Figs. 10 and 11.

Referring now to Fig. 3, steering, or yaw control, of the vehicle may be accomplished by adding a turning command to the wheel amplifiers and have the following form. Inputs (described below) corresponding to values of vehicle parameters are used by Pitch Controller **500** and Yaw Controller **502** to derive a balance control signal $BalCmd$ and a yaw control signal $YawCmd$ according to algorithms discussed in the succeeding paragraphs.

$$LeftCmd = BalCmd + YawCmd \quad (2)$$

$$RightCmd = BalCmd - YawCmd \quad (3)$$

The $LeftCmd$ and $RightCmd$ are the command sent by the controllers **500** and **502** to the left and right motor amplifiers, respectively, after differentiation or other conditioning as appropriate. For instance and as shown by way of example in Fig. 3, the $LeftCmd$ and $RightCmd$'s may be conditional, respectively, by differentiators **504** and **506**. The $LeftCmd$ and $RightCmd$ represent voltage if the amplifiers are in voltage control mode, current if the amplifiers are in current control mode, or duty cycle if the amplifiers are in duty cycle control mode. $BalCmd$ is the command sent by the Pitch Controller **500** to each amplifier to maintain the transporter in a balanced state while moving or while at rest. The $YawCmd$ causes the transporter to turn by reducing the command to one of the wheels while increasing the command to the other wheel. For example, a positive $YawCmd$ increases the command to the left wheel while decreasing the command to the

right wheel thereby causing the transporter to execute a right turn. The YawCmd may be generated by a yaw-input device described above with no feedback loop or in a closed cycle loop to correct yaw position errors as described in U.S. Patent no. 6,288,505.

Pitch controller **500** is described in detail with reference to Figs. 4A and 4B. The inputs include a desired pitch θ_{desired} , the actual measured pitch θ , the pitch rate $\dot{\theta}$, and the component of the wheel rotation velocity that is common to the two primary wheels, ω_{com} . Both θ and $\dot{\theta}$ may be derived from inertial sensing, as described in U.S. Patent no. 6,332,103, which is incorporated herein by reference.

Desired pitch θ_{desired} and current instantaneous pitch θ are differenced in summer **520** to produce a pitch error θ_{err} . In accordance with certain embodiments of the present invention, pitch limiting is unilateral, such that a limit is provided on one end of a range of allowed values of pitch. If that pitch is exceeding, a restoring torque moves the vehicle in the direction of the pitch limit.

In accordance with some embodiments of the invention, the user may shift her weight backward, thereby 'popping' the vehicle into a two-wheeled balancing condition where stability is maintained until she shifts her weight forward to restore operation on all wheels.

A term quadratic in pitch error θ_{err} (preserving the sign of the actual pitch error) may also be provided, as shown in Fig. 4B, thereby providing more intense response to large deviations in pitch as may result from encountering an obstacle, for example. In a voltage control mode, it is desirable to provide an additional term proportional to the wheel rotational velocity to compensate for all, or a portion, of the back-emf generated in proportion to the rotational velocity of the motors.

Yaw controller **502** is described in detail with reference to Figs. 5A-5C. Fig. 5A depicts the differencing, in summer **522**, of the current yaw value ψ with respect to the desired yaw value ψ_{desired} to obtain the current yaw error ψ_{err} . Desired yaw value ψ_{desired} is obtained from a user input such as joystick **18** or other user input device employed for directional input as discussed above. The current value of yaw is derived from various state estimates, such as the differential wheel velocities, inertial sensing, etc. Derivation of the yaw command from the yaw error is provided by controller **524** according to various processing algorithms.

Two examples of yaw control algorithms are shown in Figs. 5B and 5C. Specifically, Fig. 5B shows a control law implemented input signal ψ_{err} is added, by summer **560**, to the derivative of itself (output of differentiator **562**) and the integration

of itself (output of integrator **564**). Of course, and as shown by in Fig. 5B, each signal could have a gain applied to it (for example, by gain blocks **568**, **569**, and **570**) or other signal processing such as smoother **566**.

Another possibility is to simply omit the derivative signal as shown in Fig. 5C.

Of course, various controller transfer strategies may be implemented with proportional, derivative, and 'three term' 'PID' functions as depicted.

The present invention may also be embodied in a balancing all-terrain vehicle as depicted in Fig. 6 and designated generally by numeral **10**. User **8**, as shown in Fig. 6, is in a seated position on user support **12** of all-terrain vehicle **10**. Aft wheels **21** and **22** are shown as coaxial about an axis defined as the **Y** axis. Referring now to the perspective view of all-terrain vehicle **10**, from the top, shown in Fig. 7, each of rear wheels **21** and **22** is driven by a motor actuator **24** such that steering may be effectuated through differential torque applied to of rear wheels **21** and **22**. Compensating, by differential actuation of the rear wheels for the increased rotational travel of the outer wheel on a turn may be referred to herein as an "active differential." Rider **8** may be supported on vehicle **10** in various body positions, thereby controlling the position of the center of mass of the vehicle, as governed by the distribution of weight of the load, namely the user. For example, user **8** may be seated, as shown in Fig. 6, on seat **12**, with his feet resting on platform **26** (shown in Fig. 7), and may shift his weight relative to the vehicle by positioning himself along the length of seat **12**. Alternatively, user **8** may stand on platform **26**, with legs athwart seat **12**, as shown in Fig. 8, or may sit on seat **12** with feet resting on foot rests **28**, as shown in Fig. 9.

Referring again to Fig. 6, the embodiment shown of vehicle **10**, additionally, has two forward wheels, **13** and **14**, typically in contact with the ground during ordinary operation. In the embodiment of the invention shown, by way of example in Fig. 7, each forward wheel **13** and **14** is mounted on a separate suspension strut **29** such that each forward wheel is suspended independently of one another.

Controller **30** (shown in Fig. 7) provides for stability of the vehicle by continuously sensing the orientation of the vehicle and the commanded velocity, as has been described above, determining the corrective action to maintain stability, and commanding the wheel motors to make any necessary corrective action. In accordance with preferred embodiments of the present invention, the same control law may be applied whether or not forward wheels **13** and **14** of the vehicle **10** are in contact with the ground.

Steering or other control may be provided by the user's rotation of handlebar **18** (shown in Fig. 7) about pivot **17**, or by any other user input mechanisms. A variety of steering devices which are further examples of user input mechanisms that may be employed within the scope of the present invention are described in U.S. Patents nos. 6,581,714 and 6,789,640, which are incorporated herein by reference. Handlebar **18** may also support user instruments and other user controls such as a throttle, within the scope of the invention.

