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Ross et al.

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(54) **ROBOTIC APPARATUSES, SYSTEMS AND METHODS**

(75) Inventors: **William P. Ross**, Saranac Lake, NY (US); **James F. Hoburg**, Baden, PA (US); **Christopher Fromme**, Sycamore, PA (US); **John Bares**, Wexford, PA (US); **Mark DeLouis**, Pittsburgh, PA (US)

(73) Assignee: **Carnegie Mellon University**, Pittsburgh, PA (US)

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(51) **Int. Cl.**[7] **G06F 19/00**

(52) **U.S. Cl.** **700/245**; 700/254; 700/257; 700/258; 700/260; 700/264; 104/281; 104/282; 104/138.1; 104/139; 104/283; 104/284; 104/286; 310/12; 310/90.5; 310/180; 310/181; 310/255

(58) **Field of Search** 310/90.5, 180, 310/181, 255, 12; 355/216, 299; 700/245, 254, 257, 258, 260, 264; 104/138.1, 139, 281–284, 286

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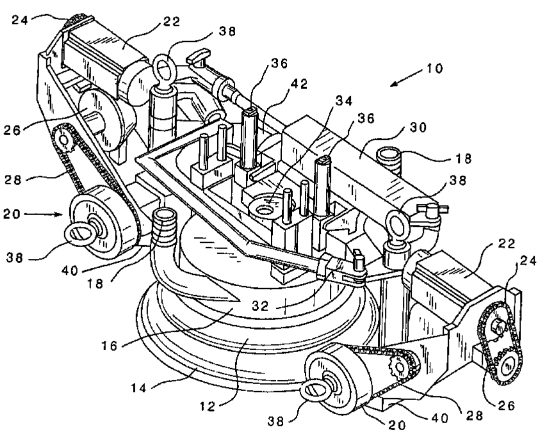
Primary Examiner—Thomas G. Black
Assistant Examiner—McDieunel Marc
(74) *Attorney, Agent, or Firm*—Kirkpatrick & Lockhart LLP

(57) **ABSTRACT**

A mobile device for traversing a ferromagnetic surface. The device includes a frame and at least one surface contacting device attached to the frame. The device also includes a Halbach magnet array attached to the frame, wherein the Halbach magnet array provides a magnetic force to maintain the surface contacting device substantially into contact with the ferromagnetic surface.

5 Claims, 12 Drawing Sheets



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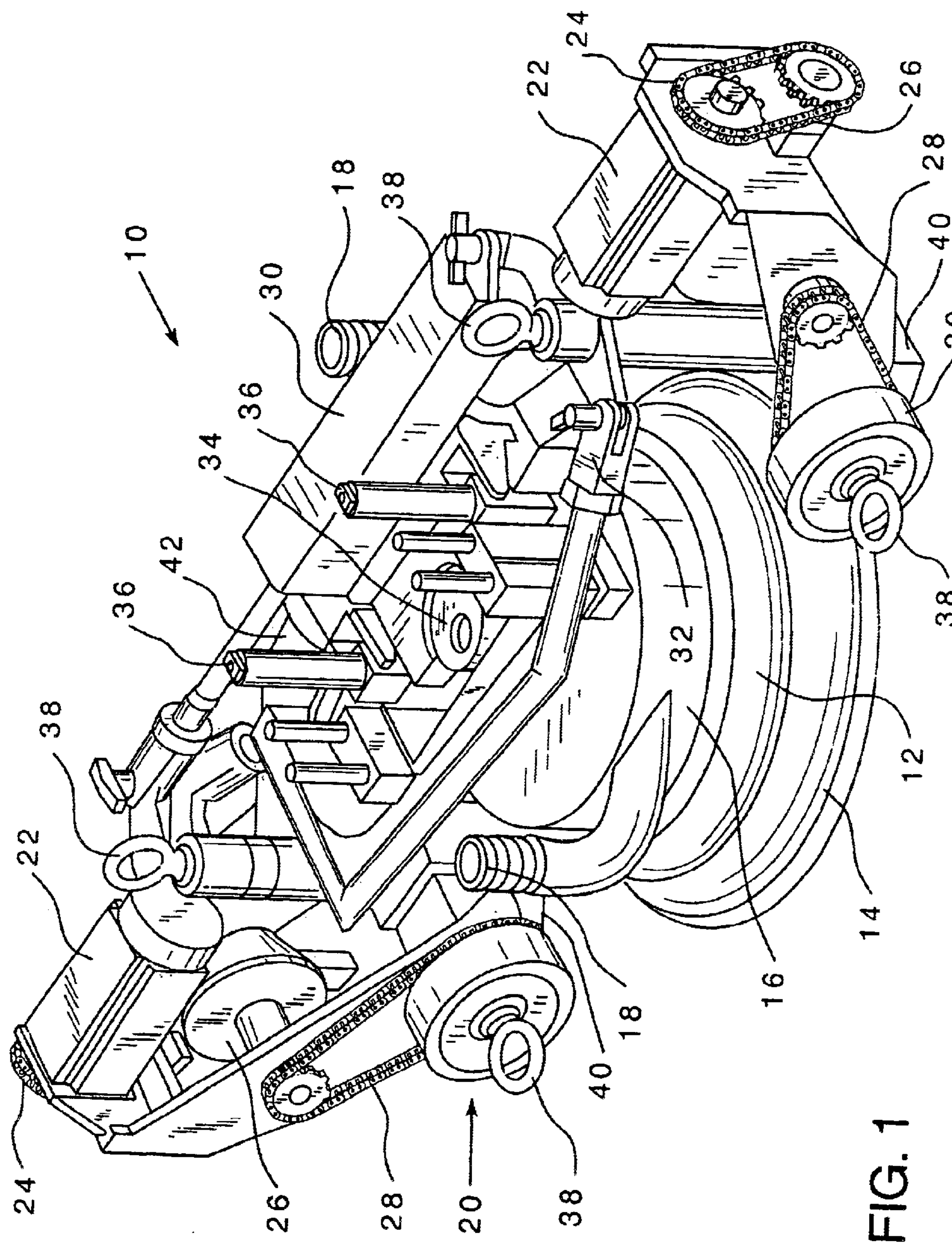
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18
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38
22
24
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12
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28
20
38
24

