

APPARATUS AND METHOD FOR PERFORMING SURFACE TRANSITION ON MAGNETIC SURFACES

BACKGROUND

Technical Field

5 Embodiments of the invention relate to apparatus, e.g. vehicles, mobile robots, capable of climbing and making transitions, e.g. between angled surfaces of both internal and external walls of a confined-space structure.

Description of Related Art

10 In some existing mobile robots or vehicles for surface transition on ferromagnetic surfaces, mechanisms, e.g. an active lifter wheel, is required to detach a wheel from the previous surface and also to reduce the impact and stress on the wheel and shaft as the robot transits and move off onto the next surface.

 Examples of such existing robots are provided in US Patent No. 9,487,254 B2
15 "Vehicle and Method for the Independent Inspection of Hard-to-Reach Inner Spaces" and EP Patent Application Publication No. 2003044 A1 "Automotive Inspection Vehicle".

 Other references of existing robots include:

 F. Rochat, P. Schoeneich, B. Luthi, F. Mondada, H. Blueier, "Cymag3D: a simple and miniature climbing robot with advance mobility in ferromagnetic environment", Proc. of The
20 13th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR), September 2010.

 W. Fischer, G. Caprari, R. Siegwart, R. Moser, "Compact Magnetic Wheeled Robot for Inspecting Complex Shaped Structures in Generator Housings and Similar Environments", Proc. of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems,
25 2009. Limitation/Difference: Passive extra wheels take up more space and robot will be less compact.

 W. Fischer, G. Caprari, R. Siegwart, R. Moser, "Very Compact Climbing Robot rolling on Magnetic Hexagonal Cam-Discs, with High Mobility on Obstacles but Minimal Mechanical Complexity", ISR / ROBOTIK 2010. Limitation/Difference: Requires hexagonal wheels

30 W. Fischer, F. Tâche, G. Caprari, R. Siegwart, "Magnetic Wheeled Robot with High Mobility but only 2 DOF to Control", Proc. of The 11th International Conference on Climbing and

Walking Robots and the Support Technologies for Mobile Machines (CLAWAR), 2008.
Limitation/Difference: Requires 4 drive wheels. Requires high torque and high friction coefficient for surface transition

Wang, X. (2008). "Climbing robot with magnetic adhesion. Student project report, EPFL.
5 Limitation/Difference: Requires an additional mechanism to flip the magnet to the next surface

In view of the above and other issues, improved robots for surface transition on ferromagnetic surfaces are highly desirable.

SUMMARY

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The invention relates to a magnetic assembly that is capable of controlling magnetic flux production and/or distribution of magnet(s) to optimize mobile robot performance, such as in surface transition operation. For this purpose, such magnetic assembly comprises a magnetic flux distribution controller which cooperates with a magnetic flux producer to vary
15 magnetic flux distribution. More particularly, by utilising an appropriately-shaped magnetic flux distribution controller (e.g. a source magnet which, itself, also produces magnetic flux, or a magnetically permeable structure, e.g. mild steel, in combination with a magnetic flux producer, e.g. source magnet which may be permanent magnet and/or electromagnet), magnetic flux distribution at the magnetic assembly can be varied which in turn affects a
20 torque required by a driven wheel or motor thereof to have the robot perform a surface transition from a current workpiece surface to a next or target workpiece surface. Depending on embodiment, such magnetic assembly may be provided at a driven wheel or a non-driven wheel or both.

According to one aspect of the invention, a mobile robot capable of performing
25 surface transition on ferromagnetic surfaces is provided. The robot comprises:

a chassis;

at least one driven magnetic wheel assembly rotatably mounted to the chassis and operative to drive the chassis;

at least one non-driven magnetic wheel assembly rotatably mounted to the chassis,

30 wherein at least the driven magnetic wheel assembly or the non-driven magnetic wheel assembly comprises:

a non-magnetic wheel operative to maintain contact with one of the ferromagnetic surfaces;

a magnetic assembly rotatably coupled to the non-magnetic wheel, wherein the magnetic assembly comprises:

5 a magnetic flux producer; and

a magnetic flux distribution controller which, in cooperation with the magnetic flux producer, is operative to produce a varying magnetic force on a ferromagnetic surface adjacent to the magnetic assembly by varying an air gap distance therebetween and/or a surface area of the magnetic flux distribution controller in
10 proximity with the ferromagnetic surface, wherein the magnetic flux distribution controller having a rotational profile defined by an entire perimeter of the magnetic flux distribution controller configured to be in proximity with the ferromagnetic surface to provide the air gap distance during rotation of the magnetic flux distribution controller.