In operation of a vehicle that may operate on either two or four wheels, it may be beneficial that if a turn is initiated in one mode, it be smoothly continued, either as wheels leave the ground or as wheels remake ground contact. To that end, in accordance with preferred embodiments of the invention, a mechanical linkage is provided between the user yaw input and the forward wheels, while the rear wheels are controlled, in synchrony with any turn initiated by the user input, by means of differential rotation of the wheels. Referring to Fig. 10, vehicle steering is implemented, in accordance with the embodiment shown, by turning handlebar **18** about pivot **17**. This serves two functions: steering the forward wheels, and providing electrical input to cause differential rotation of the aft wheels. To steer the forward wheels, motion is transferred, via bellcrank **80**, to fore-aft axial motion of upper push rods **82**, as indicated by arrows **83** in Fig. 7. Bellcrank **80** is a lever with two arms forming a fixed angle between them, and a fulcrum at the apex of the angle. This allows rotational motion (of the handlebar pivot) substantially transverse to the ground to be transferred to motion (of the upper push rods) having a significant component parallel to the ground. Upper push rods **82**, in turn, via middle bellcranks **84**, transfer motion to lower pushrods **90**, shown in Fig. 11, which turn forward wheels **13** and **14** by causing them to pivot about vertical pivot axes **92**. It is to be understood that any other couplings, mechanical or motorized, between the user input and the angle of forward wheels **13** and **14**, may also be employed within the scope of the present invention.

At the same time that the user yaw input, such as the handlebar, governs the steering of the forward wheels as described above, a signal is generated, by means of a rotational transducer, or otherwise, to serve as the input to yaw controller **502** (shown in Fig. 3) to govern differential actuation of the rear wheels. Thus, the user-intended steering is accomplished, in accordance with this invention, whether or not the forward wheels are in contact with the ground. Various means of converting the mechanical user input (such as handlebar rotation angle) to a yaw signal input to the controller **70** are known in the

art, such as those described in U.S. Patent no. 6,581,714, for example, and any such means are encompassed within the scope of the present invention.

The described embodiments of the invention are intended to be merely exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims.

Claims

1. A method for fore-aft stabilization of a vehicle for motion in a specified direction over an underlying surface, where the vehicle having a plurality of driven wheels including a forward wheel and an aft wheel, and with the forward wheel characterized by a force normal to the instantaneous direction of motion of the vehicle, the method comprising:
 - applying a torque to the aft wheel based on the force on the forward wheel normal to the direction of motion.
2. A method according to claim 1, further comprising:
 - applying a periodic torque to at least one of the wheels for inducing a small pitch modulation.
3. A method according to claim 2, further comprising:
 - detecting pitch variation of the vehicle in response to the applied periodic torque;
 - and
 - applying a stabilizing torque to the aft wheel on the basis, at least, of any detected pitch variation in response to the applied periodic torque.
4. A method for fore-aft stabilization of a vehicle for motion in a specified direction over an underlying surface, where the vehicle having a plurality of driven wheels including a forward wheel and an aft wheel, and with the forward wheel characterized by a force normal to the instantaneous direction of motion of the vehicle, the method comprising:
 - applying a torque to the aft wheel based on the force on the forward wheel normal to the instantaneously sensed tilt of the vehicle.
5. A method according to claim 4, further comprising:
 - applying a periodic torque to at least one of the wheels for inducing a small pitch modulation.
6. A method according to claim 5, further comprising:

detecting pitch variation of the vehicle in response to the applied periodic torque;
and

applying a stabilizing torque to the aft wheel on the basis, at least, of any detected pitch variation in response to the applied periodic torque.

7. An apparatus for pitch stabilization of the motion of a vehicle having at least one forward wheel and at least one aft wheel, the apparatus comprising:

a sensor for sensing a force on the forward wheel normal to an instantaneous direction of motion of the vehicle;

a motor actuator for driving the aft wheel; and

a controller for applying a torque to the aft wheel on the basis of a control law based at least on the normal force on the forward wheel.

8. An apparatus according to claim 7, further comprising a second sensor for sensing a force on the forward wheel normal to the instantaneous direction of motion of the vehicle.

9. An apparatus according to claim 7, wherein the controller causes the motor actuator to apply a periodic torque to the at least one aftwheel to induce a small pitch modulation.

10. An apparatus according to claim 9, further comprising:

a pitch detector to detect a pitch variation of the vehicle in response to the periodic torque;

wherein the controller causes the motor actuator to apply a stabilizing torque to the at least one aft wheel on the basis, at least, of any detected pitch variation in response to the applied periodic torque.

11. A stabilized vehicle comprising:

at least one forward wheel;

at least one aft wheel;

at least one sensor for sensing a force on the forward wheel normal to an instantaneous direction of motion of the vehicle;

at least one sensor for sensing an instantaneous pitch of the vehicle;

a motor actuator for driving the aft wheel;
and a controller for applying a torque to the aft wheel on the basis of a control law based at least on the normal force on the forward wheel.

12. A stabilized vehicle according to claim 11, wherein the vehicle is a pedal-driven bicycle.

13. A stabilized vehicle according to claim 11, wherein the vehicle is a motorcycle.

14. A stabilized vehicle according to claim 11, wherein the vehicle is an all terrain vehicle.

15. A stabilized vehicle according to claim 11, wherein the vehicle is a wheelchair.

16. A stabilized vehicle according to claim 11, wherein the controller controls operation of the vehicle in the same manner regardless of whether the forward wheel is in contact with a surface being traversed.

17. A stabilized vehicle comprising:
at least one forward wheel;
at least one aft wheel;
at least one sensor for sensing an instantaneous pitch of the vehicle;
a motor actuator for driving the aft wheel;
and a controller for applying a torque to the aft wheel on the basis of a control law based at least on a function of the instantaneous pitch of the vehicle.

18. A stabilized vehicle according to claim 17, wherein the vehicle is a pedal-driven bicycle.

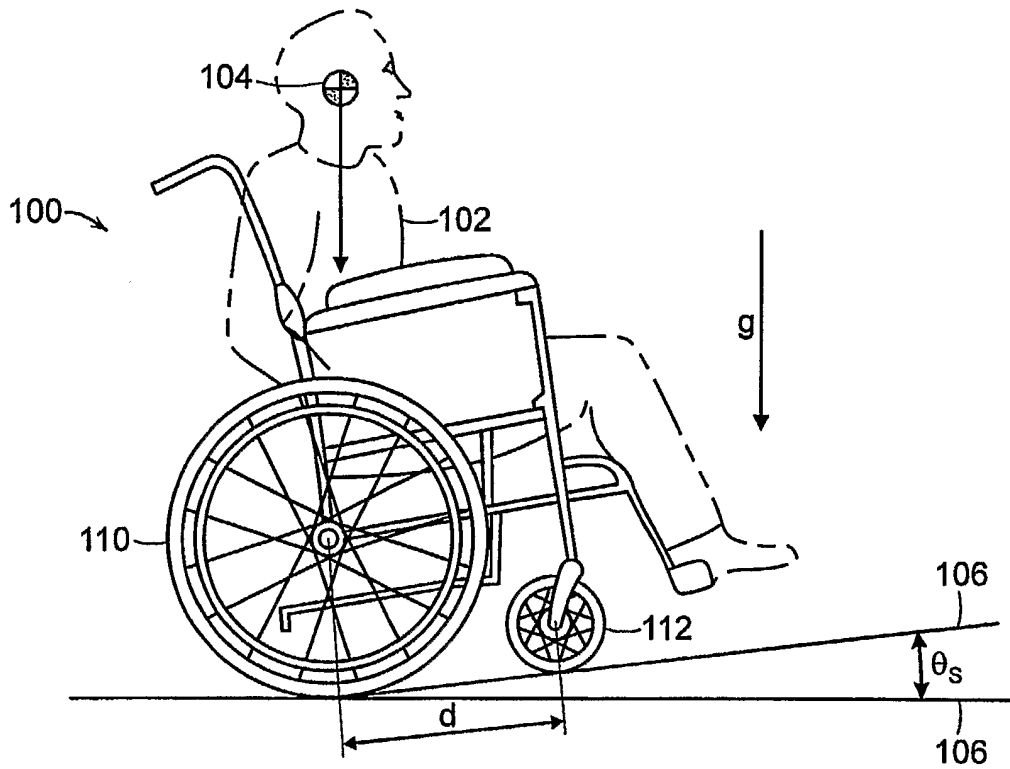
19. A stabilized vehicle according to claim 17, wherein the vehicle is a motorcycle.