FIG. 1

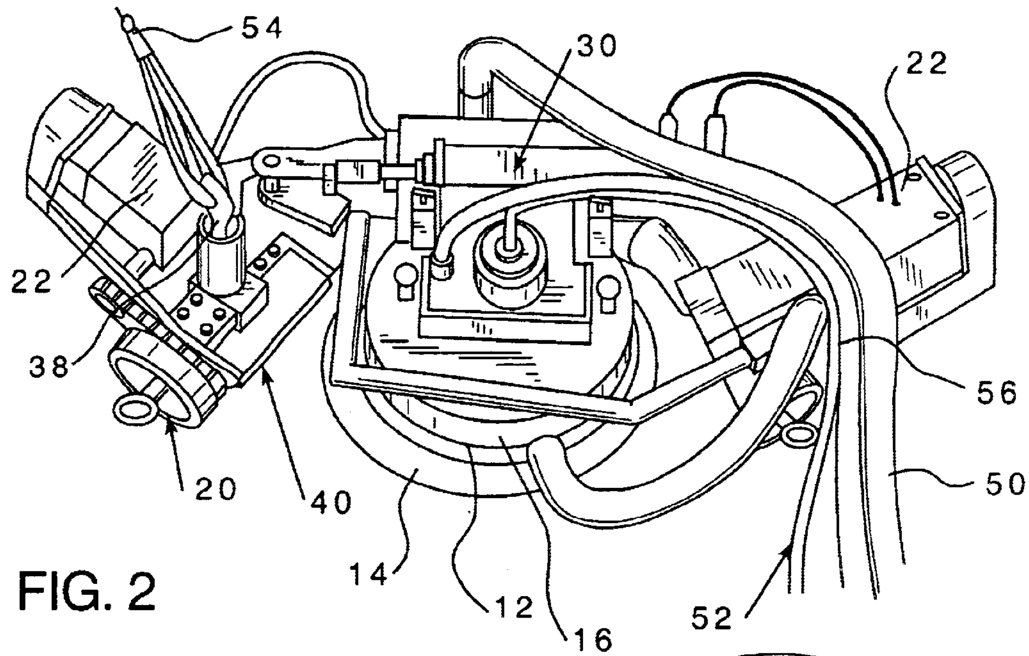

FIG. 2

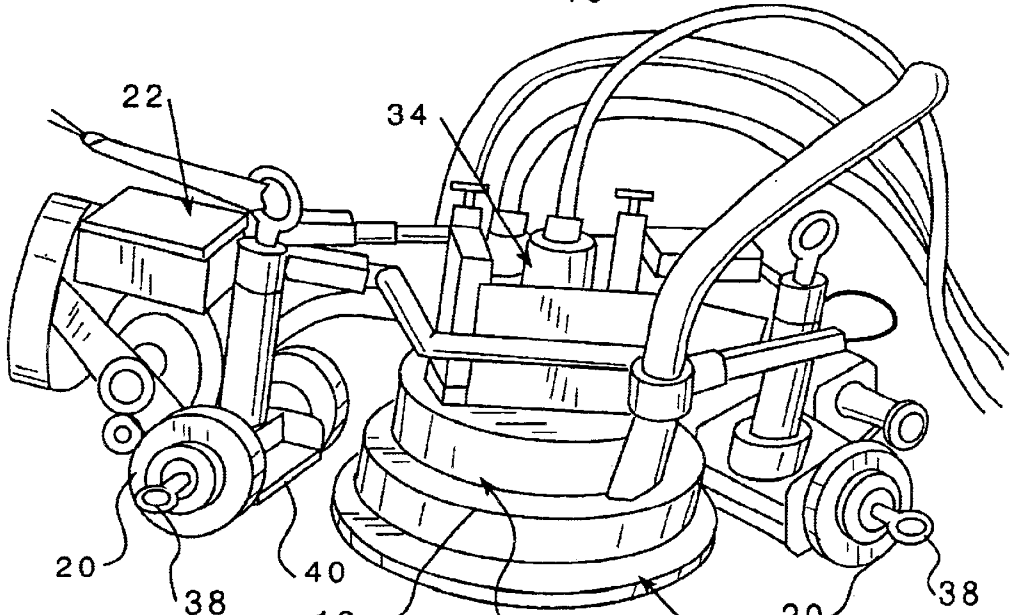

FIG. 3

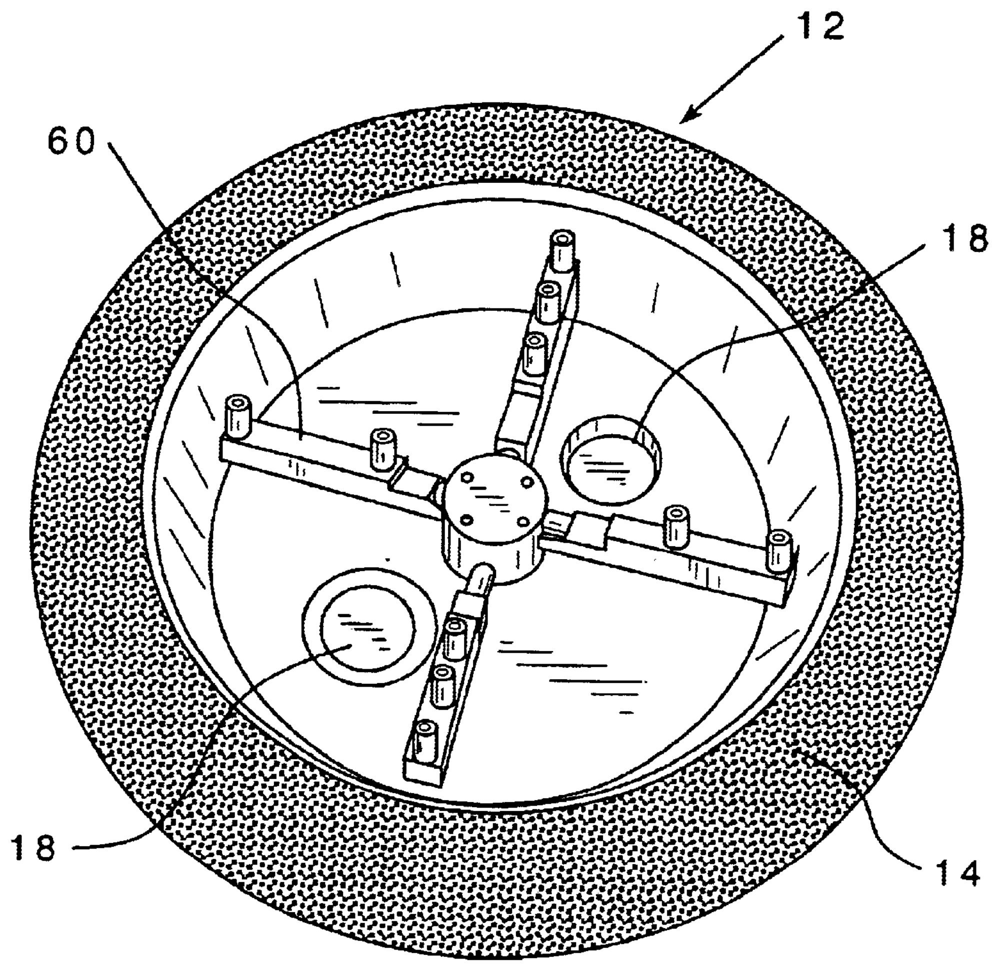

FIG. 4

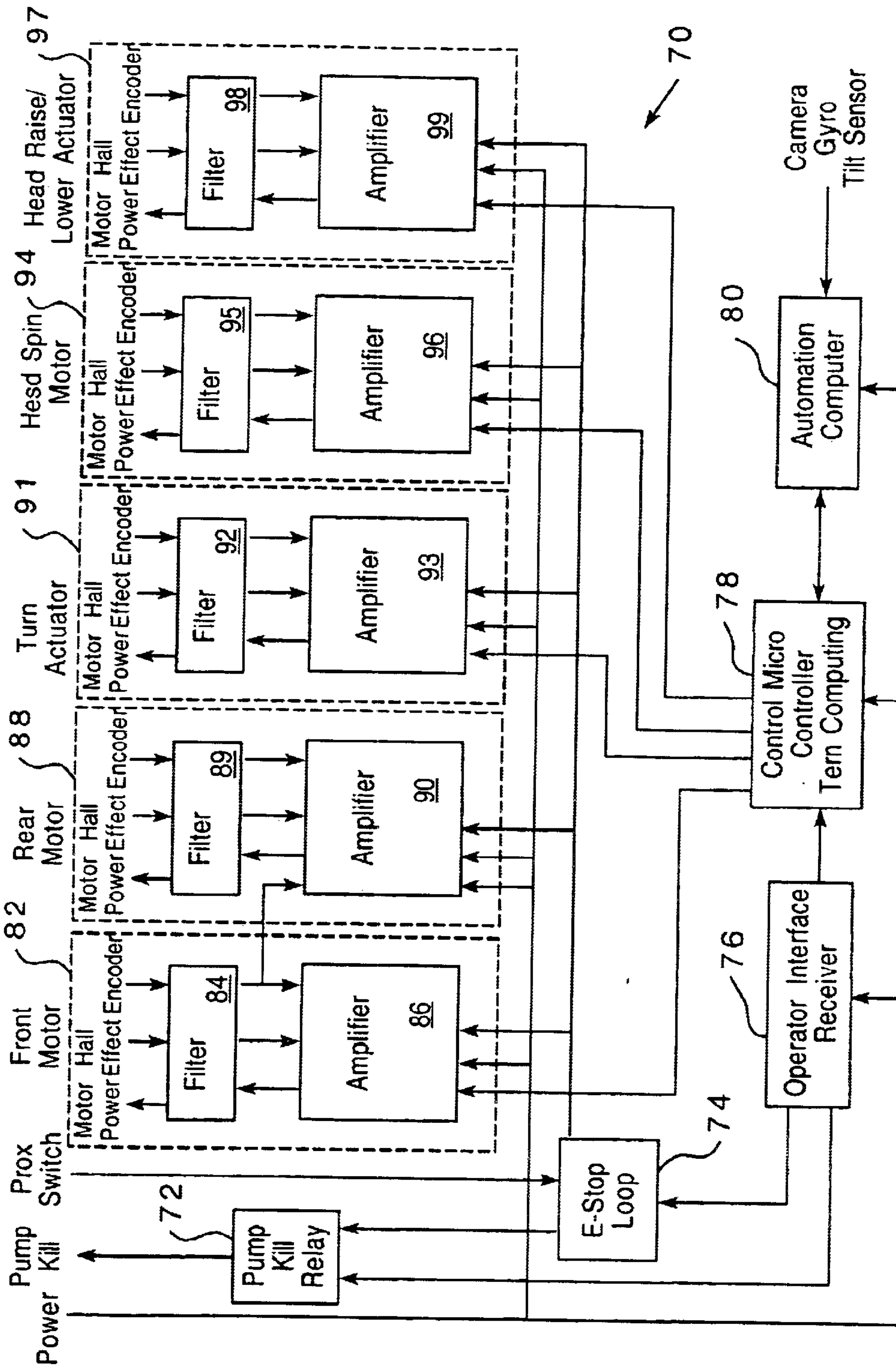
70
Head Raise/
Lower Actuator
97
Motor Hall
Power Effect Encoder
Filter
98
Amplifier
99
Hesd Spin
Motor
94
Filter
95
Amplifier
96
Turn
Actuator
91
Filter
92
Amplifier
93
Rear
Motor
88
Filter
89
Amplifier
90
Front
Motor
82
Filter
84
Amplifier
86
Prox
Switch
Pump
Kill
Power
72
Pump
Kill
Relay
E-Stop
Loop
74
Operator Interface
Receiver
76
Control Micro
Controller
Tern Computing
78
Automation
Computer
80
Camera
Gyro
Tilt Sensor