15 According to another aspect of the invention, a method of operating a robot capable of performing surface transition on ferromagnetic surfaces is provided. The method comprises:

moving a mobile robot along one of the ferromagnetic surfaces by rotating wheel assemblies of the mobile robot; and

20 performing, by one of the wheel assemblies, surface transition between the ferromagnetic surfaces by rotating a magnetic flux distribution controller and a non-magnetic wheel coupled thereto and,

while maintaining the non-magnetic wheel in contact with an adjacent ferromagnetic surface, varying an air gap distance between the magnetic flux distribution controller and an adjacent ferromagnetic surface, and/or a surface area of
25 the magnetic flux distribution controller in proximity with the ferromagnetic surface, to vary a magnetic force on the adjacent ferromagnetic surface, wherein the magnetic flux distribution controller having a rotational profile defined by an entire perimeter of the magnetic flux distribution controller configured to be in proximity with the
30 ferromagnetic surface to provide the air gap distance during rotation of the magnetic flux distribution controller.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention are disclosed hereinafter with reference to the drawings, in which:

35 Figures 1A to 1D illustrate a surface transition sequence of a mobile robot from a vertical surface to an overhead surface, according to one embodiment of the invention;

Figure 2 includes an exploded view (on left side of figure) of a non-driven magnetic wheel assembly and a front view (on right of figure) a non-driven magnetic wheel assembly according to one embodiment of the invention;

40 Figures 3A to 3G illustrate a various examples of a mild steel plate;

Figures 4A and 4B illustrate a surface transition from a horizontal surface to a vertical surface;

Figures 5A and 5B illustrate a surface transition from a vertical surface to a horizontal surface;

5 Figures 6A and 6B illustrate a surface transition from a first vertical surface to a second vertical surface;

Figures 7A and 7B illustrate a surface transition from a vertical surface to an overhead surface;

10 Figures 8A and 8B illustrate a surface transition from an overhead surface to a vertical surface;

Figure 9 shows the torque required in various transition types for various mild steel shapes;

Figures 10A to 10D illustrate a surface transition sequence of a mobile robot from a vertical surface to an overhead surface, according to one embodiment of the invention;

15 Figures 11A to 11C illustrate a surface transition sequence of a mobile robot from a vertical surface to an overhead surface, according to one embodiment of the invention;

Figures 12A to 12D illustrate a surface transition sequence of a mobile robot from a horizontal surface to a vertical surface, according to one embodiment of the invention;

20 Figure 13A is an exploded view of a driven wheel assembly according to one embodiment of the invention;

Figure 13B is a front view of the driven wheel of Figure 13A;

Figures 14A and 14B illustrate a surface transition from a horizontal surface to a vertical surface;

25 Figures 15A and 15B illustrate a surface transition from a vertical surface to an overhead surface;

Figures 16A and 16B illustrate a surface transition from an overhead surface to a vertical surface; and

Figures 17A to 17E illustrate a surface transition sequence of a mobile robot from a horizontal surface to a vertical surface, according to one embodiment of the invention.

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DETAILED DESCRIPTION

In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative embodiments of the invention. It will be understood, however, to one skilled in the art, that embodiments of the invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure pertinent

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aspects of embodiments being described. In the drawings, like reference numerals refer to same or similar functionalities or features throughout the several views.

Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

As used herein, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements.

As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.

As used herein, the terms “first,” “second,” and “third,” etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

As used herein, the terms “operative”, “adapted to” and “configured to” are interchangeable.

As used therein, the term “coupled” and related terms are used in an operational sense and are not necessarily limited to a direct physical connection or coupling. Thus, for example, two devices may be coupled directly, or via one or more intermediary devices.

In accordance with some implementations of one embodiment of the invention, Figures 1A to 1D illustrate a surface transition sequence of a mobile robot 10 from a vertical surface to an overhead surface. During the illustrated transition, relative magnetic forces acting on the surfaces vary and, throughout Figures 1A to 1D, the variation is represented by the size, e.g. width, of the arrows originating from a rear wheel. Progressing from Figure 1A to 1B, magnetic force acting on the vertical surface decreases. Progressing from Figure 1B to 1C, magnetic force acting on the vertical surface decreases further, while magnetic force acting on the overhead surface increases. Progressing from Figure 1C to 1D, magnetic force

acting on the overhead surface increases further while magnetic force on the vertical surface decreases.