20. A stabilized vehicle according to claim 17, wherein the vehicle is an all terrain vehicle.

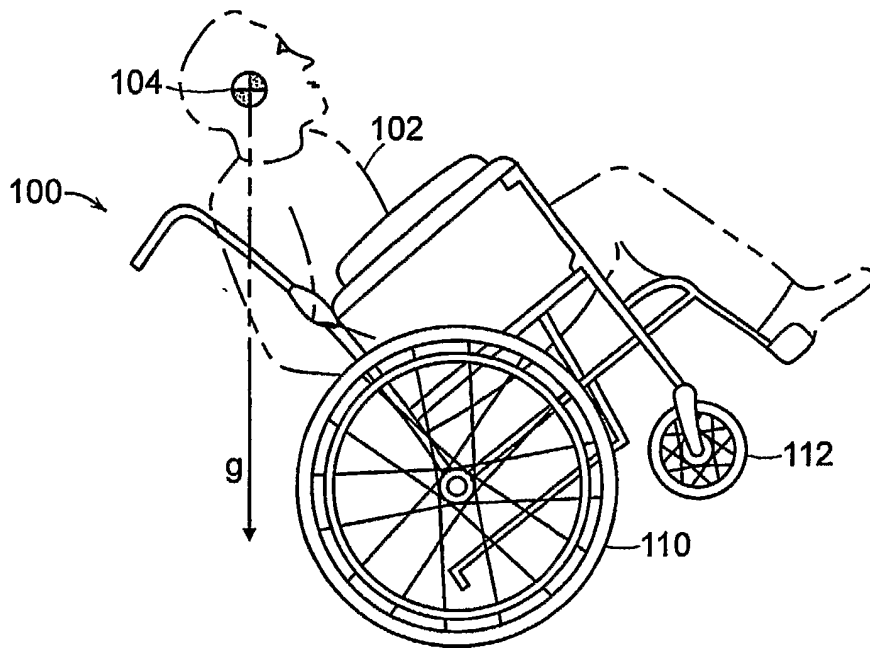
21. A stabilized vehicle according to claim 17, wherein the vehicle is a wheelchair.

22. A stabilized vehicle according to claim 17, wherein the control law is based at least on the instantaneous pitch of the vehicle.

