(54) Title: SELF-BALANCING VEHICLE HAVING ONLY ONE WHEEL OR HAVING ONE SEGMENTED WHEEL, AND METHOD FOR SELF-BALANCING CONTROL OF SUCH A VEHICLE

(57) Abstract: Present invention relates to a personal vehicle (101, 113, 201, 140) with one wheel or one segmented wheel and to a method for balancing said vehicle. Said vehicle comprising a body (102,202); a wheel assembly (103, 203, 301, 350); a wheel turning motor (213, 406, 71, 81) mechanically attached between the body and the wheel assembly having an axis of rotation perpendicular to fore direction (109, 209, 135, U); at least one wheel (107, 207, 307, 309, 357, 359, 408, 506, 507) attached to the wheel assembly having an axis of rotation (106, 302, 353, 355, 505, 605) perpendicular to the vertical axis (110, 210) and powered by at least one wheel rotation motor (77, 85, 86), the wheel having a direction of travel (111, 211, W) and a turning angle (θ) between the wheel direction of travel and the fore direction, the wheel rotation motor operatively configured to rotate the wheel and move the personal vehicle forwards or backwards in the wheel direction of travel; control system establishing a balancing wheel direction required for adjusting the vehicle balance and a balancing amount of travel along said balancing direction required for adjusting the vehicle balance; where said wheel is operatively configured to: (i) turn to the balancing wheel direction (W), (ii) travel the balancing amount of travel (Ω) along the balancing wheel direction (W), and (iii) turn the vehicle body to realign the fore direction to the wheel direction of travel.
FIELD OF INVENTION

The present invention relates to the field of personal vehicles or transporters, and more specifically to personal vehicles that require balancing in all directions.

BACKGROUND OF THE INVENTION

Personal vehicles include a large number of human and motor powered vehicles intended for the transport of at least one person. Such vehicles are used for recreation, utility (transportation), and assistance for motion-challenged individuals. Some examples of personal transporters are bicycles, motorcycles, monocycles, unicycles, and personal transporters of the type commonly known by the brand name Segway®. In recent years, there has been a lot of interest in self-balancing transporters that use powered motors and control algorithms to simplify and enable the use of vehicles with either two wheels or one that would be unstable without the self-balancing control algorithms. The advantages of using control algorithms to balance such vehicles are (i) to enable the user to ride the vehicle without learning how to ride, and (ii) that the vehicle is balanced even while not in motion. One desirable requirement for personal transporters is to present a footprint that is as small as that of a person. This would enable the use of personal transporters in the same areas used by pedestrians, including sidewalks, offices, hallways, and elevators. The interest in vehicles with only one wheel (commonly referred to as unicycles) is that they potentially have the smallest footprint of all personal vehicles. However, a conventional human-powered unicycle has the disadvantage that the user must learn how to ride it and hence this eliminates the vast number of potential users including the elderly and disabled
persons. Furthermore, the unicycle requires a certain amount of space around it for maneuvering, while the size of that space depends on the skill of the rider. Another desired characteristic of personal vehicles is the ability to ride on a broad range of terrains, which include office floor, sidewalk, grassy and rocky terrains, and sloped terrains (both in fore direction and laterally sloped). None of the prior art discloses a vehicle which simultaneously satisfies the abovementioned requirements for a desired personal vehicle. Clearly, a personal vehicle with only one wheel whose maneuvering space and riding efficiency do not depend on the skill of the rider, while it has an ability to ride on a broad range terrains would be very advantageous as it could potentially allow the use of such vehicles in areas designated solely for pedestrians. This application discloses such as vehicle.

BACKGROUND ART

The following is a list of patents and patent applications that disclose art related to the current invention.

U.S. Pat. No. 4,106,786 issued to E. R. Talbott on Aug. 15, 1978, entitled "Recreational Vehicle For Use On Sloping Terrains," discloses a circular platform having a large single central wheel and a handle at the front. A rider shifts his/her weight to ride the device, including scraping the rear runners on the ground as a braking means.

The family of patents by the inventor of the Segway®, Dean Kamen, US 6,367,817, US 7,690,447, US 7,275,607 B2, and others describes the operation of a personal transporter with two wheels located on the same axis of rotation, equipped with an algorithm for stabilization in the fore and aft direction. This personal transporter (PT) uses two independently-motorized wheels and a control algorithm that moves the wheels back and forth to maintain balance (this control problem is commonly referred to as the "inverter pendulum problem"). The person standing on the platform of the PT needs to lean forward to make the PT increase the speed and/or move forward. The turning of the PT is accomplished by rotating one of the wheels slightly faster than the other. A major disadvantage of the Segway® and similar two-coaxial-wheel personal transporters is that maintaining balance in the lateral direction requires a
relatively large lateral separation between the two wheels (close to two feet). This makes the Segway® too wide and cumbersome to fit on many sidewalks and that they are dangerous to operate on terrains that have a lateral slope. Since the vehicle stands perpendicular to the terrain (defined by the two widely separated wheels), riding on a laterally sloped terrain can make the person fall sideways and suffer injury. This problem is inherent in personal transporters with two side-by-side wheels, but is not a problem in vehicles such as bicycles, where the two wheels are substantially in line in one plane and is potentially not a problem with vehicles such as the unicycle, which employ only one wheel. The term "unicycle" conventionally refers to a human-powered vehicle with only one wheel although unicycles may be motorized and automated.

Several US and international patents disclose unicycles with platforms on which the user can stand or sit, while balance in the fore and aft direction (in the direction of travel) is accomplished automatically. However, all these previous inventions disclose solutions in which the rider either has to learn how to ride the vehicle, the vehicle has to keep moving to maintain balance, or the vehicle can ride efficiently only on a very flat and well-controlled terrain.

Patent application WO2009120157 discloses a motorized unicycle which features a control algorithm for maintaining balance in the fore and aft direction, while the user has to lean and turn the wheel relative to his or her body to maintain balance in the lateral direction. This unicycle also has to be in motion to remain stable.

In 2008, Murata Manufacturing of Japan disclosed a unicycle-riding robot which uses a control algorithm to balance in the fore and aft direction by driving a single primary wheel, while lateral balance is accomplished using a flywheel located within the robot and oriented so the flywheel's axis of rotation points in the direction of robot propagation. This orientation enables the flywheel to exert torque to keep the unicycle balanced in the lateral direction. PCT Publication 2011/106847 discloses a similar moving direction controller and computer program for use in similar applications.