In accordance with some implementations of another embodiment of the invention, Figures 12A to 12D illustrate a surface transition sequence of a mobile robot 10 from a horizontal surface to a vertical surface. During the illustrated transition, relative magnetic forces acting on the surfaces vary and, throughout Figures 12A to 12D, the variation is represented by the size, e.g. width, of the arrows originating from a front wheel. Progressing from Figure 12A to 12B, magnetic force acting on the horizontal surface decreases. Progressing from Figure 12B to 12C, magnetic force acting on the horizontal surface decreases further, while magnetic force acting on the vertical surface increases. Progressing from Figure 12C to 12D, magnetic force acting on the vertical surface increases further while magnetic force on the horizontal surface decreases further or becomes non-existent.

Mobile Robot and its Components

According to embodiments of the invention, a mobile robot 10 comprises a chassis 12, at least one driven magnetic wheel assembly 14 rotatably mounted to the chassis 10 and operative to drive the chassis 12, at least one non-driven magnetic wheel assembly 16 rotatably mounted to the chassis 12.

The mobile robot 10 may be any motorized or automotive apparatus which is capable of moving along surfaces e.g. ferromagnetic surfaces, and performing surface transition. The mobile robot 10 may be controlled by wired connection or wireless means. The mobile robot 10 can be employed in various operations, including but not limited to welding, blasting, inspection, installation work, etc., which are associated with magnetic surfaces in confined-areas or at elevated height, where accessibility is hard and/or hazardous for humans.

The chassis 12 may be a carriage or housing which supports a payload. The chassis 12 may include at least a first axis and a second axis. One or more wheels may be rotatably mounted to each axis. In some examples, the first and the second axes may be parallel to each other.

At least one driven magnetic wheel assembly 14 (also referred to as "driven wheel") is rotatably mounted to the chassis 12, e.g. the first axis thereof, and operative by motor or other actuation means to drive the chassis 12. This wheel assembly 12, e.g. front wheel, may further be rotatable about its own axis which may be different from the first axis. In examples where two or more driven wheels are provided, the driven wheels may be controlled or maneuvered by one or more motors or actuation means.

At least one non-driven wheel assembly 16 (also referred to as “non-driven wheel”) is rotatably mounted to the chassis 12, e.g. the second axis thereof, and operative to be driven or actuated by the driven wheel 14.

The driven magnetic wheel assembly 14 or the non-driven magnetic wheel assembly 16 or both may each comprise a non-magnetic wheel 21 and a magnetic assembly 22 for producing and controlling distribution of magnetic flux, as further described below.

The non-magnetic wheel 21 is fixedly coupled to a shaft 31 which may be aligned to the appropriate axis of the chassis 12, depending on whether the magnetic assembly 22 for producing and controlling distribution of magnetic flux is arranged at the driven wheel or non-driven wheel. The non-magnetic wheel 21 is operative to maintain frictional contact with at least one of the ferromagnetic surfaces, by magnetic force generated by the magnetic assembly 22, while the mobile robot 10 is driven along surface or performing surface transition. The non-magnetic wheel 21 may be a circular / cylindrical component, or may take on other shapes as appropriate.

The magnetic assembly 22 is operably coupled to the shaft 31 common to the non-magnetic wheel 21 and, depending on the embodiment, the magnetic assembly 22 is operative to rotate with or independent of the non-magnetic wheel 21. They may be interposed by appropriate roller bearing and washers. The magnetic assembly 22 is operative to control and/or vary magnetic attraction force exerted on an adjacent ferromagnetic surface 1 by controlling and/or varying magnetic flux distribution around the magnetic assembly 22.

The magnetic assembly 22 comprises a magnetic flux producer and a magnetic flux distribution controller, and may be implemented in various ways, including but not limited to the following:

- (i) In some implementations, the magnetic flux producer comprises at least one source magnet, e.g. permanent magnet and/or electromagnet, while the magnetic flux distribution controller comprises a magnetically permeable structure. The permanent magnet or electromagnet is fixedly or removably attached to the magnetically permeable structure, e.g. mild steel, ferromagnetic material. The magnetically permeable structure is operative to cooperate with the permanent magnet or electromagnet to vary magnetic flux distribution at an area on an adjacent or proximate ferromagnetic surface 1 being currently traversed by the relevant wheel assembly (hereinafter “current

workpiece surface”) and thereby vary magnetic force on the current workpiece surface 1.