1/11



(PRIOR ART)
FIG. 1A



(PRIOR ART)
FIG. 1B

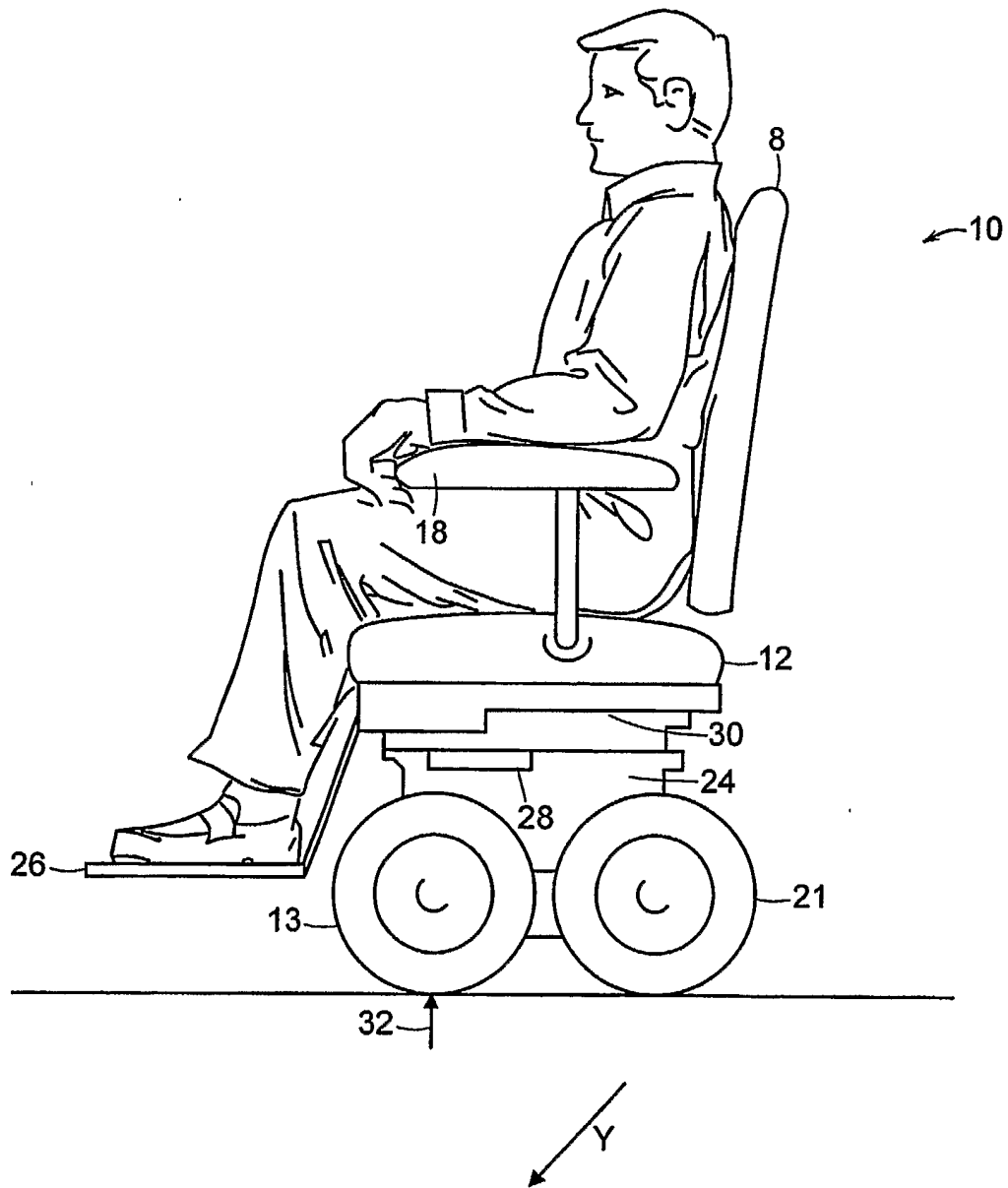


FIG. 2

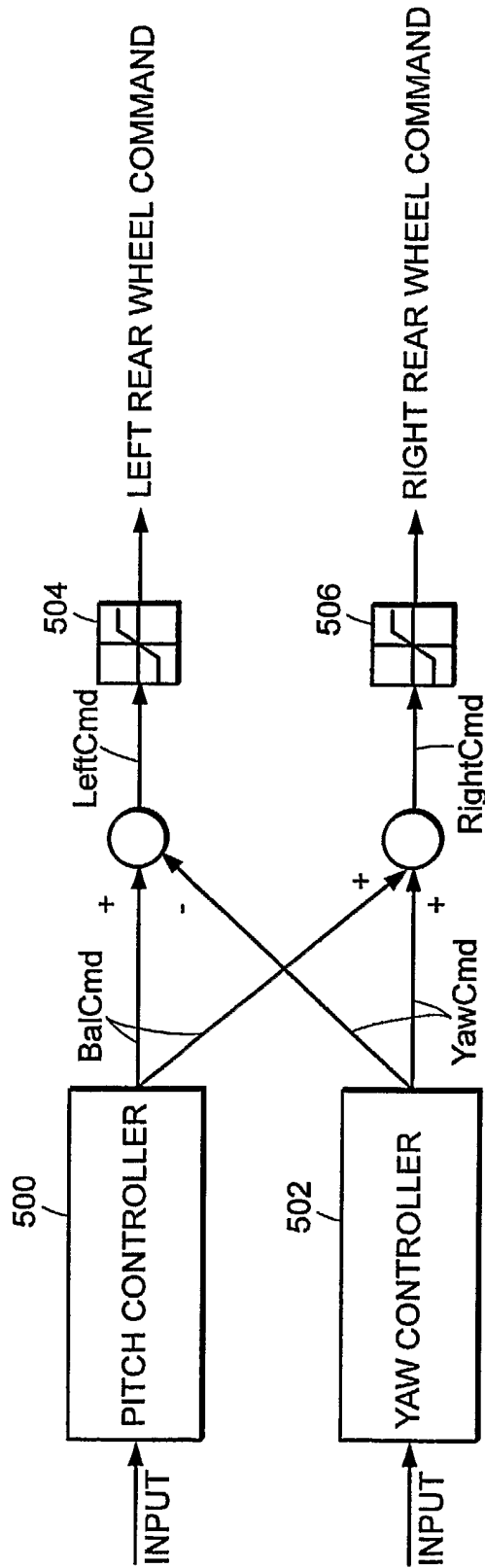


FIG. 3