US patent publication 2011/0010013 discloses a robot moving using only one primary wheel. The robot utilizes a control algorithm for fore and aft balance that drives that wheel, while lateral balance is accomplished using a flywheel.
US patent 5,314,034 discloses a unicycle with a balancing feature for fore and aft balancing, and a large flywheel with its axis of rotation directed perpendicular to the ground and to the axis of rotation of the single wheel to maintain lateral balance. This unicycle is heavy and cumbersome because of the flywheel.

Chinese patent publication CN 200810179658.8 discloses a unicycle with an automatic fore-and-aft balancing function according to a special control algorithm but the rider has to control lateral balancing and the vehicle is stable only when in motion.

A single-wheel personal transporter branded U3-X was announced in 2009 by Honda of Japan. The vehicle, whose design is disclosed in US Design Patent D626892, balances in both fore-and-aft and lateral directions using the Honda Omni Traction Drive System, in which the surface of one large wheel can rotate in the direction that is orthogonal to the rotation of the wheel. In this way, any direction of motion can be achieved without the need to jerk the wheel (as in a classic unicycle). However, the vehicle was demonstrated to operate and maneuver only on flat surfaces, such as office floors, due to the fine structure of the wheel, and is not amenable to laterally sloped surfaces and rough terrain.

Slovenian Patent SI 22748 and PCT publication WO 2009/120157 A1 disclose a unicycle with a principle of operation and riding that is very similar to those for a regular bicycle. The control algorithm only takes care of fore-and-aft stability, while lateral stability is realized by the user leaning to the left or right in the same manner as one would ride a regular bicycle with no hands. The Slovenian invention is not stable when not in motion.

Further prior art relevant to the disclosed invention is as follows:

US 2010/0140009; US 7,847,504 B2; US 7,314,225 B2; US 6,382,640 B1; US 5,314,034; US 4,740,001; EP 2,028,089 Al; CN 101417682A

From the prior art it is clear that, although significant progress has been made in the field of self-stabilizing vehicles, several disadvantages exist in all the disclosed inventions: None can be used to ride on laterally sloped and uncontrolled terrain and remain stable when not in motion.
OBJECTS OF THE INVENTION

An objective of this invention to provide a self-balancing vehicle (a vehicle with one wheel or a vehicle with one segmented wheel) that exhibits a footprint smaller than any currently available or known personal transporter and hence may be widely adopted in the market.

Another objective of the present invention is to provide a self-balancing unicycle that may easily and safely be ridden on laterally sloped terrain.

Still other objects and advantages of the invention will become clear upon review of the following detailed description in conjunction with the appended drawings.

SUMMARY OF THE INVENTION

This application discloses a self-balancing personal transporter with one wheel that can be used on arbitrary terrains and that remains balanced when not in motion, and the method for accomplishing the self-balancing. Vehicles using one wheel are inherently unstable and require control loops with sensors and actuators to provide balance. This furthermore application discloses a personal vehicle with a segmented wheel which comprises two wheels positioned side-by-side that are operatively configured to rotate independently and to move relative to each other in a linear motion. Said personal vehicle with a segmented wheel is also inherently unstable and employs a control loop for balancing.

Definitions

For the purposes of this application, personal transporters (or vehicles) that are unstable in one direction (e.g., Segway®) are referred to as being unidirectionally unstable and for that reason require balancing control in only one direction: fore and aft direction. Vehicles that require balancing in all directions (e.g., classical unicycle) or are only marginally stable in at least
one direction are referred to as being omnidirectionally unstable and require balancing algorithms and hardware to support stabilization in all directions. An example of a marginally stable vehicle is a classical unicycle with a flat and wide tire which can potentially stand upright on its own while stationary, but when a person rides it he or she must actively balance it to avoid falling to any side. For the purposes of this application, the word unicycle will be used for all vehicles that are omnidirectionally unstable whether they have one or more points of contact to the terrain, i.e., one or more wheels or wheel segments.

Wheel rotation means rotating the wheel around the axis of wheel's rotational symmetry, while wheel turning means rotating the wheel along an axis that is (i) perpendicular to the axis of rotational symmetry and (ii) substantially perpendicular to the direction of wheel travel when it rotates. The amount of wheel turning is measured relative to the terrain on which the wheel travels. Wheel direction means direction of wheel travel when the wheel rotates and is in contact with the terrain, and wheel travel refers to the linear motion of the rotating wheel in the wheel direction or the distance along said direction. Fore direction means the direction to which the body of the unicycle points. In an embodiment, a personal vehicle comprises of a drive frame having a vertical axis; one wheel attached to said drive frame having an axis of rotation perpendicular to said vertical axis; a control algorithm sensing the balance of said personal vehicle, the control algorithm establishing a wheel direction required for balancing and amount of travel along the direction required for balancing; wherein the wheel is operatively configured to turn to a direction required for balancing and travel the amount in the direction required for balancing as to balance the vehicle;

According to another embodiment, the unicycle features a segmented wheel. For the purpose of this patent application, term "segmented wheel" is considered as two wheels placed in the immediate proximity of each other so they look and feel like a single wheel: their rotation is controlled independently, but they turn together as one wheel. The distance between the two wheels and the wheel assembly are such that they do not significantly alter the lateral stability of the vehicle. Namely, lateral balancing mechanism is required to maintain the unicycle stable. A segmented wheel can turn in a spot by rotating two segments in opposite directions without producing a net angular moment on the vehicle thereby eliminating the net angular momentum
acquired by the rider (and the unicycle body) upon wheel turning. In one embodiment, the preferred split-wheel unicycle may be used to climb stairs. In another embodiment, the wheel segments are separated by any distance.

BRIEF DESCRIPTION OF THE DRAWINGS

Hereafter the invention is described in detail referring to the figures where:

Fig. 1: Exemplary view of embodiments of a self-balancing vehicle with one wheel utilizing a solid wheel: (a) original, and (b) with foot rests.

Fig. 2: Exemplary view of an embodiment of a self-balancing vehicle with one wheel utilizing a segmented wheel.

Fig. 3: Two views of an exemplary wheel assembly employing a segmented wheel: (a) rotational axes of both wheel segments coincide, and (b) rotational axes of two wheel segments are displaced differentially around an equilibrium line.