In some examples of the implementations of (i), the magnet (permanent or electromagnet) is interposed between a pair of mild steel plates. In some other examples, the magnet is arranged adjacent to or juxtaposed with a single mild steel plate. In some other examples, the magnet may be provided as a plurality of magnets. In yet some other examples the magnetically permeable structure may be a unitary structure. Other examples or combinations of the above examples are possible.

(ii) In some implementations, the magnetic flux producer and the magnetic flux distribution controller are integrally provided, e.g. by a source magnet which, by itself, produces magnetic flux as well as controls magnetic flux distribution. In other words, the magnetic flux controller refers to or is provided by the magnetic flux producer.

In Figure 2A, in accordance with implementations of (i), the magnetic flux producer, e.g. permanent magnet 222, and magnetic flux distribution controller, e.g. mild steel plates 224, are provided at the non-driven wheel 16, e.g. rear wheel. More particularly, the permanent magnet 222 or electromagnet is interposed between and fixedly coupled to the two mild steel plates 224. Roller bearing 24 and washers 25 may be coupled to the shaft 31 and interposed between non-magnetic wheel 21 and mild steel plates 224. A wheel cover 29a may be provided to retain the non-magnetic wheel 21 and magnetic assembly 22 in place.

In Figures 13A and 13B, in accordance with implementations of (ii), the magnetic flux producer, e.g. permanent magnet 222, and magnetic flux distribution controller, e.g. flux guides 224, are provided at the driven wheel 14, e.g. front wheel. More particularly, a permanent magnet 222 or electromagnet is interposed between and fixedly coupled to two flux guides 224. A gearbox assembly 40 may be provided and operably coupled to the driven wheel 14 through the shaft 31 common thereto. Locator pins 26 may be interposed between flux guides 224, and also between the gearbox assembly 40 and each flux guide 224. Bearing 24, spacer 27 and/or key 28 may be provided between each flux guide 224 and a non-magnetic wheel 21. A stopper 29b may be provided to retain the non-magnetic wheel 21 and magnetic assembly 22 in place.

Operation

In operation, the mobile robot 10 may be moved along ferromagnetic surfaces by rotating the driven and non-driven wheel assemblies, e.g. actuating the driven wheel assembly 14 and allowing the non-driven wheel assembly 16 to be actuated by the driven wheel assembly 14. When the magnetic assembly or its components are disposed in very close proximity or adjacent to the current workpiece surface 1, a closed loop magnetic circuit is formed among the magnetic flux producer, magnetic flux distribution controller and the current workpiece surface 1 which is directly under the magnetic assembly 22.

A reluctance between the magnetic flux distribution controller and the current workpiece surface 1 can be varied. Its variation depends on the shape, position and orientation of the magnetic flux distribution controller with respect to the current workpiece surface 1. Changes in reluctance affect or vary the amount of magnetic flux passing through them and, consequently, a magnetic force between the magnetic flux distribution controller and the current workpiece surface 1 changes or varies. To reduce or decrease the magnetic force, either the surface area of the magnetic flux distribution controller in predetermined or close proximity to the current workpiece surface has to be decreased, or the distance between the magnetic flux distribution controller and the current workpiece surface has to be increased, so that a decreased magnetic flux is produced. On the other hand, to increase magnetic force on the current workpiece surface 1, either the surface area of the magnetic flux distribution controller that is in predetermined or close proximity to the current workpiece 1 has to be increased, or the distance between the magnetic flux distribution controller and the current workpiece surface 1 has to be decreased, so that an increased magnetic flux is produced.

To perform surface transition by a relevant wheel, its magnetic flux distribution controller is rotated while the non-magnetic wheel 21 may be continually and freely rotating. During this rotation, the non-magnetic wheel 21 maintains contact with an adjacent ferromagnetic surface while (i) a gap distance between the magnetic flux distribution controller and the adjacent ferromagnetic surface and/or (ii) a surface area of the magnetic flux distribution controller in proximity with the surfaces varies. The aforementioned adjacent ferromagnetic surface may refer to surface 1 in Figures 1A to 1D if the relevant wheel is the rear wheel, or to surface 2 in Figures 12A to 12D if the relevant wheel is the front wheel, as further described below.