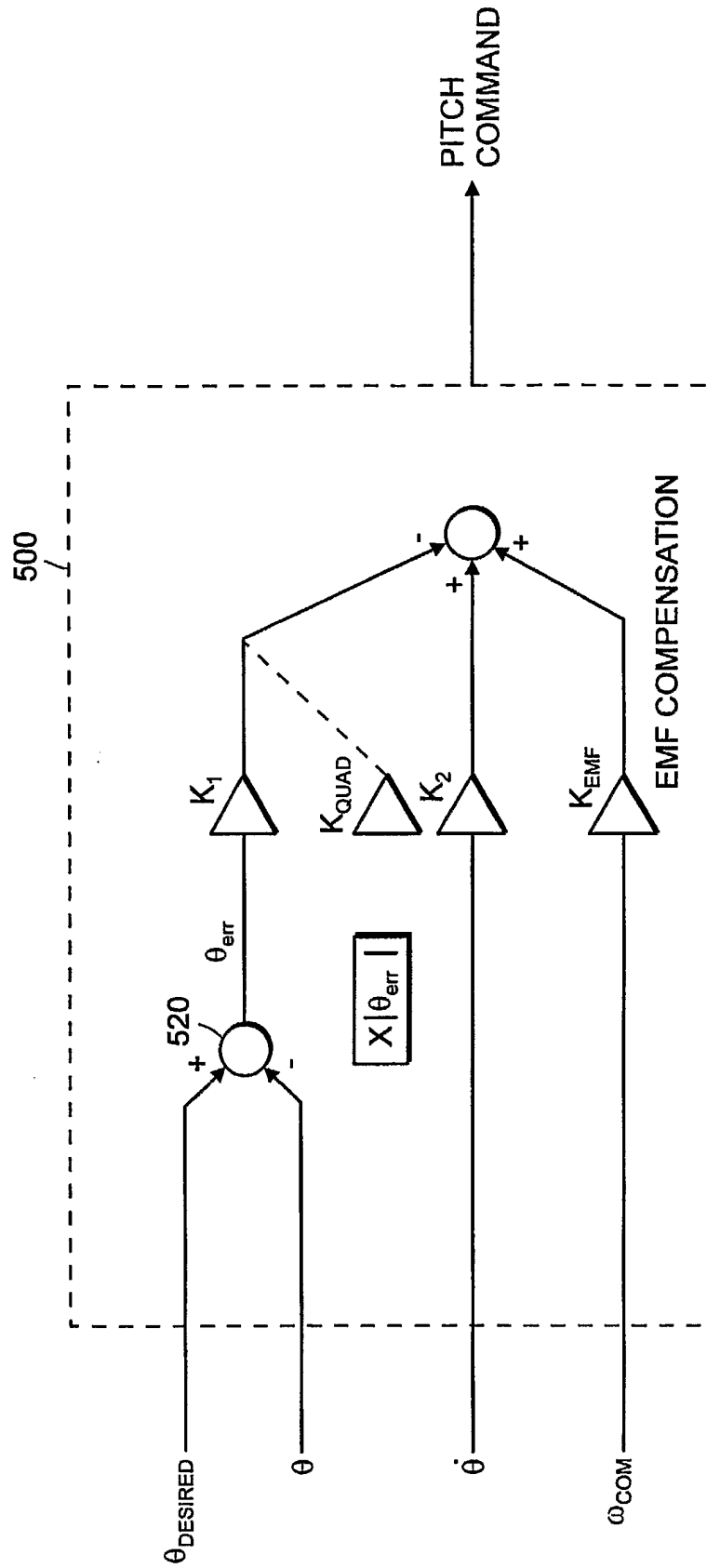


FIG. 4A

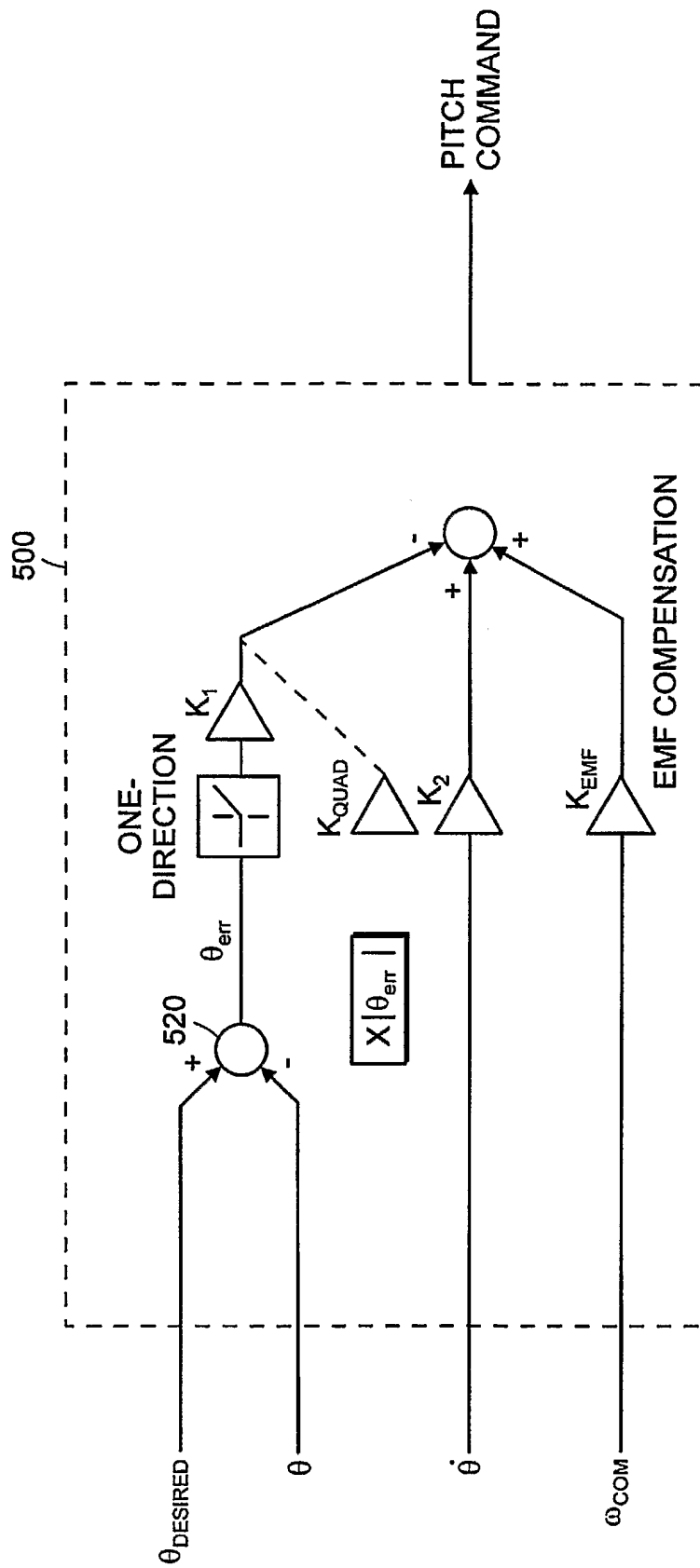


FIG. 4B

6/11

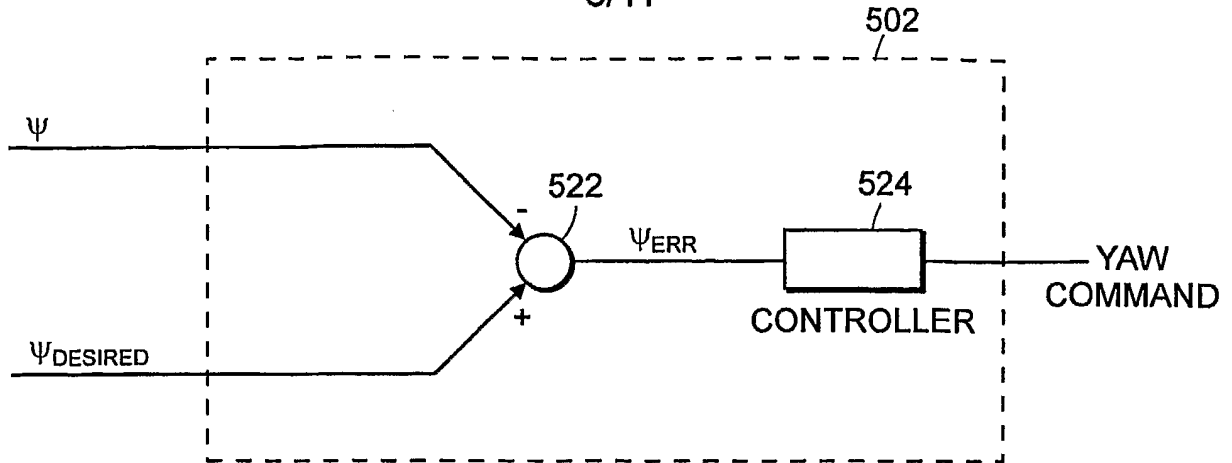