FIG. 5

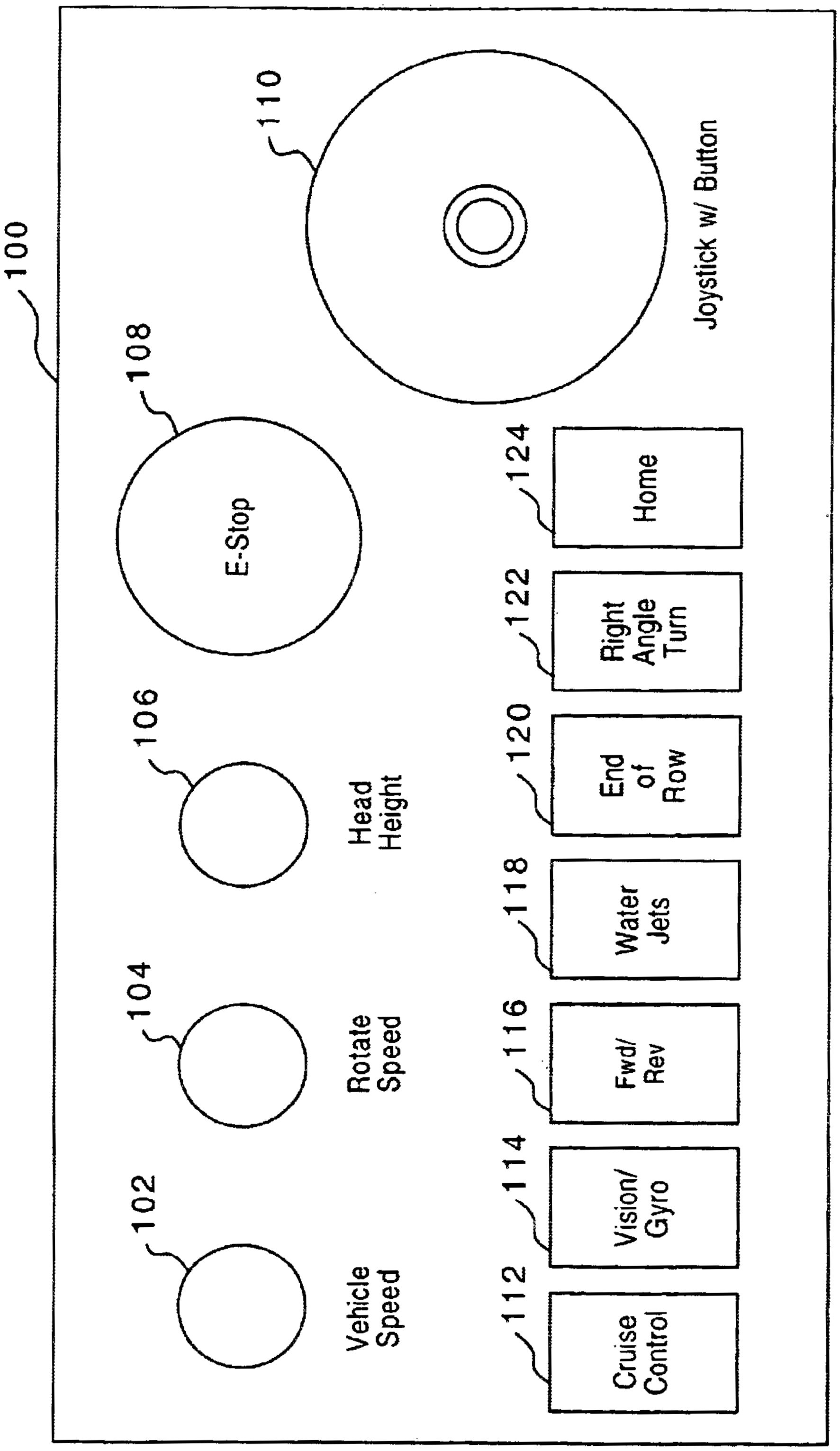
100
102
Vehicle Speed
104
Rotate Speed
106
Head Height
108
E-Stop
110
Joystick w/ Button
112
Cruise Control
114
Vision/ Gyro
116
Fwd/ Rev
118
Water Jets
120
End of Row
122
Right Angle Turn
124
Home

FIG. 6

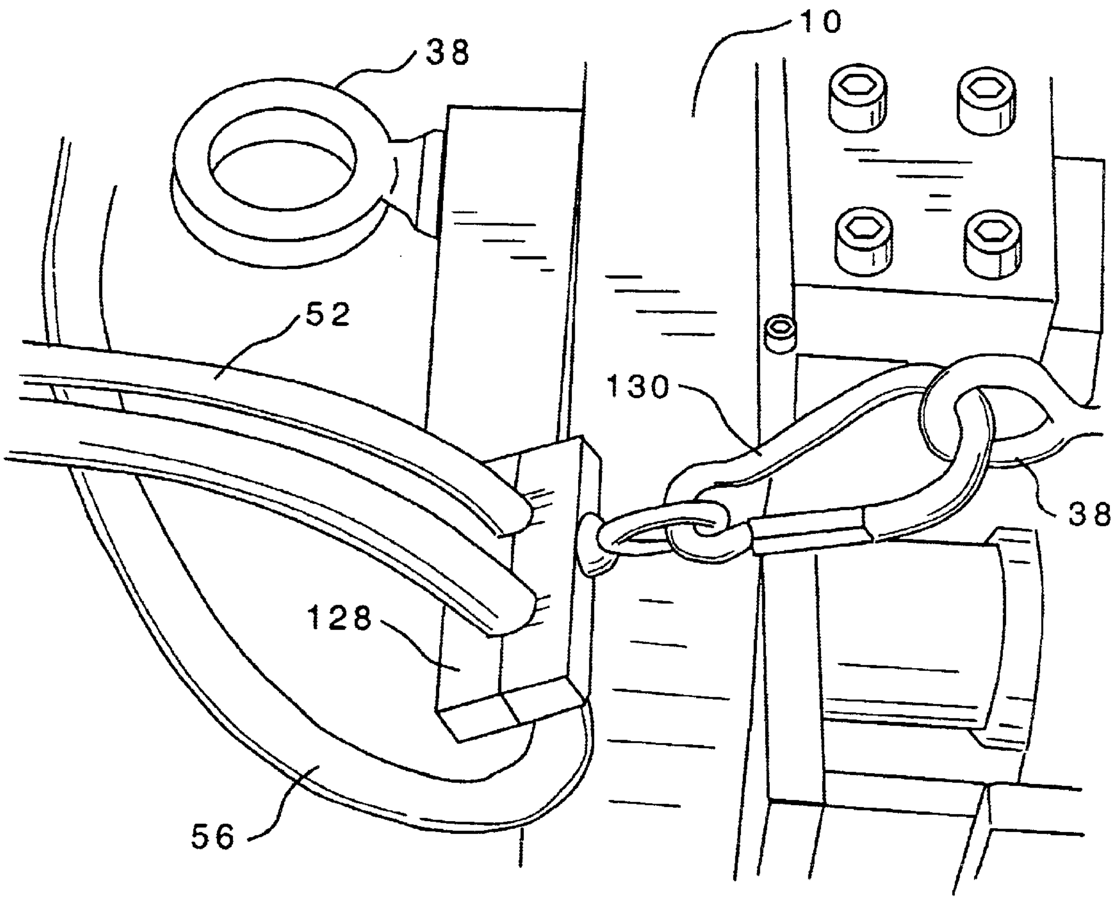

FIG. 7

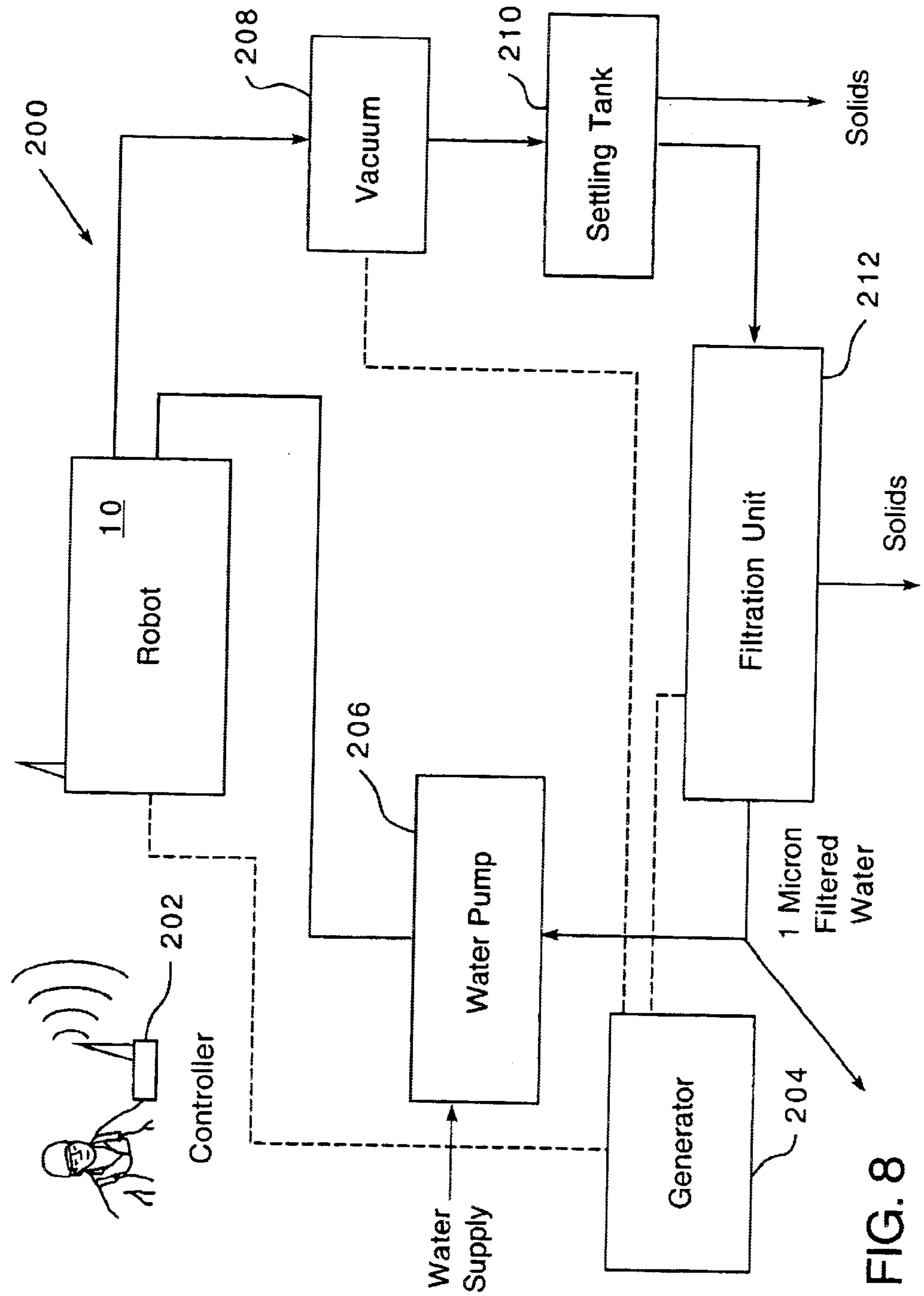
200
208
Vacuum
210
Settling Tank
Solids
212
Filtration Unit
Solids
10
Robot
206
Water Pump
1 Micron
Filtered
Water
202
Controller
Generator
204
Water
Supply