In the implementation shown by Figures 1A to 1D, the above-described magnetic assembly 22 is provided at the non-driven wheel, e.g. rear wheel, and the magnetic flux distribution controller is provided as having a semi-circle shape. As the non-driven wheel

progressively approaches a surface 2 where it is to land or transit to (hereinafter “destination workpiece surface”), surface area of the semi-circular shape proximate to the current workpiece surface 1 decreases which reduces the magnetic flux distribution and magnetic attraction force between the magnetic assembly 22 and the current workpiece surface 1 (see
5 Figures 1B and 1C). On the other hand, a gap distance between the non-driven wheel and destination workpiece surface 2 decreases. This reduction in gap distance increases magnetic attraction force between the magnetic assembly 22 and the destination workpiece surface 2. As such, a force required to detach the non-driven wheel from the current workpiece surface 1 is reduced whilst adhesion force of the driven wheel to the destination
10 workpiece surface 2 is stronger or increased. The shape of the magnetic flux distribution controller may, in this and/or other implementation, be appropriately designed such that the non-driven wheel will land on the destination workpiece surface 2 at the position where a surface area of the magnetic flux distribution controller in proximity with the destination workpiece surface 2 is larger or largest, hence producing greater or greatest magnetic
15 attraction force on surface 2.

In the implementation shown by Figures 12A to 12D, the above-described magnetic assembly 22 is provided at the driven wheel, e.g. front wheel, and the magnetic flux distribution controller is provided as having a tear-drop shape. As the driven wheel progressively approaches a destination workpiece surface 2, the driven wheel first contacts
20 the destination workpiece surface 2 (see Figure 12B). When the robot or its driven wheel contacts the surface 2, most of the magnetic flux is redirected to the surface 2 due to a larger surface area in proximity with the surface 2. This results in a reduction of magnetic flux directed to the current workpiece surface 1. Also in Figure 12C, an air gap distance between magnetic flux distribution controller and surface 1 increases, thus decreasing the
25 magnetic attraction force between the magnetic assembly 22 and the surface 1. As such, a force required to detach the driven wheel from the current workpiece surface 1 is lesser or reduced whilst adhesion of the driven wheel to the destination workpiece surface 2 is stronger or increased.

In some embodiments, at least the magnetic assembly and/or various wheels may be
30 customized to parameters, e.g. dimensions, of the workpiece. In designing the magnetic assembly, relative arrangement, e.g. positioning and assembly of the magnetic flux producer and magnetic flux distribution controller with respect to the workpiece, have to be considered to ensure production of sufficient magnetic forces for carrying payload. The magnetic flux distribution controller is appropriately shaped and arranged to provide a gap or separation
35 (see Figures 2B and 13B) between the current workpiece surface and the magnetic flux distribution controller. This gap may be varied e.g. increased and/or decreased, while the

robot traverses the current workpiece surface, to vary magnetic flux distribution which in turn varies magnetic attraction force between the magnetic assembly of the relevant wheel assembly and the current and/or destination workpiece surface.

Suitable shapes of magnetic flux distribution controller may be non-conforming or different with the shape of the non-magnetic wheel. Figures 3A to 3G illustrate possible but non-exhaustive shapes of magnetic flux distributor controller, e.g. mild steel plates. Such shapes include a circle with a cut-out portion of any shape including but not limited to a rectangular, square, sector, or curved cut-out (e.g. Figures 3A, 3C and 3D), a sector of a circle (e.g. minor sector Figure 3B, major sector which is not illustrated), a tear-drop (e.g. Figures 3E and 3F), an amalgamated circle with rectangle or square (e.g. Figure 3G). In various examples, these shapes may be varied by varying their parameters including, but not limited to, angles, widths, lengths, depth, curvature.

Various surface transitions were experimented – Horizontal to Vertical (H2V), Vertical to Horizontal (V2H), Vertical to Vertical (V2V), Vertical to Overhead (V2O), Overhead to Vertical (O2V). The torque required was also measured to determine which magnetic wheel configuration required least torque.

Experiments were performed using a robot prototype wherein the invention is applied to non-driven or caster wheels of the robot. Figures 4 to 8 show schematic representations of this robot prototype performing various surface transitions in a confined-space structure and using one of the mild steel shapes in the magnetically permeable structure. Figures 4A and 4B illustrate a surface transition from a horizontal surface to a vertical surface. Figures 5A and 5B illustrate a surface transition from a vertical surface to a horizontal surface. Figures 6A and 6B illustrate a surface transition from a first vertical surface to a second vertical surface. Figures 7A and 7B illustrate a surface transition from a vertical surface to an overhead surface. Figures 8A and 8B illustrate a surface transition from an overhead surface to a vertical surface.