FIG. 5A

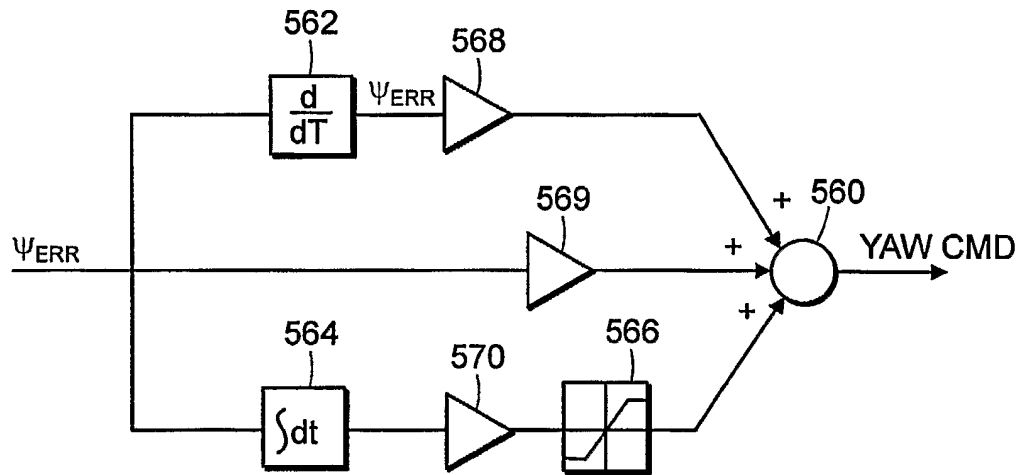


FIG. 5B

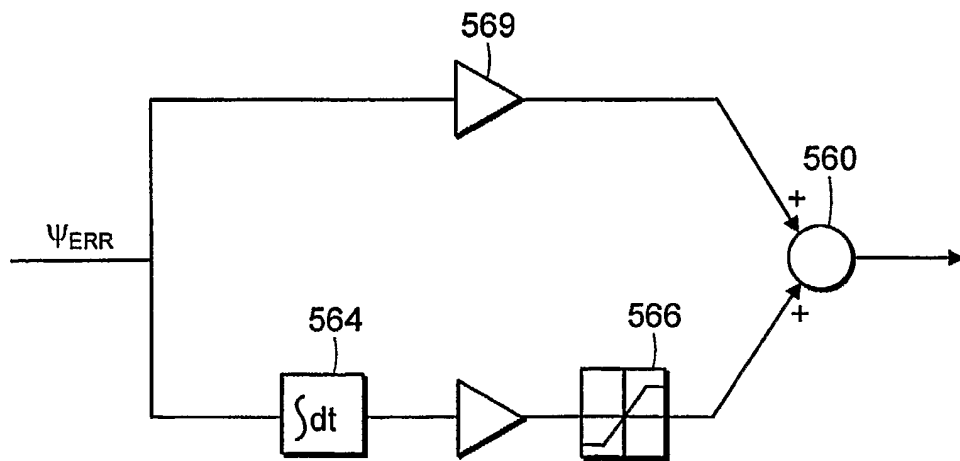
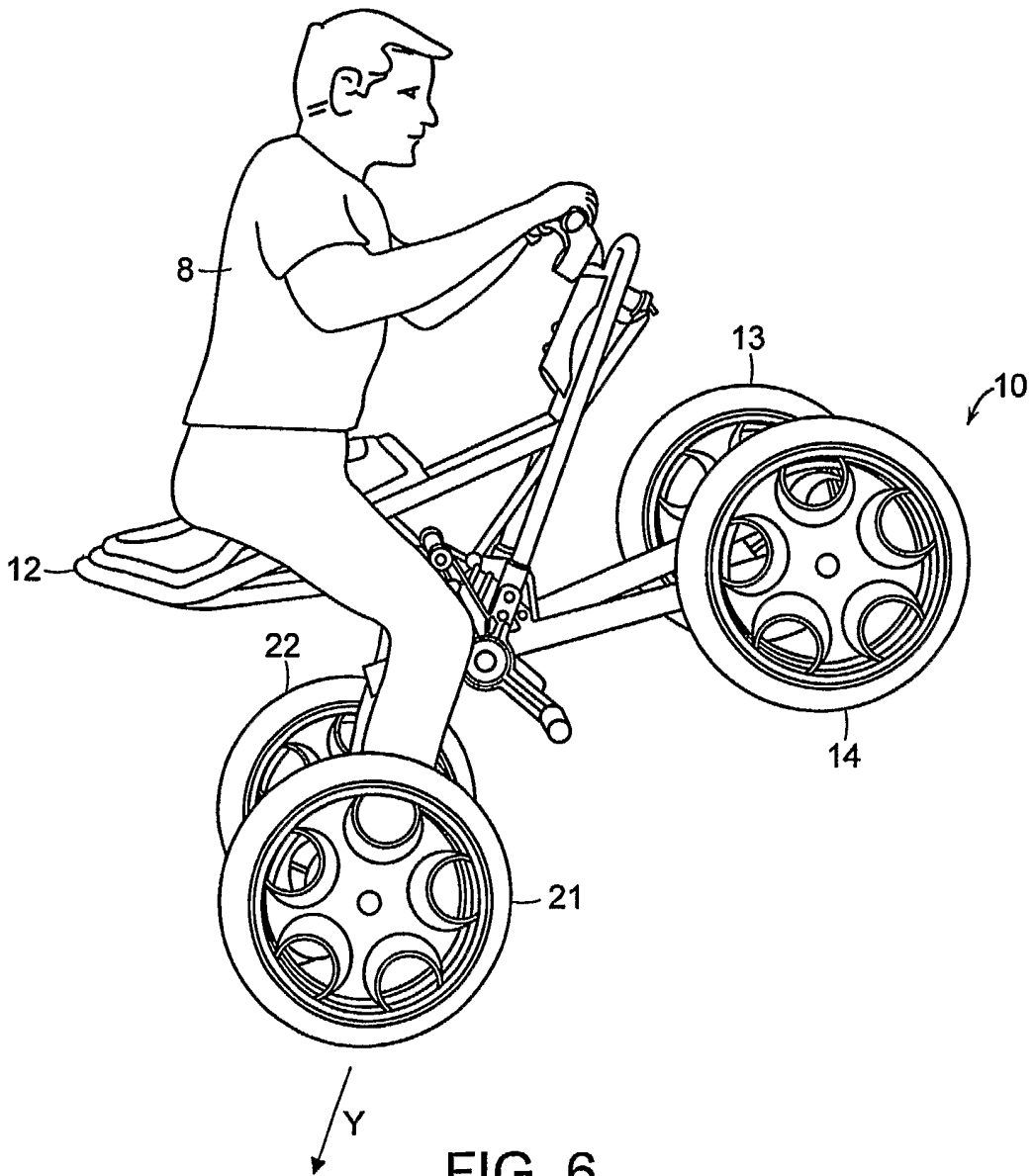