FIG. 8

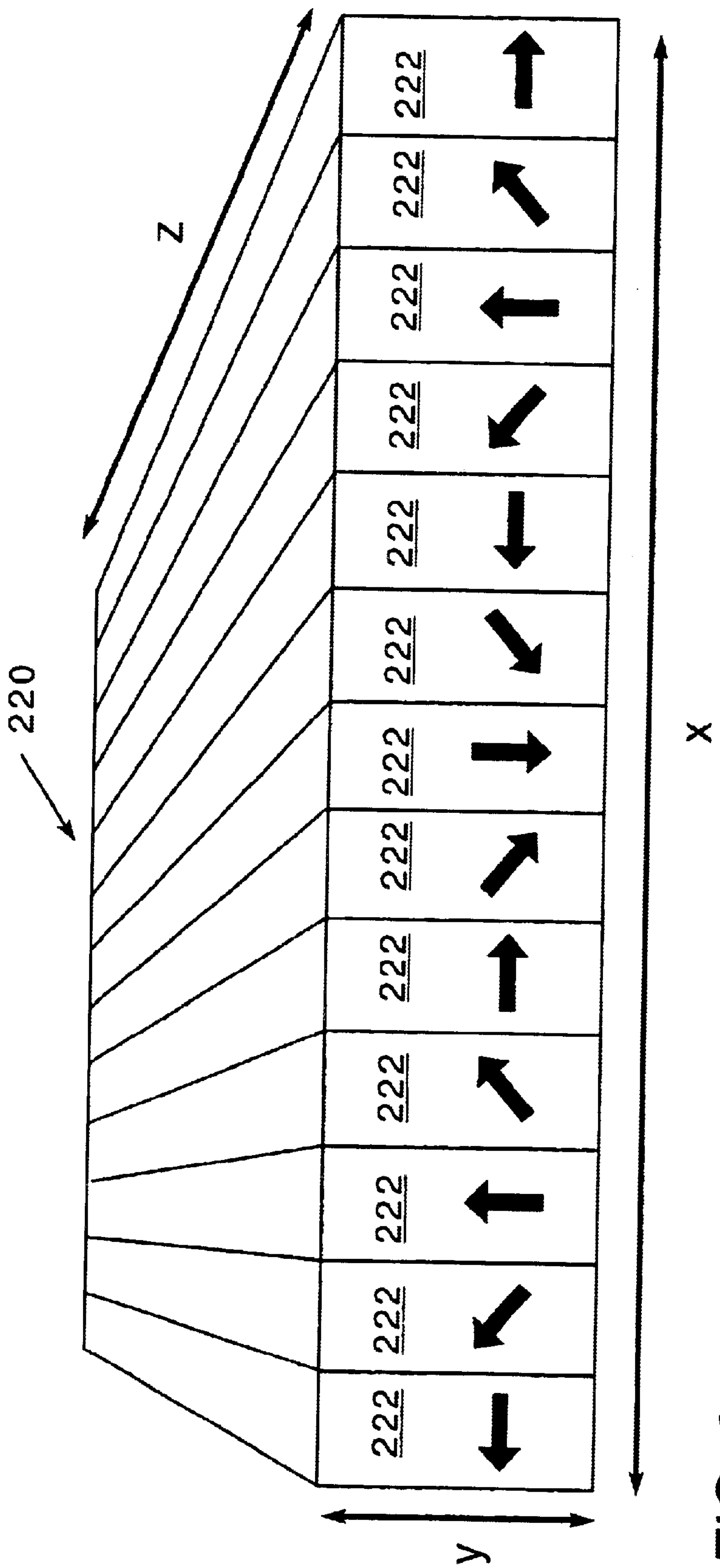

FIG. 9

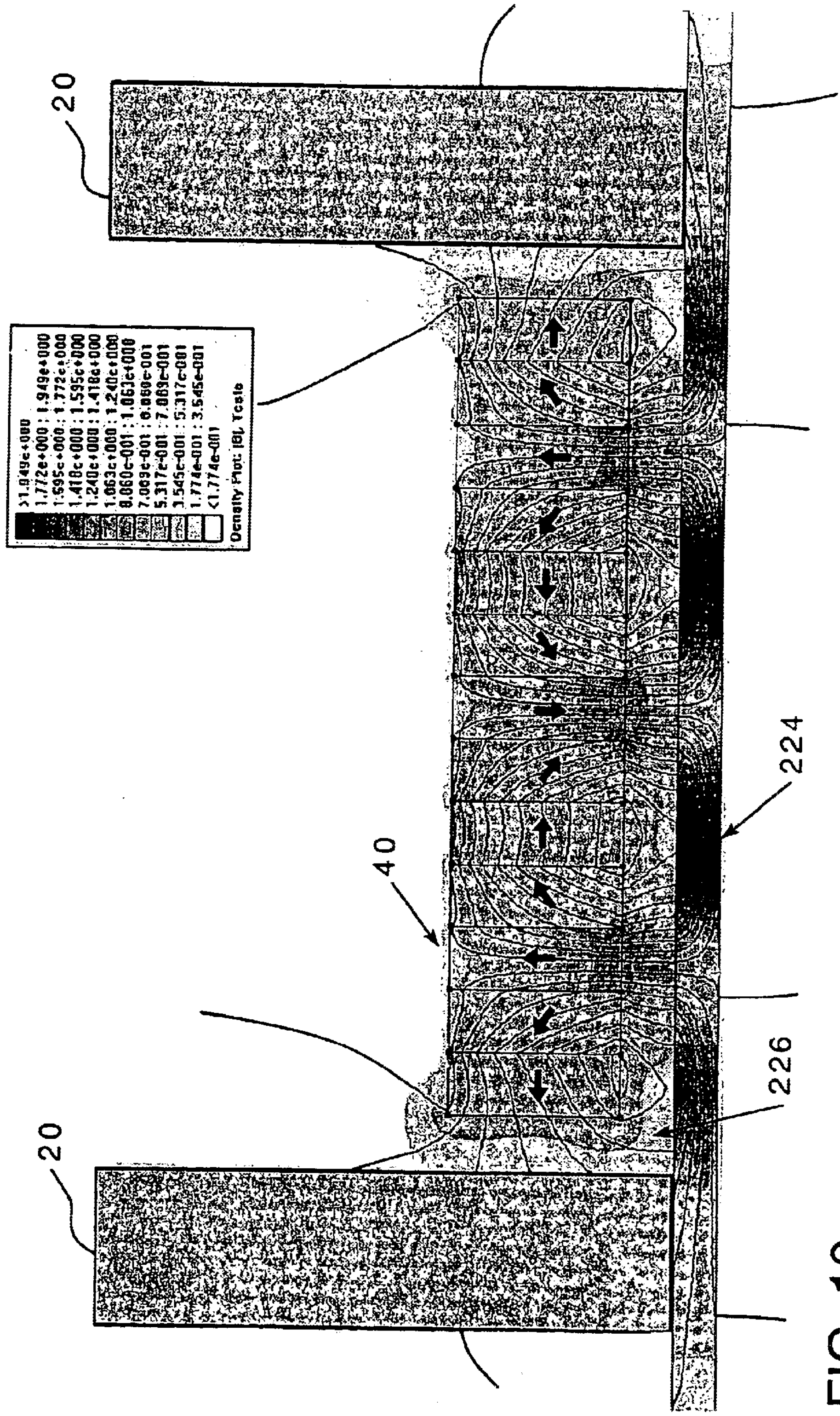

FIG. 10

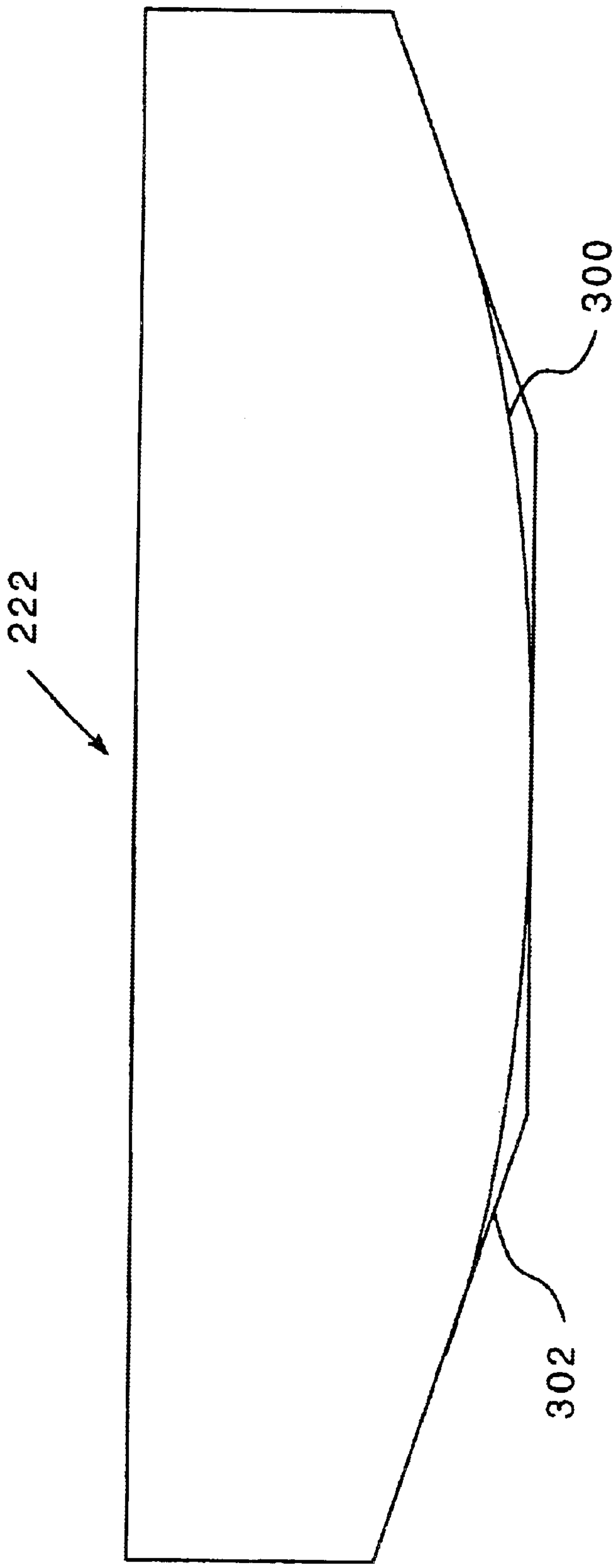

FIG. 11

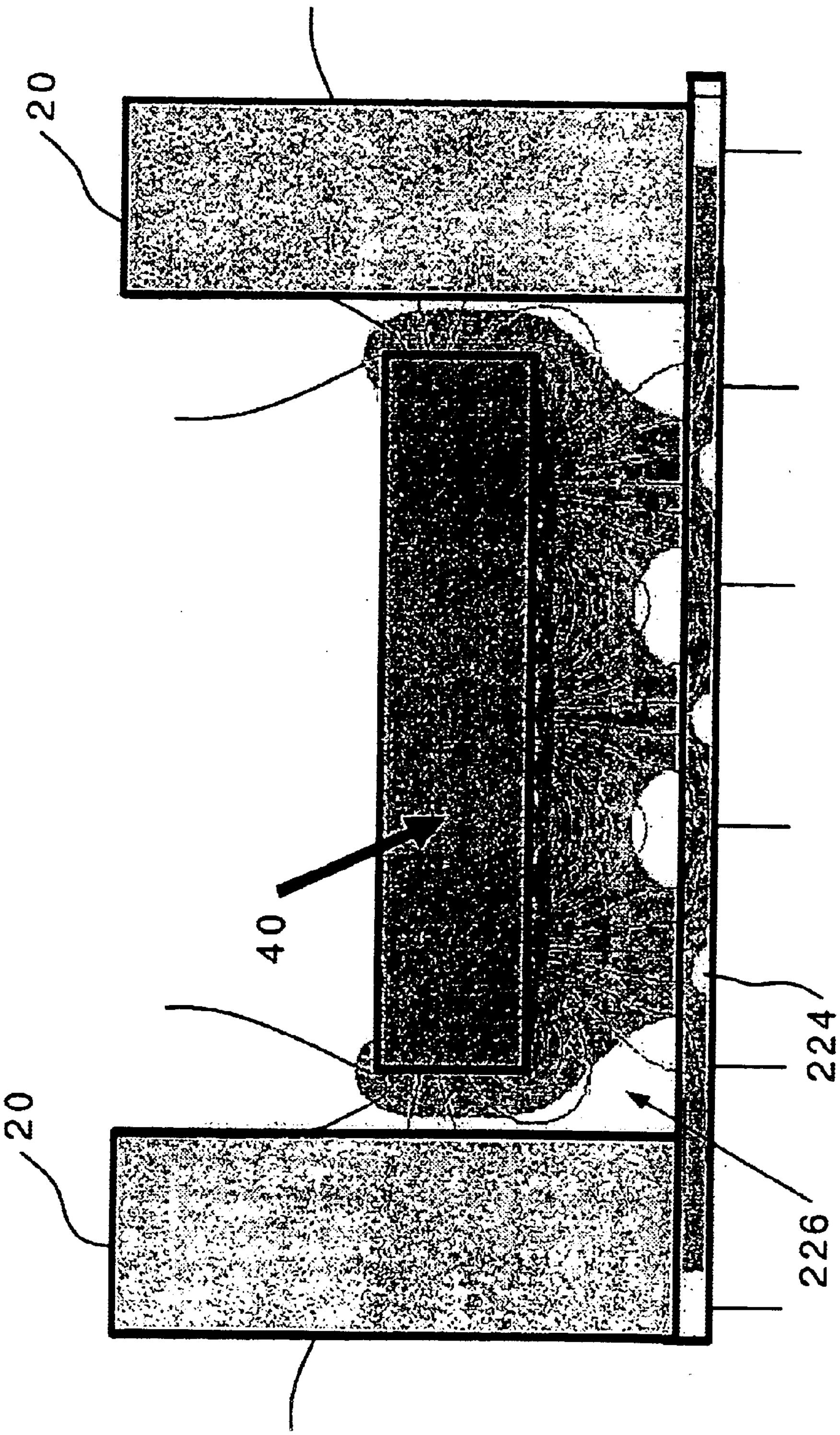

FIG. 12

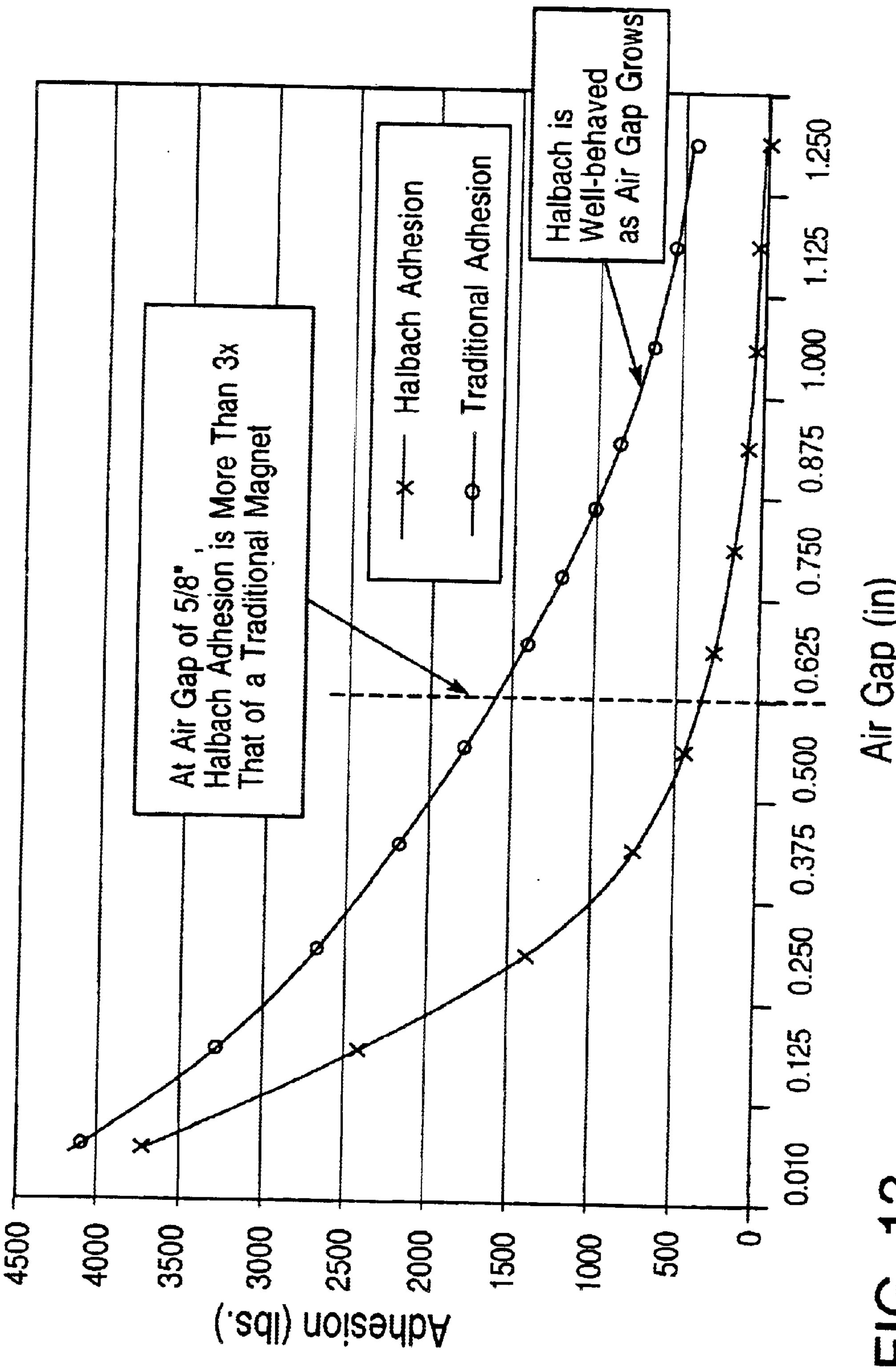
At Air Gap of 5/8", Halbach Adhesion is More Than 3x That of a Traditional Magnet
Halbach Adhesion
Traditional Adhesion
Halbach is Well-behaved as Air Gap Grows
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Adhesion (lbs.)
0.010
0.125
0.250
0.375
0.500
0.625
0.750
0.875
1.000
1.125
1.250
Air Gap (in)

FIG. 13

ROBOTIC APPARATUSES, SYSTEMS AND METHODS

CROSS REFERENCE TO RELATED APPLICATION

The present invention claims priority under 35 U.S.C. 119 to U.S. Provisional Patent Application No. 60/292,948 filed May 23, 2001.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was partially funded by the U.S. Government pursuant to NASA Grant No. NCC5-223. The U.S. Government may have certain rights in this invention.