Fig. 4: An illustration of the segmented-wheel assembly showing sliders and guides, and the turning motor.

Fig. 5: Illustration showing geometric quantities related to the tilting of the segmented-wheel assembly.

Fig. 6: Illustration how the force of the weight of the vehicle and the rider is applied to the segmented wheel assembly.

Fig. 7: Illustration of a vehicle-person assembly with notations of axes and directions relevant for understanding the operation of preferred embodiments.

Fig. 8: Illustration of pitch and roll displacements as applied to the personal vehicle with one wheel.
Fig. 9: Diagram illustrating the wheel direction \( \vec{W} \) its correction to new wheel direction \( \vec{W}' \) during self-stabilization relative to the fore direction \( \vec{U} \).

Fig. 10: Flow-chart illustrating self-balancing control of the vehicle with one solid wheel.

Fig. 11: Flow-chart illustrating self-balancing control of the vehicle with one segmented wheel.

**DETAILED DESCRIPTION OF THE INVENTION**

The following detailed description is of the best mode or modes of the invention presently contemplated. Such description is not intended to be understood in a limiting sense, but to be an example of the invention presented solely for illustration thereof, and by reference to which in connection with the following description and the accompanying drawings one skilled in the art may be advised of the advantages and construction of the invention.

**Solid-wheel unicycle**

One embodiment of the present invention will be explained with the help of Figure 1. Figure 1 shows an exemplary view of a vehicle referred to as a solid-wheel unicycle. The vehicle 101 comprises at least a body (or a drive frame) 102, wheel assembly 103, and an optional handle 104. The wheel assembly 103 comprises a wheel 107 attached to a fork 108. The wheel can rotate around axis of rotation 106, while the fork 108 can turn the wheel by rotating around an axis 110 which is substantially perpendicular to the axis 106. The wheel 107 rotation around axis 106 is controlled using a wheel-drive motor (not shown) which enables the wheel to rotate and move the vehicle forwards and backwards in the wheel direction 111. The body 102 has a fore direction 109. The rotation of the fork 108 around the axis 110 relative to the body 102 is controlled by a turning motor included within the body 102 (not visible in Figure 1). The turning
motor controls the relative angle $\Theta$ between the fore direction 109 and the wheel direction 111. In one embodiment, the turning motor is a servo motor, namely, a motor equipped with a position-sensing device and a control circuit. In another embodiment, the turning motor is a stepper motor.

In one embodiment, a person may ride the vehicle 101 by resting one's feet on the optional foot rests 105 shown in the assembled view 113 of vehicle 101 (two foot rests 105A and 105B are shown). Vehicles 101 and 113 are identical with the exception that vehicle 113 has the optional foot rests 105A and 105B. In another embodiment, a person may stand on the body 102 top surface 112 or any other surface attached to the body 102 that is suitable for standing. In yet another embodiment, a person may sit on a seat (not shown) centrally located on and attached to the body 102 and keep one's feet on the foot rests 105. In view 113, one foot rest 105A is shown collapsed for transport, while the other 105B is shown in normal mode when the rider can rest his or her foot on the foot rest. In order to start riding the vehicle 113, the rider first has to step and place all of his or her weight on one of the foot rests. This produces a large offset in center of mass and should the vehicle try to correct for this center-of-mass offset, it would have to produce an unnaturally high roll angle which would be uncomfortable for the user, and the user would be hesitant to proceed in placing the other foot on the other foot rest. For this reason, in one embodiment, the foot rests are equipped with switches 115 (one on each foot rest) which are actuated when the rider rest his or her foot on the foot rest, the switches control the application of the lateral (roll-angle) stability algorithm in that one foot on any foot rest defeats the roll-angle stability portion of the algorithm, but maintains the fore-and-aft balancing algorithm active. If no foot is placed on any of the foot rests or if both feet are on respective foot rests (both switches actuated), the vehicle stability is controlled, namely, both the lateral stability and the fore-and-aft stability algorithms are active. In other words, said omnidirectional balancing algorithm can be separated into fore-and-aft balancing algorithm and a lateral balancing algorithm, and the switches on the respective foot rests when engaged at least defeat said lateral balancing algorithm of the vehicle.
A transporter vertical axis (TVA) is the line passing through (i) the center of mass of the rider-vehicle system and (ii) the center of wheel force on the ground (effective point where the wheel force is exerted). As the person riding the transporter may shift his or her weight or extend arms during the ride, the TVA necessarily moves and changes while riding as well as when the person is climbing up to ride. The axes relevant for description of the control algorithm are defined with the help of Figure 7 which illustrates a person 131 is standing on a segmented-wheel unicycle described later with help of Figure 2, but the definitions equally apply to the solid-wheel unicycle shown illustratively in Figure 1. A person 131 is standing on the vehicle standing surface 128 and holding onto the handlebar 132. The fore direction 135 is defined by the body of the vehicle. The joint center of mass of the vehicle and the person is denoted with 129. The vehicle touches the ground via the wheel (solid or segmented) and the center of force the wheel exerts is indicated with spot 133. The TVA 127 passes through the center of mass 129 and the center of gravity force 133. A gravity line 130 is defined as the line that passes through the center of force on the ground 133 and is parallel to the gravitational force (or the sum of the gravitational and inertial forces appearing during riding). The gravity line 130 and the fore direction 135 define a fore-and-aft plane. The stability and control parameters of the vehicle 140 depend on the pitch angle $\phi_p$, defined as the angle between (i) the projection of the TVA 127 on the fore-aft plane and (ii) the gravity line 130 (both belonging to the fore-aft plane), and the roll angle $\phi_r$, defined as the angle between (i) the TVA 127 and (ii) the projection of the TVA 127 on the fore-aft plane.

This definition is schematically illustrated in Figure 8, where pitch angle $\phi_p$ is indicated with the vehicle tilting forward in the fore direction, while roll angle $\phi_r$ is indicated with tilt in a direction that is perpendicular to the fore direction. When the vehicle is moving out of balance by falling over in the fore direction 109, we speak of an increase in pitch angle $\dot{\phi}_p > 0$. The dot above the angle indicates time derivative. If the vehicle wants to fall backwards, then $\dot{\phi}_p < 0$. Similarly, if the vehicle wants to fall to the right side, the roll angle will start increasing $\dot{\phi}_r > 0$, and if it wants to fall to the left, one will detect $\dot{\phi}_r < 0$. The objective of a control algorithm is to maintain the
vehicle stable and upright. This is expressed with $\langle \phi_p \rangle = 0$ and $\langle \phi_r \rangle = 0$, where parenthesis ( ) mean time average. The condition of stability does not preclude linear motion of the entire vehicle in fore or any other direction.