FIG. 5C



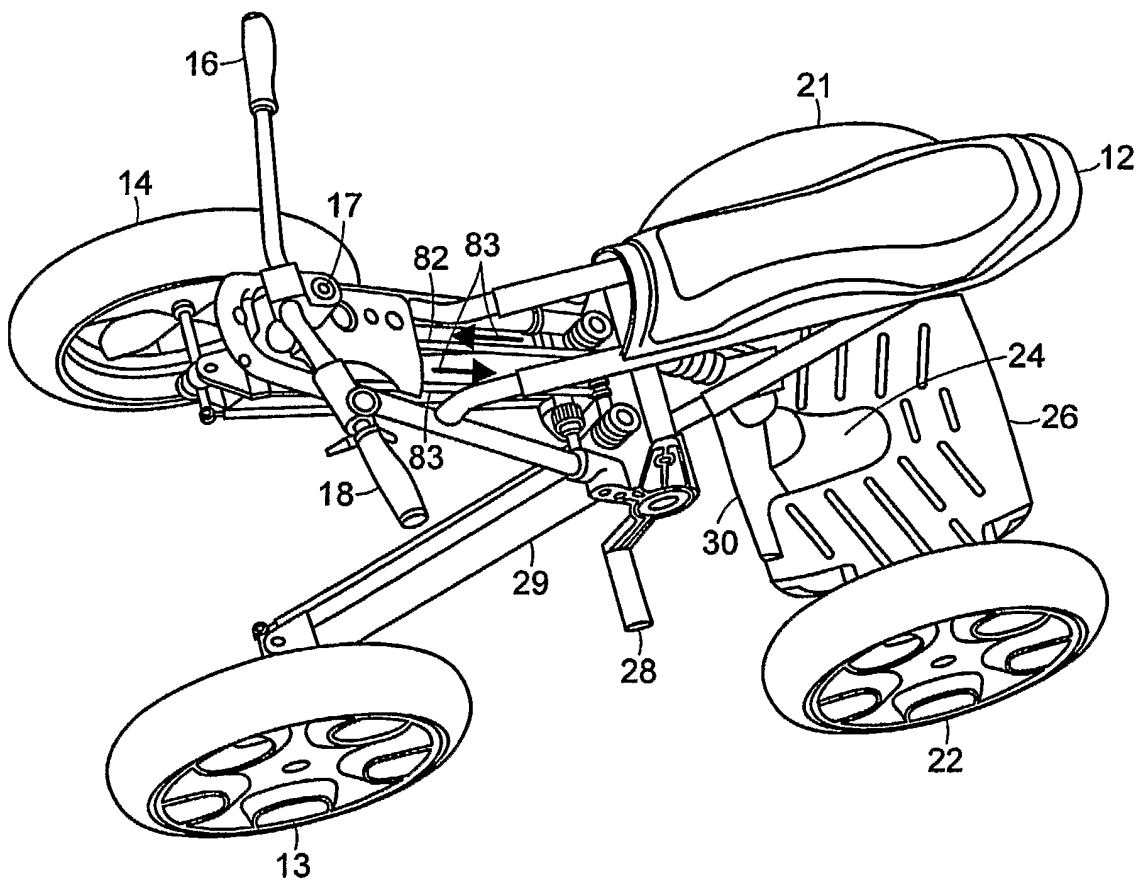


FIG. 7

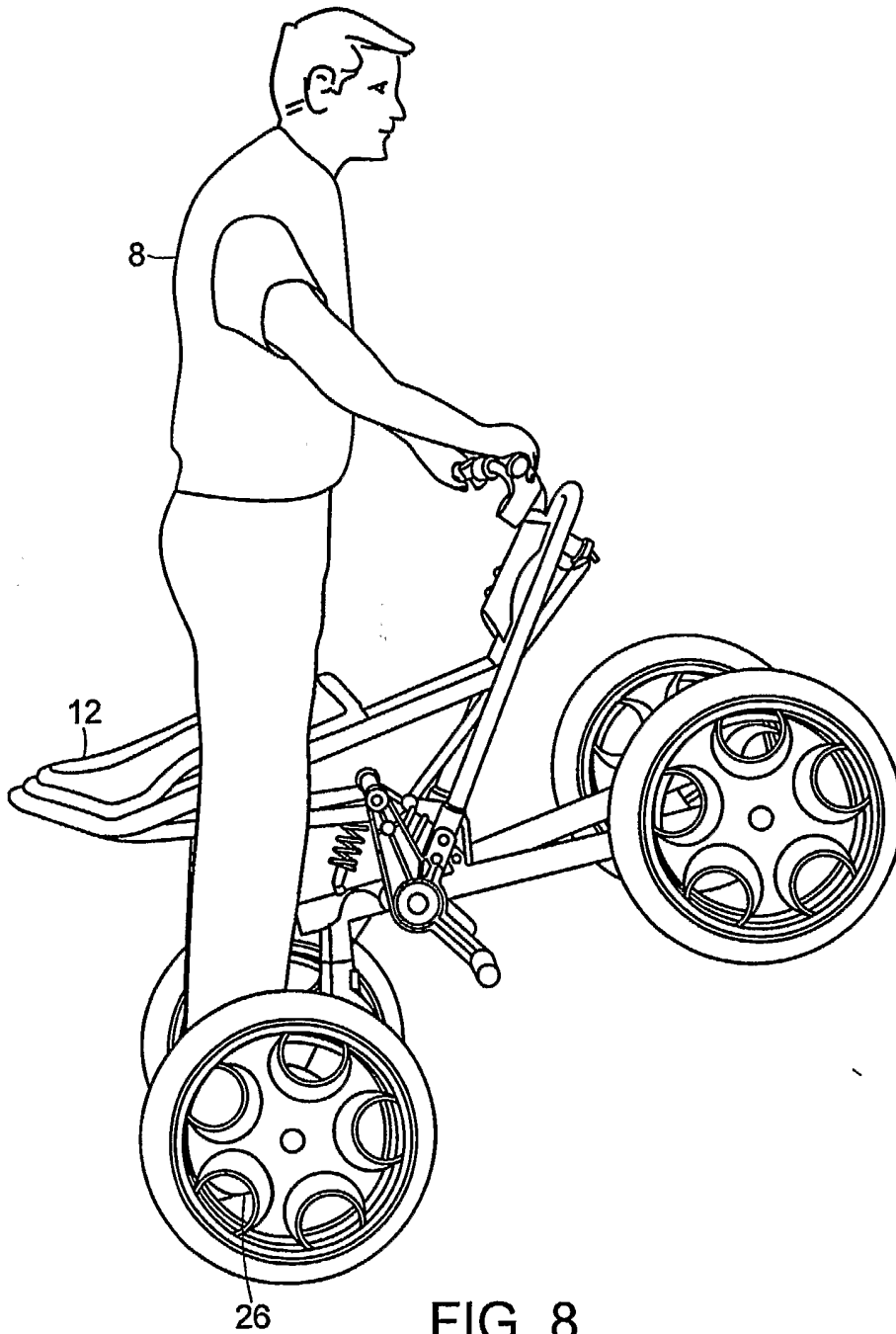


FIG. 8

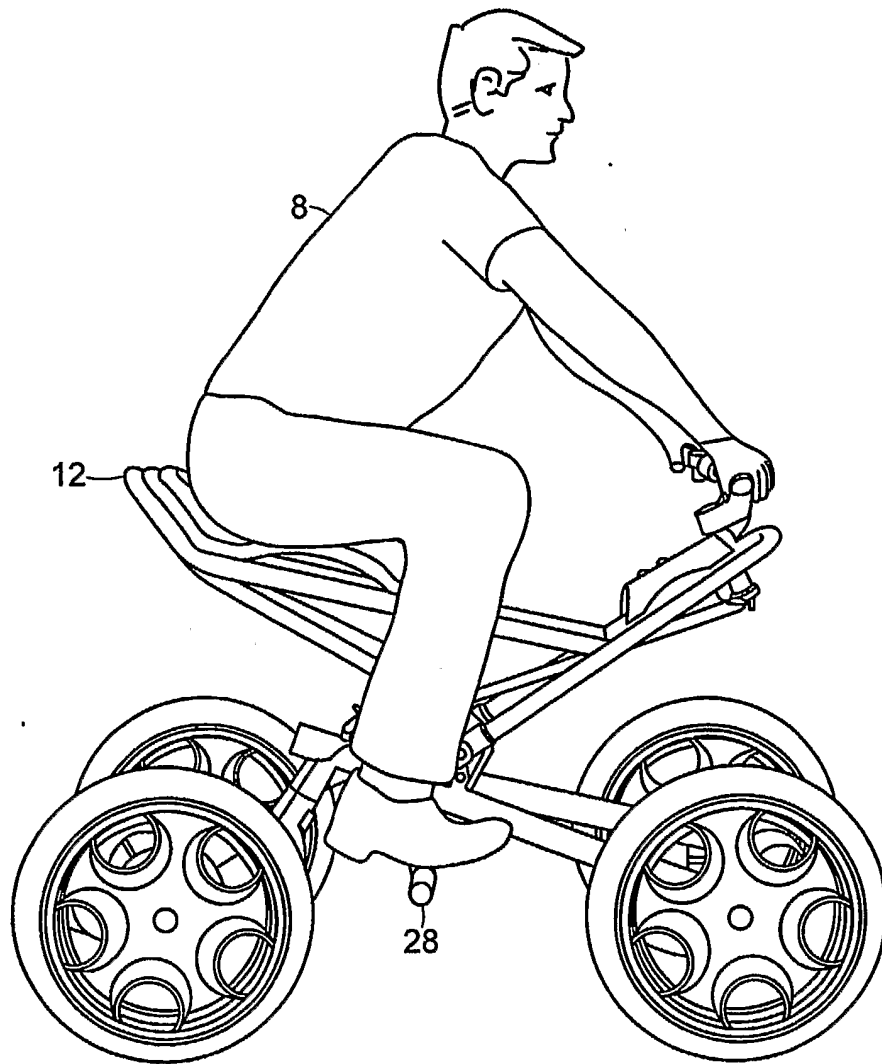


FIG. 9

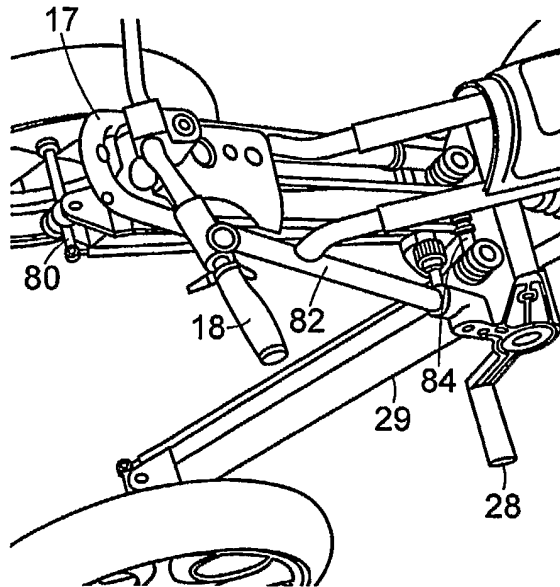


FIG. 10

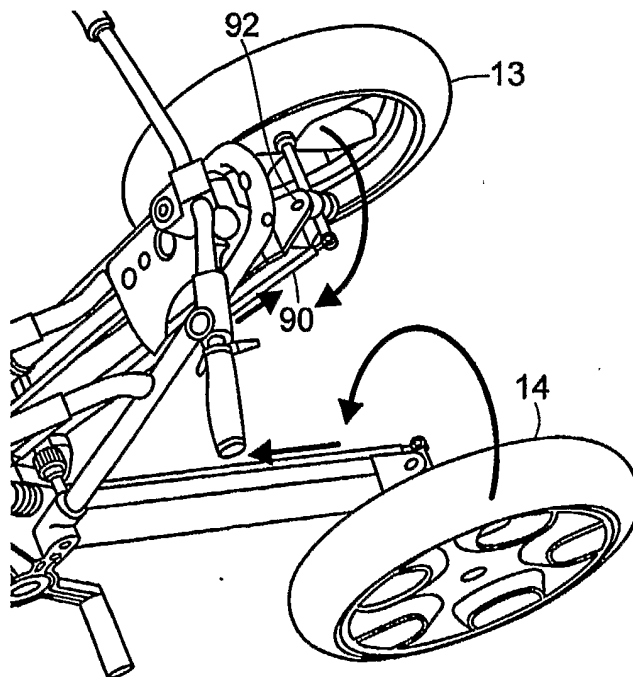


FIG. 11

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US2005/036798

A. CLASSIFICATION OF SUBJECT MATTER

B60W10/04 B60W10/18 B60K41/04 B62M1/00 B62K17/00
A61G5/04 B62M23/02 B62D37/00

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)

B60K A61G B62M B62K B62D

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2003/014167 A1 (PEDERSEN SOREN ET AL) 16 January 2003 (2003-01-16) the whole document -----	1-6, 17, 20, 22 9, 10
X	WO 2004/007264 A (DEKA PRODUCTS LIMITED PARTNERSHIP) 22 January 2004 (2004-01-22) the whole document -----	1, 4, 7, 11
X	GB 2 388 579 A (* FORD GLOBAL TECHNOLOGIES LLC; * FORD GLOBAL TECHNOLOGIES, LLC) 19 November 2003 (2003-11-19) the whole document -----	1, 4, 7, 11
X	US 2003/226698 A1 (KAMEN DEAN L ET AL) 11 December 2003 (2003-12-11) the whole document -----	1, 4, 7, 11, 15, 17, 21
	-/--	

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

° Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *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
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *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.
- *Z* document member of the same patent family

Date of the actual completion of the international search

25 January 2006

Date of mailing of the international search report

03/02/2006

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Tsitsilonis, L

INTERNATIONAL SEARCH REPORT

 International Application No
 PCT/US2005/036798

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6 003 624 A (JORGENSEN ET AL) 21 December 1999 (1999-12-21) the whole document -----	1,4,7, 11,15, 17,21
A	US 2002/121394 A1 (KAMEN DEAN L ET AL) 5 September 2002 (2002-09-05) the whole document -----	1,4,7, 11,15, 17,21