BACKGROUND

Robotic devices have become increasingly prevalent in industrial settings where automation of hazardous, time-consuming, and precise operations is desirable. For example, robots have been employed to inspect and repair storage tanks, pipelines, and nuclear facilities, and to strip paint and to apply finishes.

In paint stripping operations, for example, the process of manually stripping paint and other finishes off of large structures such as storage tanks, ships, and bridges is a labor-intensive process that is often performed by humans using grit blasting or ultra high pressure (UHP) water jetting techniques and devices. Such techniques and devices, in addition to being labor-intensive, may also create waste disposal problems because, for example, in the case of grit blasting, the grit is intermixed with paint and coating particles (e.g. fungicides) and thus must be disposed of in an environmentally-friendly manner.

Various robotic devices have been developed for use in stripping paint from large structures. For example, the Flow Hydrocat™ manufactured by Flow International Corporation, uses a vacuum to attach to the surface being stripped. The Hydro-Crawler™, manufactured by JetEdge®, uses rigid magnetic tracks that attach to the surface being stripped and propel the robot on the surface.

SUMMARY

In one embodiment, the present invention is directed to a mobile device for traversing a ferromagnetic surface. The device includes a frame and at least one surface contacting device attached to the frame. The device also includes a Halbach magnet array attached to the frame, wherein the Halbach magnet array provides a magnetic force to maintain the surface contacting device substantially into contact with the ferromagnetic surface.

In one embodiment, the present invention is directed to a system. The system includes a generator and a mobile device in communication with the generator, the mobile device for traversing a ferromagnetic surface. The mobile device includes a frame, at least one surface contacting device attached to the frame, and a Halbach magnet array attached to the frame, wherein the Halbach magnet array provides a magnetic force to maintain the surface contacting device substantially into contact with the ferromagnetic surface.

In one embodiment, the present invention is directed to an apparatus for traversing a ferromagnetic surface. The apparatus includes a frame, surface contacting means, and magnetic means attached to the frame, wherein the magnetic means provides a magnetic force to maintain the surface contacting means substantially into contact with the ferromagnetic surface, and wherein the magnetic means is configured in use to be spaced from the ferromagnetic surface.

In one embodiment, the present invention is directed to a robotic device for operating on a ferromagnetic surface. The device includes a frame, at least one wheel attached to the frame, wherein the wheel has a polymeric coating on a surface that is configured to contact the ferromagnetic surface, and a Halbach magnet array attached to the frame, wherein the magnet array holds the wheel in substantially constant contact with the ferromagnetic surface and wherein the Halbach array is configured in use to be spaced from the ferromagnetic surface.

In one embodiment, the present invention is directed to a mobile device for traversing a ferromagnetic surface. The device includes a frame and at least one surface contacting device attached to the frame. The device also includes a magnet array attached to the frame, wherein the magnet array includes a plurality of magnet bars oriented such that the magnet array provides a magnetic force to maintain the surface contacting device substantially into contact with the ferromagnetic surface.

BRIEF DESCRIPTION OF THE DRAWINGS

Further advantages of the present invention may be better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:

FIG. **1** is a diagram illustrating a robotic device according to one embodiment of the present invention;

FIG. **2** is a diagram illustrating a top view of the robotic device of FIG. **1** according to one embodiment of the present invention;

FIG. **3** is a diagram illustrating a side view of the robotic device of FIG. **1** according to one embodiment of the present invention;

FIG. **4** is a diagram illustrating the jet/vacuum system of the robotic device of FIG. **1** according to one embodiment of the present invention;

FIG. **5** is a simplified schematic diagram of an electrical control device located on the robotic device of FIG. **1** or located remote from the device according to one embodiment of the present invention;

FIG. **6** is a simplified diagram illustrating a control panel of a wireless control device for controlling the robotic device of FIG. **1** according to one embodiment of the present invention;

FIG. **7** is a diagram illustrating a strain relief connector that can be used in conjunction with the robotic device of FIG. **1** according to one embodiment of the present invention;

FIG. **8** is a diagram illustrating a system in which the robotic device of FIG. **1** may be used according to one embodiment of the present invention;

FIG. **9** is a diagram illustrating a Halbach magnet array according to one embodiment of the present invention;

FIG. **10** is a diagram illustrating the magnetic fields of the Halbach magnet array of FIG. **9** according to one embodiment of the present invention;

FIG. **11** is a diagram illustrating a side view of a magnet used in the Halbach magnet array of FIG. **9**;

FIG. **12** is a diagram illustrating detection of lift off according to one embodiment of the present invention; and

FIG. **13** is a graph which illustrates the difference between the holding power of a Halbach array and the holding power of a conventional, multi-pole magnet array with iron pole pieces which has identical mass.

DESCRIPTION

It is to be understood that the figures and descriptions of the present invention have been simplified to illustrate elements that are relevant for a clear understanding of the present invention, while eliminating, for purposes of clarity, other elements. Those of ordinary skill in the art will recognize, however, that these and other elements may be desirable. However, because such elements are well known in the art, and because they do not facilitate a better understanding of the present invention, a discussion of such elements is not provided herein.

Although the present invention is illustrated herein as being embodied as a robotic device that has paint stripping and removal capabilities, it can be understood that the principles of the present invention may be employed with devices that may perform a variety of tasks such as, for example, spraying finishes, machining, welding, and inspecting surfaces or structures.

FIG. **1** is a diagram illustrating a robotic device **10** according to one embodiment of the present invention. The device **10** includes a jet/vacuum assembly **12** that can be used for jetting fluids and vacuuming the fluids and removed particles after jetting. The assembly **12** includes a seal **14**, a shroud **16**, and ports **18**. The seal **14** may be, for example, spring-loaded such that an adequate seal is maintained when the device **10** traverses an uneven or obstructed surface. Although the device **10** is illustrated in FIG. **1** as having one jet/vacuum system **12**, it can be understood that multiple jet/vacuum systems may be included on the device **10**.

The device **10** includes surface contacting devices, such as wheels **20** that contact the surface that is to be stripped of paints or coatings. The wheels may be constructed of, for example, a metal such as aluminum with a polymeric (e.g. urethane or polyurethane) coating of, for example, ¼" thickness. Such a coated wheel provides traction for the device **10** but does not mar the surface on which the device **10** is operating. It can be understood that any suitable type of surface contacting device may be used such as, for example, tracks or skids. Actuation devices, such as motors **22**, provide power to the wheels **20** to provide locomotion for the device **10**. The motors **22** may be, for example, sealed electric motors compliant with the National Electrical Manufacturers Association (NEMA) **17** standard. However, it can be understood that the actuation devices may include, in addition to or instead of electric motors, a hydraulic or pneumatic drive system.

The motors **22** are connected via chain drives **24** to differentials **26** and the differentials **26** are connected via chain drives **28** to the wheels **20**. The differentials **26** may be, for example, limited-slip differentials. The chain drives **24** may provide, for example, a 1:1 to 2:1 reduction and the chain drives **28** may provide a 2:1 reduction. The differentials **26** may provide, for example, a 3.14:1 reduction. However, it can be understood that the drive system may include, in addition to or instead of chain drives, any of a variety of other devices for power transmission such as a hydraulic transmission, belt drive or gear drive.

The device **10** includes a steering system for providing, for example, four-wheel steering capability to the device **10**. A steering actuator **30** controls a steering linkage **32** that provides directional movement of the wheels **20**. The steering actuator **30** may provide, for example, 1200 lbs. of thrust. The linkage **32** may include, for example, pinned connections and the bushings for the steering system may be, for example, oil-impregnated bushings.

The device **10** includes an ultra high pressure (UHP) fluid connection **34** that accepts the fluid to be used for stripping, for example, water. The device **10** also includes air connections **36** that accept compressed air that can be used to provide downward force to hold the jet/vacuum assembly **12** against the surface on which the device **10** is operating and which can be used for a variety of other functions such as to raise and lower the jet/vacuum assembly **12**.

The device **10** includes lifting/safety rings **38** that can be used to lift the device **10** in place using, for example, a crane or other lift device. One or more safety lines may be attached to the rings **38** to ensure that the device **10** does not fall to the ground if the device **10** loses contact with the surface on which it is operating.

In one embodiment, the device **10** is designed to operate on surfaces that are ferromagnetic, such as storage tanks and ship hulls. The device **10** is thus provided with magnets **40** to adhere the device **10** to such surfaces. The magnets **40** may be any type of suitable fixed magnet or electromagnet. In one embodiment, the magnets **40** are Halbach arrays constructed of, for example, neodymium-iron-boron (NdFeB), that provide, for example, 1400 lbs. to 2400 lbs. of pull, as described further hereinbelow. The presence of the magnets **40** allows for the device **10** to operate on structures that have inclined or vertical surfaces and allows for the device **10** to operate in an upside-down position on, for example, the bottom of the hull of a ship and provides so much surplus holding force that the device **10** can pull heavy loads (such as hoses full of water) vertically up the side of a smooth ferromagnetic structure even in the presence of water and oil on the surface. The magnets **40** may be designed and constructed, as described hereinbelow, such that the magnets **40** do not wear from contact with the surface on which the device **10** is operating and so that the magnets **40** do not mar the surface on which the device **10** is operating.

The various components of the device **10**, including a frame **42**, may be constructed of any suitable material such as, for example, plastic, stainless steel, titanium, aluminum, or coated steel.