From the experiments, the various surface transitions were successful. Motor torques required for the transition of the caster wheel were recorded against each mild steel shape to determine which mild steel shape required least torque (see Figure 9). The torques of the two mild steel shape plates (represented by T0P0 and T0P15 in Figure 9) which were tested are compared against a normal magnetic wheel (represented by Normal in Figure 9), along with the standard deviation as illustrated in Figure 9.

From Figure 9, it can be observed that the embodiments under tests, which uses different mild steel shaped plates, requires lesser torque for a successful surface transition

compared to using a normal magnetic wheel. A lower torque requirement results in lesser stress on the motors resulting from detaching the caster or non-driven wheel from the previous workpiece surface.

Experiments were performed using another robot prototype wherein the invention is applied to a driven wheel of the robot. Figures 14 to 16 show schematic representations of this robot prototype performing various surface transitions in a confined-space structure. Figures 14A and 14B illustrate a surface transition from a horizontal surface to a vertical surface. Figures 15A and 15B illustrate a surface transition from a vertical surface to an overhead surface. Figures 16A and 16B illustrate a surface transition from an overhead surface to a vertical surface.

Variations to the above embodiments may be envisaged, as follows.

For example, one or more driven wheel assemblies may be provided as front wheel(s) while one or more non-driven wheel assemblies may be provided as rear wheel(s). Alternatively, one or more driven wheel assemblies may be provided as rear wheel(s) while one or more non-driven wheel assemblies may be provided as rear wheel(s). Alternatively, driven wheel assemblies may be provided as front and rear wheels.

For example, Figures 10A to 10D illustrate a surface transition sequence of a mobile robot 10 from a vertical surface to an overhead surface, according to one embodiment of the invention. In this embodiment, the non-driven wheel assembly includes mechanical control to control or adjust the magnetic force that will be exerted on the current workpiece surface at any one time. Such mechanical control may include controlling or adjusting the position and orientation of the magnetically permeable structure with respect to the non-magnetic wheel independently (see Figures 11A to 11C), and/or partitioning the total magnetic flux by managing the position or orientation of the magnetic assembly, e.g. magnetically permeable structure, with respect to the two adjacent ferromagnetic walls, e.g. current and destination workpiece surfaces, and/or the quantity and shapes of mild steel plates used (Figures 10A to 10D). This will allow better control of the magnetic flux during surface transition and reduce or eliminate reliance on the rotation of the chassis in the earlier embodiments. In another example, Figures 17A to 17E illustrate a surface transition sequence of a mobile robot from a horizontal surface to an overhead surface, according to one embodiment of the invention. In this embodiment, the driven wheel assembly includes active mechanical control to control or adjust the magnetic force that will be exerted on the current workpiece surface at any one time, as described in relation to Figures 11A to 11C.

Embodiments of the invention provide several advantages including, but not limited to, the following:

- The invention allows the driven wheel(s) or non-driven wheel(s) or both to be provided with magnetic flux distribution control.
- The invention does not require additional mechanism to aid surface transition, thus reducing the overall complexity and size of the robot. The invention allows horizontal force acting on the relevant wheel to be sufficiently reduced and below the driving force limitation of the motors, but at the same time able to meet the requirement on the minimum force required for vertical to overhead transition. This will allow a smoother transition and prevents additional stress onto the wheel shaft and robot chassis. By using a magnetic flux distribution controller to vary an air gap from a current and/or destination workpiece surface, or vary a surface area of the controller in proximity with a current and/or destination workpiece surface, or vary both, magnetic flux distribution is varied and therefore magnetic attraction force acting between the magnetic assembly and the current workpiece surface is varied. For example, by increasing the gap, the magnetic attraction force is decreased therefore the wheel can be detached from the current workpiece surface with lower motor torque requirement. For example, by decreasing surface area of the controller in proximity with the current workpiece surface, magnetic attraction force therebetween is decreased therefore the wheel can be detached from the current workpiece surface with lower motor torque requirement. By reducing this magnetic attraction force, motor torque required to detach the relevant wheel from the surface is reduced.
- The invention allows a robot to be customised to a workpiece, i.e. by replacing the magnetic assembly and/or the magnetically permeable structure with another which is dimensioned and/or shaped to suit parameters, e.g. dimensions, of the workpiece.
- Reduced power requirements due to non-powered rear wheel for surface transition.
- Increased payload for same power input.
- Improved compactness of the whole robot chassis.

Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments of the invention.

What is claimed is:

1. A mobile robot capable of performing surface transition on ferromagnetic surfaces, the robot comprises:

a chassis;

at least one driven magnetic wheel assembly rotatably mounted to the chassis and operative to drive the chassis; at least one non-driven magnetic wheel assembly rotatably mounted to the chassis,

wherein at least the driven magnetic wheel assembly or the non-driven magnetic wheel assembly comprises:

a non-magnetic wheel operative to maintain contact with one of the ferromagnetic surfaces;

a magnetic assembly rotatably coupled to the non-magnetic wheel, wherein the magnetic assembly comprises:

a magnetic flux producer; and

a magnetic flux distribution controller which, in cooperation with the magnetic flux producer, is operative to produce a varying magnetic force on a ferromagnetic surface which is adjacent to the magnetic assembly by varying an air gap distance therebetween and/or a surface area of the magnetic flux distribution controller in proximity with the ferromagnetic surface, wherein the magnetic flux distribution controller having a rotational profile defined by an entire perimeter of the magnetic flux distribution controller configured to be in proximity with the ferromagnetic surface to provide the air gap distance during rotation of the magnetic flux distribution controller.

2. The mobile robot of claim 1, wherein the magnetic flux producer is a permanent magnet or an electromagnet, and wherein the magnetic flux distribution controller is a magnetically permeable structure.

3. The mobile robot of claim 2, wherein the permanent magnet or the electromagnet is interposed between the magnetically permeable structure.

4. The mobile robot of claim 1, wherein the magnetic flux producer and the magnetic flux distribution controller are integrally provided.

5. The mobile robot of any one of claims 1 to 4, wherein the magnetic flux producer and the magnetic flux distribution controller are rotatable about a same axis of rotation which is about the geometric centre of the magnetic flux distribution controller.
6. The mobile robot of any one of claims 1 to 5, wherein the shape of the magnetic flux distribution controller is one selected from the group consisting of a semi-circle, a tear-drop, circle with cut-out portion, a sector of a circle and an amalgamated circle with rectangle or square.
7. A method of operating mobile robot capable of performing surface transition on ferromagnetic surfaces, the method comprises:
 - moving a mobile robot along one of the ferromagnetic surfaces by rotating wheel assemblies of the mobile robot; and
 - performing, by one of the wheel assemblies, surface transition between the ferromagnetic surfaces by rotating a magnetic flux distribution controller and a non-magnetic wheel coupled thereto and,
 - while maintaining the non-magnetic wheel in contact with an adjacent ferromagnetic surface, varying an air gap distance between the magnetic flux distribution controller and an adjacent ferromagnetic surface, and/or a surface area of the magnetic flux distribution controller in proximity with the ferromagnetic surface, to vary a magnetic force on the adjacent ferromagnetic surface, wherein the magnetic flux distribution controller having a rotational profile defined by an entire perimeter of the magnetic flux distribution controller configured to be in proximity with the ferromagnetic surface to provide the air gap distance during rotation of the magnetic flux distribution controller.
8. The method of claim 7, wherein the one of the wheel assemblies comprises a driven wheel or a non-driven wheel.
9. The method of any one of claim 7 and claim 8, wherein the magnetic flux producer is a permanent magnet or an electromagnet, and wherein the magnetic flux distribution controller is a magnetically permeable structure.
10. The method of claim 9, wherein the permanent magnet or the electromagnet is interposed between the magnetically permeable structure.
11. The method of any one of claim 7 and claim 8, wherein the magnetic flux producer and the magnetic flux distribution controller are integrally provided.

12. The method of any one of claims 7 to 11, wherein the magnetic flux producer and the magnetic flux distribution controller are rotatable about a same axis of rotation which is about the geometric centre of the magnetic flux distribution controller.

13. The method of any one of claim 7 to claim 11, wherein the shape of the magnetic flux distribution controller is one selected from the group consisting of a semi-circle, a teardrop, circle with cut-out portion, a sector of a circle and an amalgamated circle with rectangle or square.