In Figure 1, the vector diagram below the vehicle 101 describe the direction of the body 109 (fore direction) with vector $\vec{U}$ and the direction of the wheel $\vec{W}$. The plane parallel to the vector $\vec{U}$ and the gravity line direction belongs to the fore-and-aft plane. The angle between the fore direction 109 (vector $\vec{U}$) and the wheel direction (vector $\vec{W}$) is denoted with $\Theta$. In one embodiment, the angle $\Theta$ can vary from zero to above 360 degrees, i.e., the wheel can point in any direction without having to return. The fore direction 109 relative to a fixed coordinate system is denoted with angle $\phi_y$ (yaw angle).

In one embodiment, the unicycle with a solid wheel comprises at least the following sensors: (1) a sensor for unicycle body balance continuously measuring and delivering the instantaneous pitch $\phi_p$ and roll $\phi_r$ angle values, referred to as the phi-sensor, and (2) a sensor for the relative angle $\Theta$ between the body of the unicycle and the wheel direction, referred as the theta-sensor. The theta-sensor is commonly implemented as an integral part of the wheel turning motor.

**Balancing algorithm utilizing the solid wheel embodiment**

The method for stabilizing a solid wheel unicycle illustrated in Figure 1 is illustrated with the help of Figures 9 and 10. In one embodiment, the unicycle comprises of at least one motor controlling the wheel rotation (rotation motor 77) and at least one motor turning the wheel (turning motor 71); the control algorithm comprises at least three control loops (illustrated in Figure 10): a fast wheel rotation loop (WRL), a fast wheel turning loop (WTL), and a slow loop that performs fore direction correction (FDC).
The fast control loop starts with the measurements of pitch $\phi_p$ and roll $\phi_r$ angles (via the phi-sensor 79) and the instantaneous position of the wheel assembly relative to the unicycle body $\Theta$ (via the theta-sensor 78), are fed as inputs to the fast control module 72. The target value for the angle $\Theta$ (the output from the theta-sensor) is zero as the rider wishes to travel forward. Generally, during normal operation, the pitch and roll angles will be non-zero and a correction of balance will be necessary. The fast control module 72 uses the pitch $\phi_p$ and roll $\phi_r$ angles to determine the direction to which the wheel has to travel to restore balance, i.e., to bring the pitch and roll angles to zero. The output from the fast control module are hence the new angle $\theta'$ between the wheel direction $\vec{W}$ and the unicycle body direction $\vec{U}$ and the amount of wheel rotation $\Omega$ in this new direction $\vec{W}'$ required to restore balance. The new angle $\theta'$ is given in terms of a new turning torque $T_{wTL}$ to be applied to the wheel turning motor 71 (within the WTL). In order to turn the wheel in one place, the static friction force has to be surmounted. For this to happen, the turning torque has to exceed the slipping threshold torque $T_{ST}$, which is provided by a separate slipping threshold module 74. The dead zone module 75 passes only torque that exceeds the slipping threshold $T_{ST}$ before it is fed as input to the wheel turning motor 71. The wheel-turning motor 71 produces torque sufficient to cause slipping of the wheel sideways and turning the wheel to the new angle &. As soon as the new wheel direction is established (within the WTL), the wheel travels an amount equal to $\Omega$ as provided by the wheel rotation motor 77 (defined within the WRL). The fast control loop cycle repeats, following the response of the mechanical system indicated with dashed lines in Figure 10. The user change the direction of the vehicle by leaning to the side and this will change pitch $\phi_p$ and/or the roll $\phi_r$ angles. This serves as mechanical input into the fast control loop.

The sudden jerking of the solid wheel assembly resulting from the application of the turning torque $T_{wTL}$ provides a parasitic angular momentum in the other direction and this, if ignored, results in the wheel direction different from the fore direction ($\Theta \neq 0$). In order to realign the fore direction with the wheel direction, the slow fore-direction correction (SDC) control module 70 applies a restoring torque $T_{FDC}$ to the wheel turning motor 71 to restore $\Theta = 0$. The
restoring torque $T_{FDC}$ is always lower than the slipping threshold torque $T_{SF}$ as represented by the limiter module 76. The response time of the FDC loop is slower than the response times of both the WTL and the WRL because more than one balancing turns may happen in a short time without the need to make fore direction correction. For this reason, the loop time constant of FDC control $\tau_s$ is much longer than the fast control loop time constant $\tau_f$. A typical ratio is an order of magnitude as indicated in Figure 10. The fast control loop time constant $\tau_f$ is determined by the required balancing time scale which depends on the moments of inertia of the rider/unicycle system and is typical of the order of hundreds of milliseconds.

In summary, when the unicycle is stationary, the wheel of the preferred exhibits two types of motion: (i) it moves back and forth almost imperceptibly to maintain balance in the direction of the wheel (WRL), and (ii) it occasionally turns the wheel to a new direction in order to allow it to make a correction along that new direction (WTL). The FDC loop corrects for the acquired angular momentum during wheel turning. A person riding a classical unicycle learns to adjust this force and jolt by experience required to learn how to ride. While the unicycle is moving, the correction in lateral direction requires the rider (and the unicycle) to lean in one direction which causes precession of the wheel to compensate for torque in the same way it works for a regular bicycle (riding without hands).

When the vehicle is traveling at a constant speed, the lateral balance correction occurs in a significantly smoother routine as the sudden jerk is replaced with a gradual correction of the vehicle direction in the same manner as a regular bicycle would. The fast loop maintains the balance of the vehicle by controlling the rotation of the wheels forwards and backwards and providing lateral stability by turning the wheel when necessary to address stability in the other direction.

In one embodiment, the slipping threshold torque $T_{SF}$ is determined in an independent algorithm which uses the measured relationship between the applied torque at the input to the wheel turning motor 71 and the resulting angle $\Theta$. In another embodiment, the slipping threshold
torque $T_{ST}$ is further estimated from the measured weight of the rider, while in another embodiment, the slipping threshold torque $T_{ST}$ is kept constant for a specific type of terrain.