FIG. **2** is a diagram illustrating a top view of the robotic device **10** of FIG. **1** according to one embodiment of the present invention. In addition to the elements shown in FIG. **1**, the device **10** is illustrated in FIG. **2** having vacuum hoses **50**, electrical cables **52**, safety tether **54**, and water supply hose **56** attached thereto.

FIG. **3** is a diagram illustrating a side view of the robotic device **10** of FIG. **1** according to one embodiment of the present invention.

Although the device **10** is illustrated in FIGS. **1**–**3** as having four wheels **20**, it can be understood that any suitable number and configuration of wheels, tracks, skids, etc. may be used depending on the application for which the device **10** will be used and the desired handling characteristics of the device **10**. For example, the device **10** could be implemented with various three-wheel configurations, four-wheel cart configurations, and four-wheel articulated configurations.

FIG. **4** is a diagram illustrating a bottom view of the jet/vacuum system **12** of the robotic device **10** of FIG. **1** according to one embodiment of the present invention. The system **12** includes the seal **14**. The seal **14** may be constructed from a flexible material such as, for example, polyurethane, that creates a seal with the surface on which the device **10** is operating and allows the device **10** to operate close to obstacles. A rotating spray assembly **60** includes, for example, multiple fluid outlets. The outlets may be, for example, sapphire spray jets. The spray assembly **60** may be an assembly sold by, for example, Hammelmann Corporation. The vacuum ports **18** carry away spent fluid and debris. In one embodiment, the jet/vacuum system **12** may be constructed to have a 16 inch diameter, although any suitable diameter of the system **12** may be used depending on the desired turning radius of the device **10**.

FIG. **5** is a simplified schematic diagram of an electrical control device **70** located on the robotic device **10** of FIG. **1** or remote from the device **10** according to one embodiment of the present invention. The device **70** includes a pump relay kill **72** that can stop the operation of the jet/vacuum system **12**. An emergency stop loop **74** allows the operator of the device **10** to stop the device **10** in the event of an emergency. An operator interface receiver **76** receives operator commands via, for example, a wireless control device. A control microcontroller **78** provides control signals for controlling various systems of the device **10**. An automation computer **80** provides various automated functions for the device **10** as described hereinbelow. The computer **80** receives input from, for example, one or more cameras located on the device **10** and a gyro tilt sensor.

A front motor control circuit **82** includes a filter **84** and an amplifier **86** and a rear motor control circuit **88** includes a filter **89** and an amplifier **90**. A turn actuator circuit **91** includes a filter **92** and an amplifier **93**. A jet/vacuum system (head) spin motor circuit **94** includes a filter **95** and an amplifier **96** and a jet/vacuum system (head) raise/lower actuator circuit **97** includes a filter **98** and an amplifier **99**. The amplifiers **86**, **90**, **93**, **96**, and **99** may be, for example, Emerson EN208 amplifiers with FM3.

FIG. **6** is a simplified diagram illustrating a control panel **100** of a wireless control device for controlling the robotic device **10** of FIG. **1** according to one embodiment of the present invention. The control device on which the control panel **100** is located may be any type of control device such as a wireless or a wireline control device. A vehicle speed control dial **102** allows the operator of the device **10** to control the speed of the device **10**. A rotate speed dial **104** allows the operator of the device **10** to control the rotate speed of the device **10** and a head height dial **106** allows the operator of the device **10** to adjust the height of the jet/vacuum system **12**. An emergency stop button **108** allows the operator of the device **10** to stop the device **10** in the event of an emergency.

A joystick **110** provides for basic control of the device **10** and allows the operator of the device **10** to easily control the direction of the device **10** during operation. A cruise control button **112** enables and disables an automatic cruise control function of the device **10**. A vision/gyro button **114** enables control of the device **10** by a computer vision system. A forward/reverse button **116** allows the operator of the device **10** to change the direction of the device **10**. A water jet button **118** allows the operator of the device **10** to start and stop the flow of water to the jet/vacuum system **12**. An end of row button **120** allows the operator of the device to cause the automatic, computer-vision controlled drive to turn the device **10** around. A right angle turn button **122** allows the operator of the device **10** to efficiently cause the device **10** to make a right angle turn during operation. A home button **124** allows the operator of the device **10** to set the desired center position for the steering joystick.

FIG. **7** is a diagram illustrating a strain relief connector **128** that can be used in conjunction with the robotic device **10** of FIG. **1** according to one embodiment of the present invention. The connector **128** may connect to one of the lifting/safety rings **38** via a clip **130**. The connector **128** relieves the strain on the cables and hoses **52**, **56** during operation of the device **10**.

FIG. **8** is a diagram illustrating a system **200** in which the robotic device **10** of FIG. **1** may be used according to one embodiment of the present invention. FIG. **8** illustrates the case where the device **10** includes a jet/vacuum system **12** for stripping paint and coatings from a surface using UHP water. A controller **202**, on which the control panel **100** of FIG. **6** may be located, may be used by an operator to control the device **10**. The controller **202** may be, for example, a wireless or radio control device. A generator **204**, such as an enclosed diesel generator, provides electrical power to the device **10** and various other components of the system **200**. A water pump **206**, such as a diesel water pump, supplies water to the jet/vacuum system **12** of the device **10**. A vacuum **208**, such as an electric vacuum, vacuums spent water and removed particles via the jet/vacuum system **12** of the device **10**. In one embodiment, the vacuum **208** is a 56 kW vacuum that pulls approximately 128 m^3 per minute through the jet/vacuum system **12** with a vacuum of approximately 38 cm Hg.

The output of the vacuum **208** enters a settling tank **210** in which solid waste settles for removal. The liquid portion of the settling tank **210** is directed to a filtration unit **212**, such as an enclosed ultra filtration unit, where solids are filtered. In one embodiment, the filtration unit **212** includes a centrifuge that removes the solid waste. In one embodiment, the filtration unit **212** includes a sand filter and a secondary filter that is tailored to remove dissolved chemicals that are expected to be in the water vacuumed from the jet/vacuum system **12**. The filtered water output from the filtration unit **212** may be recycled in the system **200** by the water pump **206** or may be returned to the environment. In one embodiment, the water output from the filtration unit **212** is 1 micron filtered water.

FIG. **9** is a diagram illustrating a Halbach magnet array **220** according to one embodiment of the present invention. A Halbach magnetic array is a series of magnets which are so arranged as to simulate a magnetic monopole. The result is a magnetic assembly which, unlike most other magnetic devices, exhibits magnetic attraction predominantly on a single surface. The Halbach array uses the power of the magnet elements which comprise it in an efficient manner to produce a magnetic device of unusual strength and ability to throw magnetic flux across significant air gaps. A Halbach device might be composed of 4 or more magnetic elements with each element having a different axis of magnetic orientation. The change in orientation from one element to the next may be 90 degrees or less. Magnetic elements may be arranged in a straight line, a circular fashion or a variety of other manners to achieve the same effect. The Halbach array **220** is used for the magnets **40** of the device **10** according to one embodiment of the present invention. The Halbach array **220** includes permanent magnet bars **222** arranged and oriented in such a way that the magnetic field of the array **220**, which varies periodically in space along the array, is concentrated on one face of the array **220** and almost canceled on the opposite face (See FIG. **10**). The magnetic orientation (i.e. 0 degrees, 45 degrees, and 90 degrees) of each of the bars **222**, according to one embodiment of the present invention, is indicated with an arrow. According to one embodiment of the present invention, each of the bars **222** may be, for example, 45 MGOe Neodymium (uncoated).

The array **220** includes 3 array cycles (i.e. 13 bars **220**). However, various embodiments may use a differing number of cycles such as, for example, 1 cycle (i.e. 5 bars **220**) or

2 cycles (i.e. 9 bars **220**). In one embodiment, the x dimension of the array **220** is 6.75 in., the y dimension of the array **220** is 2 in., and the z dimension of the array **220** is 8.5 in.

FIG. **10** is a diagram illustrating the magnetic fields of the Halbach magnet array **220** of FIG. **9** according to one embodiment of the present invention. In FIG. **10**, the array **220** is included as one of the magnets **40** of the device **10**. The wheels **20** of the device **10** contact a ferromagnetic surface **224** on which the device **10** is operating. The magnet **40** does not contact the surface **224** but, rather, due to the orientation of the magnetic fields emanating from the magnet **40** as denoted by the shaded areas of FIG. **10**, the magnet **40** is separated from the surface **224** by an air gap **226**. The magnet **40** provides the necessary force required to hold the device **10** on the surface **224**, even though the magnet **40** does not contact the surface **224** and even though there may be one or more layers of paint or coatings on the side of the surface **224** on which the device **10** is operating. The magnet **40** likewise provides sufficient force to hold the device **10** when the device **10** operates in an inverted (e.g. upside-down) or vertical position. In one embodiment, the air gap **226** is a ⅝ in. air gap. As illustrated in FIG. **10**, the magnet **40** does not ride on the surface **224** and, thus, the magnet **40** will not mar the surface **224** during operation of the device **10**. Because the magnet **40** does not contact the surface **224**, the device **10** is able to traverse concave or convex and/or inverted surfaces that contain surface irregularities, dents, etc. because the wheels **20** provide the sole contact of the device **10** with the surface **224**.

FIG. **11** is a diagram illustrating a side view of a magnet **222** used in the Halbach magnet array **220** of FIG. **9**. FIG. **11** illustrates two embodiments of the shape of the bars **222** that comprise the array **220**. The first embodiment, designated as **300**, presents a curved working face and the second embodiment, designated as **302**, presents a segmented working face.