A	US 6 553 271 B1 (MORRELL JOHN B) 22 April 2003 (2003-04-22) cited in the application the whole document -----	1,7,11, 17
A	US 6 311 794 B1 (MORRELL JOHN B ET AL) 6 November 2001 (2001-11-06) cited in the application the whole document -----	1,4,11, 17
A	US 6 302 230 B1 (KAMEN DEAN L ET AL) 16 October 2001 (2001-10-16) cited in the application the whole document -----	1,4,7, 11,17
A	US 6 789 640 B1 (ARLING RICHARD W ET AL) 14 September 2004 (2004-09-14) cited in the application the whole document -----	1,4,7, 11,17
A	US 6 332 103 B1 (STEENSON, JR. JAMES HENRY ET AL) 18 December 2001 (2001-12-18) cited in the application the whole document -----	1,4,7, 11,17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US2005/036798

Patent document cited in search report	Publication date	Patent family member(s)	Publication date	
US 2003014167	A1	16-01-2003	AU 3725101 A DE 10009924 A1 WO 0165150 A1	12-09-2001 20-09-2001 07-09-2001
WO 2004007264	A	22-01-2004	AU 2003247972 A1	02-02-2004
GB 2388579	A	19-11-2003	NONE	
US 2003226698	A1	11-12-2003	NONE	
US 6003624	A	21-12-1999	NONE	
US 2002121394	A1	05-09-2002	AT 300932 T AU 774742 B2 AU 3743000 A CA 2367501 A1 DE 60021709 D1 EP 1161216 A1 JP 2002538891 T MX PA01009342 A TW 425281 B WO 0054719 A1	15-08-2005 08-07-2004 04-10-2000 21-09-2000 08-09-2005 12-12-2001 19-11-2002 14-07-2003 11-03-2001 21-09-2000
US 6553271	B1	22-04-2003	AT 309109 T AU 774856 B2 AU 3745000 A CA 2375313 A1 DE 60023879 D1 EP 1183163 A1 JP 2003500773 T MX PA01012232 A TW 425282 B WO 0073101 A1	15-11-2005 08-07-2004 18-12-2000 07-12-2000 15-12-2005 06-03-2002 07-01-2003 22-11-2002 11-03-2001 07-12-2000
US 6311794	B1	06-11-2001	NONE	
US 6302230	B1	16-10-2001	AU 766736 B2 AU 5313700 A CA 2375645 A1 EP 1181187 A1 JP 2003502002 T MX PA01012557 A WO 0075001 A1 US 6651763 B1 US 6367817 B1	23-10-2003 28-12-2000 14-12-2000 27-02-2002 14-01-2003 02-07-2002 14-12-2000 25-11-2003 09-04-2002
US 6789640	B1	14-09-2004	NONE	
US 6332103	B1	18-12-2001	NONE	