Figure 9 illustrates an example where a non-zero pitch $\phi_p$ and roll $\phi_r$ angles have been measured, while at that moment the wheels happen to be turned in the direction of vector $\vec{W}$ (angle $\Theta$). The control algorithm will mandate that the wheel assembly be turned to a new direction indicated with $\vec{W}$ (angle $\theta'$) along which wheel rotation will compensate for the instability described with the non-zero pitch and roll angles. Once the wheel assembly is turned to the new direction the control algorithm rotates the wheels to move in the direction of falling and to bring the center of mass to coincide with the gravity line, i.e., establish zero pitch and roll angles. The balance is maintained when the unit is stationary and for any constant velocity of the wheel or wheels.

In one embodiment, the transporter contains a flywheel within the body (not shown) with flywheel axis of rotation parallel to the TVA. In this embodiment, the flywheel is turned in the opposite direction to acquire equal and opposite angular momentum when the wheel assembly is turned and hence the fore direction remains unaffected by the sudden turn of the wheel assembly. In this case, the FDC control is omitted from the block diagram in Figure 10.

**Segmented-wheel unicycle**

Another embodiment of a preferred unicycle 201 is illustrated in Figure 2(a). The vehicle 201 comprises at least of a body (or a drive frame) 202, wheel assembly 203, and an optional handlebar 204. When the wheel assembly 203 turns around an axis 210, the segmented wheel 207 turns to a new direction 211 and enables motion of the segmented wheel 207 in the new wheel direction 211. The body 202 has a fore direction 209. The turning of the fork 208 around the axis 210 relative to the body 202 is controlled by a wheel-turning motor 213 included within the body 202 as is shown in Figure 2(b). The wheel-turning motor controls the relative angle $\Theta$ between the fore direction 209 and the wheel direction 211. In one embodiment, a person may
ride the vehicle 201 by resting one's feet on two foot rests (not shown) similar to the ones shown in embodiments connected to vehicle 113. In another embodiment, a person may stand on the body 202 top surface 212 or any other surface attached to the body 202 that is suitable for standing and is located above the wheels. In yet another embodiment, a person may sit on a seat (not shown) centrally located on and attached to the body 202 and keep one's feet on the foot rests.

Figure 3 illustrates the allowed motion of the wheel segments. In one embodiment, the wheel assembly 301 comprises a segmented wheel having two side-by-side wheel segments 307 and 309 that are mechanically coupled in such a way that (i) their axes of rotation 302 are substantially parallel, (ii) their respective axes of rotation can move in a linear motion relative to each other differentially, and (iii) each wheel segment has its own rotation-drive motor, namely, the wheel segments can rotate independently. The wheel rotating motor is preferably enclosed in the body of the wheel (a hub motor). The linear motion is perpendicular to the axes of rotation and parallel to the gravity line or least closing an oblique angle with the gravity line. At one point, referred to as the equilibrium state, the rotational axes of the first and the second wheel segments coincide as shown with 302 in Figure 3, case 301. Depicted in state 301, the first wheel segment 307 is attached to a first slider 308, while the second wheel segment 309 is attached to a second slider 310. The sliders 308 and 310 allow the wheel segments to slide up and down. In one embodiment, the linear motion is substantially parallel with the gravitational force (or the sum of gravitational and inertial forces). In the state shown with 350, the axis of rotation 353 of the first wheel segment 357 is always parallel to the axis of the rotation 355 of the second wheel segment 359, and the two axes can offset from each other, as shown in state 350, differentially around the equilibrium axis 354. Namely, the amount 361 by which the first axis 355 can be lowered equals the amount 362 by which the second axis 353 can be elevated relative to the equilibrium line 354 at which both axes coincide. The segmented wheels always turn together, namely, the axes of rotation of the two wheels remain parallel during turning. In one embodiment, the segmented-wheel assembly can turn more than 360 degrees - full circle without any obstacles.
In one embodiment, the mechanical coupling between the segmented wheels 307 and 309 and the fork 303 in Figure 3 is accomplished using sliding rails illustrated in a perspective drawing in Figure 4. The exemplary segmented-wheel assembly 401 is shown with the turning motor 406 attached to the turning axis 407 and the wheel assembly having a segmented wheel 408. The segmented wheel 408 is shown in an offset state similar to as is shown in Figure 3(b). The two segments of the segmented wheel 408 are each coupled to linear sliding rails. In one embodiment, the rotating axis of a first segment of the wheel is coupled to an inner rail 405 which slides within an outer rail 404 and allows the first segment to move in linear motion up and down. Similarly, the rotating axis a second segment of the wheel 408 is coupled to an inner rail 402 which slides and guided along an outer rail 403. In another embodiment, the linear-motion sliding rails appear between the wheel segments.

In one embodiment, the first wheel segment and the second wheel segment of the segmented-wheel assembly are operatively configured to be driven independently, namely, a first motor drives the rotation of the first wheel, and a second motor drives the rotation of the second wheel. In yet another embodiment, the first and second wheels are driven with two motors wherein the first motor drives the average rotation of the two wheels, while a second motor drives the rotation difference between the two wheels. The end effect of these two embodiments is identical: the wheels can be operated independently.

In one embodiment, the separation between the wheel segments in the direction parallel to the axis of rotation of any of the segmented wheel is smaller than the overall width of the transporter. Separating the wheel segments does not improve the stability of the transporter relative to having a single solid wheel only, because the segmented wheels are able to move in vertical linear motion differentially. Consequently, lateral stability control loop is still required to use the vehicle with the segmented wheel and the vehicle is hence omnidirectionally unstable. For the purposes of this application, the segmented wheel embodiment is considered to be a unicycle. Larger distance between the wheels improves the ability of the segmented wheel to turn in a spot because the static friction for of each wheel can be surmounted with a lower wheel rotation torque.
Figure 5 is used to clarify the definition and the issues related to the wheel separation. A segmented wheel with segments 506 and 507 in the equilibrium state 501 touches the riding surface 514 at points 503 and 504. Points 503 and 504 are the centers of force each wheel segment exerts on the riding surface. The rotational axes of the two wheel segments 506 and 507 coincide in the equilibrium state and are depicted with line 505. The lateral distance between the points 503 and 504 is referred to as the force center separation $D(0)$. were the zero argument implies zero angle between the surface 514 normal and the axis of turning. When the segmented wheel is in the equilibrium state, the wheel segment separation $S(0)$ equals the force center separation: $S(0) = D(0)$.