The Halbach array **200** has many advantages over methods traditionally used to hold devices on ferromagnetic surfaces such as vacuum attachments, which are unreliable and impede movement of the device, magnetic wheels and tracks, which are heavy and which mar surfaces, and conventional magnetic arrays which provide one-third the holding power of a Halbach array for their weight. The high holding power of a Halbach array for its weight, and the ability of this type of magnet to throw its magnetic field farther than other types of magnetic solutions makes it possible to build a device with unprecedented performance on ferromagnetic surfaces.

FIG. **12** is a diagram illustrating detection of lift off according to one embodiment of the present invention. If the magnet **40** starts to lose sufficient force to adhere the device **10** to the surface **224**, the size of the air gap **226** becomes increasingly larger until the wheels **20**, and thus the device **10**, lose contact with the surface **224**. Thus, if either the size of the air gap **226** or the magnetic flux at the surface **224** can be measured using appropriate sensors located on the device **10**, the operator of the device **10** may be alerted that the device **10** is about to lose contact with the surface and the operator may take corrective action. Alternatively, the device **10** may automatically take self-correcting action such that the device **10** does not lose contact with the surface **224**.

FIG. **13** is a graph which illustrates the difference between the holding power of a Halbach array and the holding power of a conventional, multi-pole magnet array with iron pole pieces which has identical mass. It can be seen in FIG. **13** that the Halbach array solution is very substantially more efficient with any reasonable air gap. This efficiency is what makes a Halbach-equipped device, as described herein, well-suited to operation on vertical and inverted ferromagnetic surfaces where high holding power and light weight are essential.

In various embodiments, the device **10** may be equipped with automated mobility features that enable the device **10** to be operated more efficiently. Such features may be implemented and controlled by the automation computer **80**. One such feature is termed "cut-line tracking cruise control." This feature may be useful when the device **10** is used to strip paint or coatings from a surface. During operation, the device **10** may make various straight-line passes over an area, with each successive pass overlapping slightly with the immediately-prior pass. Although such overlap ensures complete coverage of the device **10**, it maybe difficult for an operator of the device **10** to consistently operate the device **10** with an overlap that is neither too small nor too large.

The device **10** may thus employ, for example, a forward-looking camera that can sense, using, for example, a computer vision algorithm, a cut line that demarcates the area on which the device **10** has operated from the area on which the device **10** has not operated. Such a computer vision algorithm may be, for example, an algorithm that relies on a color histogram-based correlation to find likely cut line points, and an aggressive line fitting algorithm to fit the most likely cut line. Because the device **10** can detect the cut line, the device **10** may automatically follow the cut line with little or no operator intervention.

Another automated feature is termed the "paint residue cruise control." This feature may be useful when the device **10** is used to strip paint or coatings from a surface. As the device **10** operates, a slower speed may strip more paint or coating and a faster speed may strip less paint or coating. Because paint and coating thicknesses may vary from surface to surface or from one part of a surface to another, it may be difficult to operate the device **10** at a uniform speed and effectively remove all of the paint or coating. The device **10** may thus employ a reverse-looking camera that monitors the surface that is being stripped. The camera may feed images to an algorithm that has been trained from a set of sample images to recognize the statistical color characteristics of the stripped surface (e.g. bare steel). The algorithm may compute the percentage of paint or coating left on the surface that has been stripped and thus the device **10** may be automatically slowed if all of the paint or coating has not been removed.

The systems, methods, and techniques discussed herein allow for an improved device that allows for the use of non-surface marring wheels, provides for better traction on surfaces, provides for better maneuverability and obstacle clearing, does not mar or scratch surfaces, and provides a light weight and low cost magnetic assembly that has a high magnetic holding power.

While several embodiments of the invention have been described, it should be apparent, however, that various modifications, alterations and adaptations to those embodiments may occur to persons skilled in the art with the attainment of some or all of the advantages of the present invention. It is therefore intended to cover all such modifications, alterations and adaptations without departing from the scope and spirit of the present invention as defined by the appended claims.

What is claimed is:

1. A robotic device for operating on a ferromagnetic surface, comprising:

a frame;

a lifting/safety ring attached to the frame;

a strain relief connector attached to the lifting/safety ring;

at least one wheel attached to the frame, wherein the wheel has a polymeric coating on a surface that is configured to contact the ferromagnetic surface; and

a Halbach magnet array attached to the frame, wherein the magnet array holds the wheel in substantially constant contact with the ferromagnetic surface and wherein the Halbach array is configured in use to be spaced from the ferromagnetic surface.

2. The device of claim 1, further comprising a motor attached to the frame.

3. The device of claim 1, wherein the Halbach magnet array includes a plurality of magnetic bars, and wherein the magnetic bars are arranged such that a magnetic force created by the array extends substantially toward the ferromagnetic surface.

4. The device of claim 1, further comprising a steering system attached to the frame.

5. The device of claim 1, further comprising an actuation device attached to the frame.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,792,335 B2

APPLICATION NO. : 10/153942

DATED : September 14, 2004

INVENTOR(S) : William P. Ross et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page,
Item [56], **References Cited**, OTHER PUBLICATIONS,
"Westernstates Manufacturing" reference, delete "200" and insert -- 2000 --.

Drawings,
Sheet 12, Figure 13, in the legend, associate "Halbach Adhesion" with the circle-marked line and "Traditional Adhesion" with the X-marked line as shown on attached page.

Column 8,
Line 18, delete "maybe" and insert -- may be --.

Signed and Sealed this

Twentieth Day of June, 2006

JON W. DUDAS
Director of the United States Patent and Trademark Office

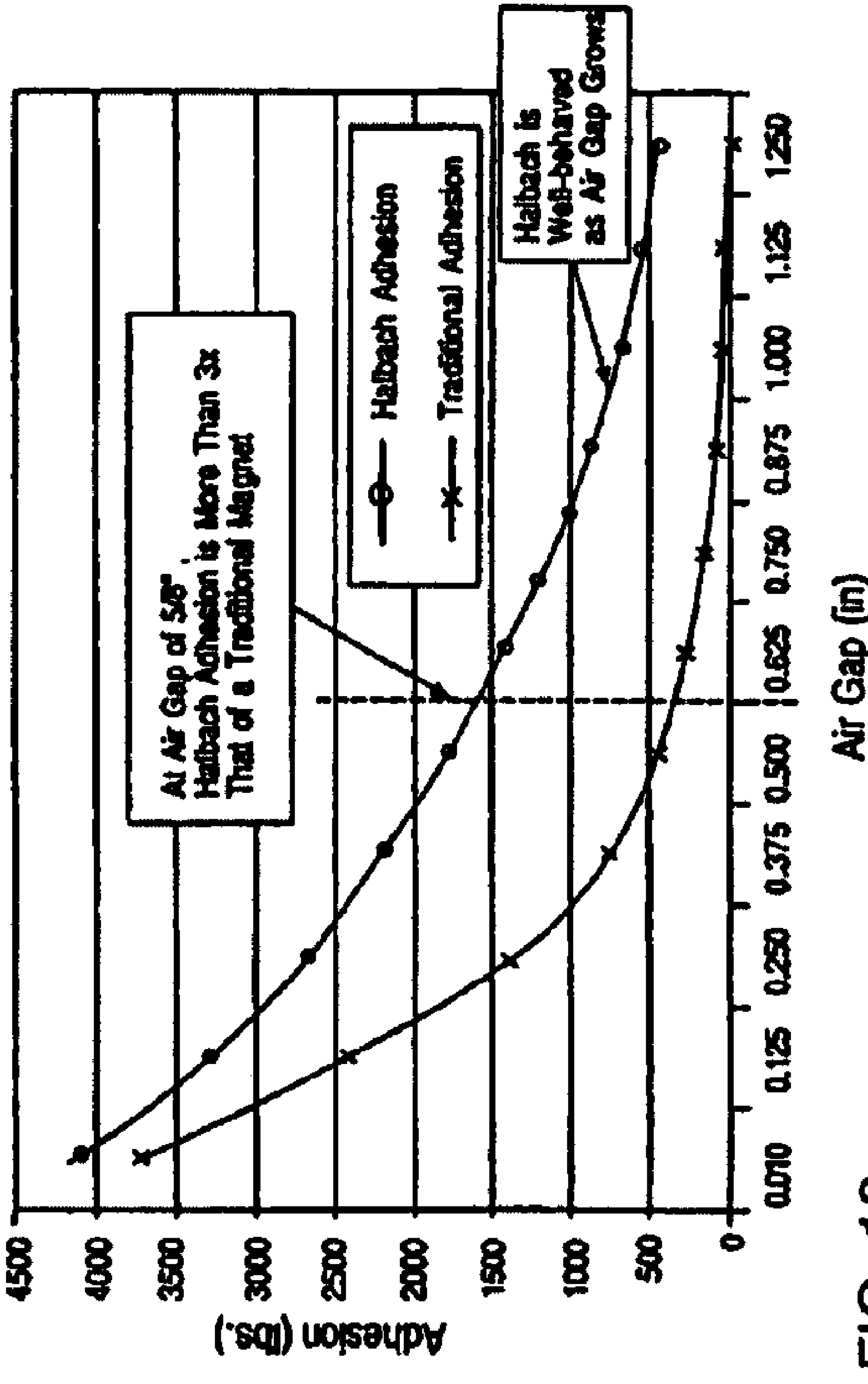
At Air Gap of 5/8",
Halbach Adhesion is More Than 3x
That of a Traditional Magnet
Halbach Adhesion
Traditional Adhesion
Halbach is
Well-behaved
as Air Gap Grows
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Adhesion (lbs.)
0.010
0.125
0.250
0.375
0.500
0.625
0.750
0.875
1.000
1.125
1.250
Air Gap (in)

FIG. 13