When the vehicle with a segmented wheel tilts to a non-zero roll or pitch angle during normal operation, the wheel segments move away from the equilibrium state and the rotational axes of the two wheel segments split as shown in 502. The distance 511 between the separate rotational axes of the wheel segments is denoted $H$. The tilted wheel segments now touch the riding surface 515 in two points 509 and 510. The points 509 and 510 are the centers of force the wheel segments exert on the riding surface. The distance between the points 509 and 501 (under wheel tilt) is generally different from what it used to be in the equilibrium state and is denoted with $D(H)$. The wheel separation generally depends on the tilts, so it is denoted with $S(H)$. In one embodiment, the wheel segment separation $S$ is kept constant, i.e., is independent of $H$. In this case, $D(H)$ varies substantially as $D(H) = \sqrt{D(0)^2 + H^2}$. The advantage of this embodiment is simplicity in design and manufacturing, but it does result in lateral wheel segment slipping when the wheel is tilted. In another embodiment, the wheel segment separation varies with the tilt, i.e., with $H$ so that the force center points remain equidistant for all practical values of $H$, i.e., $D(H) = \text{constant}$. This means that the wheel segment separation $S(H)$ has to change with tilt (and $H$) substantially as $S(H) = \sqrt{D(0)^2 - H^2}$.

Figure 6 illustrates how the weight of the vehicle and the rider is applied to the segmented wheel assembly. The segmented wheel assembly is sketched (without all the mechanical parts) in vertical position 601 and in a tilted position 602 which occurs when the vehicle has a non-zero roll angle occurring, for example, when one is riding into a curve, or riding on laterally sloped terrain. The two wheel segments (already described in Figure 5) rotate around axis 605 and are
attached to left fork 623 and right fork 624. When in vertical position, the wheel segments exert a force downwards in points 603 and 604 and are pressing against the riding surface 614. (The points 603 and 604 represent the centers of force action). The weight of the rest of the vehicle and the rider are exerted as a force 606 from the top pressing on a level 607 that touches and slides on top of the left fork 623 and the right fork 624 thereby transferring the vehicle's weight to the wheel segments approximately equally. When the segmented wheel assembly tilts as shown in 602, the left fork 625 and the right fork 626 remain parallel owing the guides (as illustrated in Figure 4), but they have moved relative to each other differentially: one went up and the other went down owing to the pressure exerted from the level 608. The weight of the vehicle is exerted as a force 636 in the center of the level 608 and applied approximately equally on to the left fork 625 and right fork 626. A person skilled in the art of mechanical design will appreciate that there other ways one can ensure differential linear motion of the two wheel segments and this illustration in Figure 6 is only one of many possible implementations.

In another embodiment, in which the wheel assembly features the segmented-wheel, the turning is executed by differentially driving the two segments of the wheel. In this case, there is no need for sudden wheel turning that has to surmount the static friction force against the vehicle moment of inertia as described for the solid-wheel embodiment (illustrated by example in Figure 1), but rather a steady differential force on the two wheels that will result in wheel turning with no or very little resulting torque on the vehicle. In one embodiment, the slow FDC loop is required to maintain proper fore direction.

In one embodiment, the unicycle with a segmented wheel comprises at least the following sensors: (1) a sensor for unicycle body balance continuously measuring and delivering the instantaneous pitch \( \phi_p \) and roll \( \phi_r \) angle values, referred to as the \( \phi \)-sensor, and (2) a sensor for the relative angle \( \Theta \) between the body of the unicycle and the wheel direction, referred as the \( \theta \)-sensor. The \( \theta \)-sensor is commonly implemented as an integral part of the wheel turning motor.

The method for stabilizing a segmented wheel unicycle illustrated in Figure 2 is illustrated with the help of Figure 11. In one embodiment, the unicycle comprises of at least two
motors controlling the wheel-segment rotation (rotation motors 85, 86) and at least one motor turning the wheel (wheel turning motor 81); the control algorithm comprises at least three control loops (illustrated in Figure 11): a fast wheel rotation loop (WRL), a fast wheel turning loop (WTL), and a slow loop that performs fore direction correction (FDC).

Starting with the fast control loop, the measured pitch \( \phi_p \) and roll \( \phi_r \) angles (via the phi-sensor 89) and the instantaneous position of the wheel assembly relative to the unicycle body \( \Theta \) (via the theta-sensor 88), are fed as inputs to the fast control module 82. The target value for the angle \( \Theta \) is zero as the rider wishes to travel forward. Generally, in the normal operation, the pitch and roll angles will be non-zero and a correction of balance will be necessary. The fast control module 82 uses the pitch \( \phi_p \) and roll \( \phi_r \) angles to determine the direction to which the wheel has to travel to restore balance, i.e., to bring the pitch and roll angles to zero. The fast control algorithm results in the new angle \( \phi \) between the wheel direction \( \vec{W} \) and the unicycle body direction \( \vec{U} \) and the amount of wheel rotation \( \Omega \) required to restore balance. The control algorithm output is fed as differential information 87 to the two wheel-segment motors 85 and 86 and wheel turning motor 81 to track the wheel assembly turn. As soon as the new wheel direction is established in the WTL, the segmented wheel travels an amount equal to \( \Omega \) as provided by the common rotation of the wheel rotation motors 85 and 86 in the WRL. The fast control loop cycle repeats following the response of the mechanical system indicated with dashed lines in Figure 11. Inasmuch as the segmented-wheel turns and the unicycle body turning may not be perfect every time, due to varying terrains conditions and static friction slipping thresholds, the fore direction may have to be realigned with the wheel direction. This is accomplished with the slow fore-direction correction (FDC) control module 80 that applies a restoring torque \( T_{FDC} \) to the wheel turning motor 81 to restore \( \theta = 0 \). The response time of the FDC loop is slower than the response times of both the WTL and the WRL because more than one balancing turns may happen in a short time without the need to make fore direction correction. For this reason, the loop time constant of FDC control \( \tau_s \) is much longer than the fast control loop time constant \( \tau_F \). A typical ratio is an order of magnitude as indicated in Figure 11. The fast control loop time
constant $\tau_p$ is determined by the required balancing time scale which depends on the moments of inertia of the rider/unicycle system and is typical of the order of hundreds of milliseconds.

In another embodiment, the segmented wheel comprises more than two segments. In one embodiment, a segmented wheel with three segments driven by two independent motors wherein a first edge wheel is driven by a first motor, a second edge wheel by a second motor, and a center wheel driven by the average of the first and second motors. In yet another embodiment, three segments are driven using three independent motors.

Embodiments related to both solid and segmented-wheel unicycles

The self-balancing vehicle with one wheel includes a wheel assembly that contains either a single solid or a segmented wheel. The wheel is powered by wheel motors (one for single wheel, and two for segmented wheel) and their turning is powered by a turning motor. A controller is coupled to the motor for providing a control signal in response to changes in the center of gravity of the assembly that includes the vehicle and a person. When a person, as shown in Figure 7, steps onto the vehicle first with one foot and then with both feet, he or she temporarily displaces the center of gravity to one side and then brings it back to an approximate center (when both feet are on). During this procedure, the controller module senses these changes in the center of gravity. If the center of gravity moves forward in the fore direction, power is provided to the wheels and the vehicle moves forward. As the center of gravity moves in the aft direction in response to the movement of the rider, the vehicle will slow and reverse direction such that the vehicle moves in the aft direction. If the center of gravity is moved to the left, the wheel assembly will turn the wheel in that direction and move the transporter in the direction of the center of gravity change to regain balance. The pitch of the vehicle may also be sensed and compensated for in the control loop. For the purposes of this application, "sensing the balance" means measuring the pitch $\phi_p$ and roll $\phi_r$ angles, and any other parameters that provide sufficient information on how to balance the vehicle.
In one embodiment, the linear vehicle motion in the fore direction and turning is performed using electrical controls on the handlebar. In yet another embodiment, pitching the handlebar forward while allowing for the vehicle to maintain balance is an instruction to add average linear motion in the fore direction. Tilting the handle sideways, namely, introducing roll, is a signal to the vehicle to turn to the side.

In one embodiment, the personal vehicle with one solid or segmented wheel can be collapsed (reduced in size) for easy transportation. The collapsing includes, but is not limited to lifting the foot rest, as is illustrated in Figure 1(b) with 105B showing normal use and 105A showing folded for transportation use, and folding the handlebar 114 down against the body of the vehicle as is shown in Figure 1(b).

It is apparent that the above embodiments may be altered in many ways without departing from the scope of the invention. It is understood that although the preferred method is been disclosed as applied to personal transporters or vehicles, that the invention can be applied to other vehicles where self-balancing is needed without departing from the scope of the invention. Further, various aspects of a particular embodiment may contain patentable subject matter without regard to other aspects of the same embodiment. Additionally, various aspects of different embodiments can be combined together. Also, those skilled in the art will understand that variations can be made in the number and arrangement of components illustrated in the above diagrams.
CLAIMS

1. A personal vehicle (101,1 13,201,140) comprising
a body (102,202) having a vertical axis (1 10,210) and a fore direction (109,209,135, $\vec{U}$); a wheel assembly (103,203,301,350); a control system sensing a vehicle balance,

   characterized by that

said personal vehicle (101,1 13,201,140) further comprising a wheel turning motor (213,406,71,81) mechanically attached between the body (102,202) and the wheel assembly (103,203,301,350), the wheel turning motor having an axis of rotation perpendicular to said fore direction (109,209,135, $\vec{U}$); at least one wheel (107,207,307,309,357,359,408,506,507) attached to the wheel assembly having an axis of rotation (106,302,353,355,505,605) perpendicular to the vertical axis (110,210) and powered by at least one wheel rotation motor (77,85,86), the wheel having a direction of travel (1 11,211, $\vec{W}$) and a turning angle ($\Theta$) between the wheel direction of travel and the fore direction (109,209,135, $\vec{U}$), the wheel rotation motor operatively configured to rotate the wheel (107,207,307,309,357,359,408,506,507) and move the personal vehicle (101,1 13,201,140) forwards or backwards in the wheel direction of travel (1 11,211, $\vec{W}$); control system establishing a balancing wheel direction required for adjusting the vehicle balance and a balancing amount of travel along said balancing direction required for adjusting the vehicle balance;

where the wheel (107,207,307,309,357,359,408,506,507) is operatively configured to:

(i) turn to the balancing wheel direction ($\vec{W}'$),

(ii) travel the balancing amount of travel ($\Omega$) along the balancing wheel direction ($\vec{W}'$), and

(iii) turn the vehicle body (102,202) to realign the fore direction (109,209,135, $\vec{U}$) to the wheel direction of travel (1 11,211, $\vec{W}$).

2. The personal vehicle (101,113,201,140) according to claim 1, characterized by that wheel assembly (103,203,301,350,401) can turn full circle without any restrictions.
3. The personal vehicle (101,113,201,140) according to claim 1, characterized by that at least one foot rest (105A; 105B) is coupled to the body (102,202).

4. The personal vehicle (101,13,201,140) according to claim 3, characterized by that at least one foot rest (105A; 105B) is equipped with at least one foot switch (115) operatively configured to defeat turning of the wheel assembly (103,203,301,350,401).

5. The personal vehicle (101,13,201,140) according to claim 1, characterized by that a handlebar (104,14,204) is coupled to the body (102,202).

6. The personal vehicle (101,13,201,140) according to claim 5, characterized by that the handlebar (104,14,204) is operatively configured to control the direction of travel of the personal vehicle.

7. The personal vehicle (101,13,201,140) according to claim 1, characterized by that at least one seat is attached to the body (102,202).

8. The personal vehicle (101,13,201,140) according to claim 1, characterized by that the personal vehicle (101,13,201,140) further comprising at least first set of sensors (78,79,88,89) for measuring the instantaneous value of vehicle pitch angle ($\phi_p$) and roll angle ($\phi_r$) and at least second set of sensors for measuring the instantaneous value of a turn angle ($0$).

9. The personal vehicle (101,113,201,140) according to claim 8, characterized by that the personal vehicle (101,13,201,140) further comprising of a fast control module (72), the fast control module using the turn angle ($0$), the pitch angle ($\phi_p$), and the roll angle ($\phi_r$) to determine a balancing turn direction and a balancing amount of wheel travel ($\Omega$) required to bring the pitch angle ($\phi_p$) and the roll angle to zero ($\phi_r$), and turning the wheel to the balancing direction and rotating said wheel by said amount of wheel travel; a slow control module (72) turning the wheel to reduce the turn angle ($\Theta$) to zero;
10. The personal vehicle (101,113,201,140) according to claim 9, characterized by that the vehicle further comprising a static friction threshold estimation module (74), the static friction threshold estimation module (74) estimating a value of lateral friction threshold torque $T_{ST}$, the fast control module (72) using the lateral friction threshold torque $T_{ST}$ to determine a first torque required for turning of the wheel to balancing direction ($\vec{W}'$), and where the slow control module (70) is using the lateral friction threshold torque $T_{ST}$ to determine a second torque required for turning the vehicle body (102,202) to realign the fore direction (109,209,135, $\vec{U}$) to the wheel direction of travel (111,211, $\vec{W}$).

11. The personal vehicle (101,113,201,140) according to claim 10, characterized by that the first torque is greater than the lateral friction threshold torque $T_{ST}$, and the second torque is smaller than the lateral friction threshold torque $T_{ST}$.

12. The personal vehicle (101,113,201,140) according to claim 9, characterized by that the fast control module (72) is characterized by a first response time and the slow control module (70) characterized by a second response time, and that the first response time is at least ten times shorter than the second response time.

13. The personal vehicle (101,113,201,140) according to claim 8, characterized by that a wheel assembly (103,203,301,350) comprises a segmented wheel (207,307,309,357,359,408, 506,507).

14. The personal vehicle (101,113,201,140) according to claim 13, characterized by that the segmented wheel (207,307,309,357,359,408,506,507) comprises two side-by-side wheel segments (207,307,309,357,359,408,506,507) each having an axis of rotation and being mechanically coupled in such a way that (i) their respective axes of rotation are parallel, (ii) their respective axes of rotation can move in a linear motion that is parallel to the vertical axis and relative to each other differentially, and (iii) each wheel segment has its own rotation-drive wheel motor (85,86).
15. The personal vehicle (101,113,201,140) according to claim 14, characterized by that a change in the wheel direction of travel is executed by differentially driving the two rotation-drive wheel motors (85,86) of the segmented wheel (207,307,309,357,359,408,506,507).

16. The personal vehicle (101,13,201,140) according to claim 15, characterized by that the personal vehicle (101,13,201,140) further comprising of a fast control module (72), the fast control module using the turn angle (Θ), the pitch angle (φₚ), and the roll angle (φₘ) to determine a balancing turn direction and a balancing amount of wheel travel (Ω) required to bring the turn angle and the roll angle to zero, and changing the segmented wheel direction to the balancing direction and rotating the wheel segments jointly by said amount of wheel travel; a slow control module (72) turning the wheel assembly to reduce the turn angle (Θ) to zero.

17. The personal vehicle (101,13,201,140) according to claim 16, characterized by that the fast control module (72) is characterized by a first response time and the slow control module (70) characterized by a second response time, and that the first response time is at least ten times shorter than the second response time.

18. A method for dynamically balancing the personal vehicle (101,113,201,140) with the wheel assembly (103,203,301,350,401) with one wheel being solid-wheel (107) or with one segmented-wheel (207,307,309,357,359,408,506,507) wherein at least one motor (77,85,86) is controlling the wheel rotation, and wherein at least one motor (71,81) is controlling turning of the wheel assembly, wherein the controlling of the wheel rotation and turning of the wheel assembly is performed by using a balancing control system characterized by following steps:

- continuously measuring of the vehicle pitch φₚ and roll φₘ angles using a phi-angle sensor (79,89), and measuring the instantaneous angle Θ of the said wheel assembly relative to said fore axis (109,209,135, U) using a theta-angle sensor (78,88);
providing a pitch angle $\phi_p$, a roll angle $\phi_r$, and angle $\Theta$ as inputs to a fast control module (72, 82) which uses the pitch $\phi_p$ and the roll angle $\phi_r$ to determine a new direction $\vec{W}'$ to which the wheel has to travel to restore balance;

- establishing by fast control module (72, 82) a turning torque $T_{WTL}$ command to be applied to the wheel turning motor (71, 81), or as a difference command to the segmented wheel motors (85, 86), or both to turn to new direction $\vec{W}$, and a command to be applied to the wheel rotation motor (77), or as a joint command to the segmented wheel motors (85, 86) to produce the amount of wheel rotation $\Omega$ in this new direction $\vec{W}'$; all in order to bring said pitch $\phi_p$ and said roll $\phi_r$ angles to zero;

- turning the wheel to the new wheel direction $\vec{W}'$ and rotating the wheel by the amount of wheel rotation $\Omega$;

- establishing by slow control module (70, 80) a turning torque $T_{WTL}$ command to be applied to the wheel turning motor (71, 81) required to realign fore direction (109, 209, 135, $\vec{U}$) to wheel direction of travel (111, 211, $\vec{W}$);

- turning the wheel to realign fore direction (109, 209, 135, $\vec{U}$) to wheel direction of travel (111, 211, $\vec{W}$) and thus to restore $\Theta = 0$,

where all steps are continuously repeated.

19. A method according claim 18, characterized by that turning torque $T_{WTL}$ command has to exceed the slipping threshold torque $T_{Sy}$, which is provided by a separate slipping threshold module (74), where dead zone module (75) passes only torque command that exceeds the slipping threshold $T_{Sy}$ value before it is fed as input to the wheel turning motor (71, 81).
20. A method according claim 18, characterized by that restoring torque $T_{FDC}$ command has to be limited up to the value of slipping threshold torque $T_{ST}$, which is provided by a separate slipping threshold module (74), where limiter module (76) passes only torque command that is limited up to the value of slipping threshold $T_{ST}$ before it is fed as input to the wheel turning motor (71).

21. A method according claim 18, characterized by that the response time of fast control module (72,82) is at least ten times faster than that of slow control module (70,80).

22. Balancing control software program loadable into memory of a digital processor, said balancing control software program comprising software code portions capable of implementing the method according to any of claims 18 to 21, when said balancing control software program is executed on the digital processor.
Figure 11
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

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)
B62K

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

<table>
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<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>wo 2009/120157 AI (POLUTNI K ALEKSANDER [SI] ) 1 October 2009 (2009-10-01) cited in the application abstract; figure 1</td>
<td>1, 18, 22</td>
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Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:

- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "O" document referring to an oral disclosure, use, exhibition or other means
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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
- "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
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- "Z" document member of the same patent family

Date of the actual completion of the international search: 19 January 2012

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Authorized officer: Clasen, Martin
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