(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
15 March 2018 (15.03.2018)

WIPO | PCT

(10) International Publication Number
WO 2018/045448 A1

(51) International Patent Classification:
B25J 5/00 (2006.01) *B25J 9/00* (2006.01)
B25J 19/02 (2006.01) *B60P 1/48* (2006.01)

(21) International Application Number: PCT/CA2017/000057

(22) International Filing Date: 10 March 2017 (10.03.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/383,747 06 September 2016 (06.09.2016) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(54) Title: MOBILE WORK STATION FOR TRANSPORTING A PLURALITY OF ARTICLES

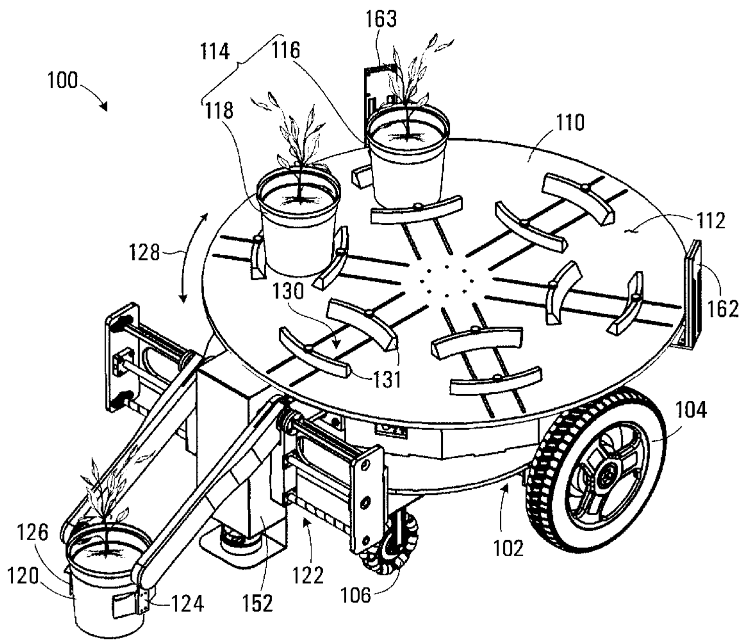

FIG. 1

(57) Abstract: An apparatus and method for transporting a plurality of articles is disclosed. The apparatus includes a wheeled chassis, and a platform disposed on the wheeled chassis. The apparatus also includes a manipulator coupled to the wheeled chassis and operably configured to load a first article of the plurality of articles at a first position on the platform, or unload the first article of the plurality of articles from the first position on the platform. The apparatus further includes at least one actuator operably configured to cause successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform for loading or unloading each subsequent article in the plurality of articles.

WO 2018/045448 A1

[Continued on next page]

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

MOBILE WORK STATION FOR TRANSPORTING A PLURALITY OF ARTICLES

RELATED APPLICATIONS

This application claims the benefit of US provisional patent application 62/383747 entitled "MULTIFUNCTIONAL UNMANNED GROUND VEHICLE", filed on September 6, 2016 and incorporated herein by reference in its entirety.

BACKGROUND

1. Field

This disclosure relates generally to transporting articles and more particularly to a robotic mobile work station for transporting and performing operations on a plurality of articles.

2. Description of Related Art

Robotic vehicles may be configured for autonomous or semi-autonomous operation for a wide range of applications including product transportation, material handling, security, and military missions. Autonomous mobile robotic vehicles typically have the ability to navigate and to detect objects automatically and may be used alongside human workers, thereby potentially reducing the cost and time required to complete otherwise inefficient operations such as basic labor, transportation and maintenance. Some autonomous vehicles track movement of driven wheels of the vehicle using encoders to determine a position of the vehicle within a workspace.

SUMMARY

In accordance with one disclosed aspect there is provided an apparatus for transporting a plurality of articles. The apparatus includes a wheeled chassis, and a platform disposed on the wheeled chassis. The apparatus also includes a manipulator coupled to the wheeled chassis and operably configured to load a first article of the plurality of articles at a first position on the platform, or unload the first article of the plurality of articles from the first position on the platform. The apparatus further includes at least one actuator operably configured to cause successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform for loading or unloading each subsequent article in the plurality of articles.

The at least one actuator may be operably configured to cause one of a rotary movement of the platform about the wheeled chassis and a rotary movement of the manipulator about the wheeled chassis.

The manipulator may be coupled to base rotatable with respect to the wheeled chassis and the at least one actuator may include a base actuator operably configured to cause rotary movement of the base and the manipulator about the wheeled chassis, a platform actuator operably configured to cause rotary movement of the platform about the wheeled chassis, the base actuator and the platform actuator being operable to cause successive relative rotational movements of both the manipulator and the platform about the wheeled chassis for providing access for loading or unloading each subsequent article in the plurality of articles.

The manipulator may be coupled to the wheeled chassis via a support and the base actuator may be operably configured to cause rotary movement of the support about the wheeled chassis.

The wheeled chassis may include at least one drive for driving wheels of the wheeled chassis and may further include a controller operably configured to cause the at least one drive to orient the wheeled chassis for movement in a direction aligned to pick up or place the plurality of articles in a line, cause the base actuator to cause rotary movement of the manipulator about the wheeled chassis to orient the manipulator for loading or unloading the plurality of articles, and cause the platform actuator to cause rotary movement of the platform to after loading each article, dispose an empty location on the platform in reach of the manipulator for loading a subsequent article, or dispose a subsequent article on the platform in reach of the manipulator for unloading.

The wheeled chassis may include a drive for driving at least one wheel of the wheeled chassis and may further include a controller operably configured to control the drive to orient the wheeled chassis to align the manipulator for loading or unloading each of the first article and the subsequent articles.

The manipulator may include a pair of outwardly directed spaced apart arms operably configured to grasp the article, an arm actuator, operably configured to vertically rotate the arms toward the platform while the article is suspended between the arms, and an end effector distally disposed on each respective arm and the end effectors may be operably configured to grasp the article and suspend the article during vertical movement of the arms.

The arms may be mounted for vertical rotation on a driven shaft and the end effectors may be coupled to the shaft via a belt such that rotation of the arms causes a respective rotation of the end effectors for maintaining an orientation of the end effectors while grasping the article.

The pair of outwardly directed spaced apart arms may be mounted for one of lateral movement and rotational movement about a pivot to cause the pair of end effectors to move to grasp or release the article.

The apparatus may include at least one tool operably configured to perform an operation on the articles while transporting the plurality of articles on the wheeled chassis.

The at least one tool may be coupled to the manipulator such that causing rotary movement between the manipulator and the platform provides access to each article for performing the operation.

The manipulator and the at least one tool may be respectively coupled to a common base mounted for rotation on the wheeled chassis such that rotary movement of the common base causes rotary movement of each of the manipulator and the at least one tool.

The at least one tool may be coupled to the wheeled chassis such that causing rotary movement between the wheeled chassis and the platform provides access to each article for performing the operation.

In accordance with another disclosed aspect there is provided a method of transporting a plurality of articles on a wheeled chassis. The method involves causing a manipulator coupled to the wheeled chassis to load a first article of the plurality of articles at a first position on a platform disposed on the wheeled chassis, or unload the first article of the plurality of articles from the first position on the platform. The method also involves causing successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform, and causing the manipulator to load or unload each subsequent article of the plurality of articles to or from the successive rotationally spaced apart positions on the platform.

Causing successive relative rotational movements may involve one of causing rotary movement of the platform about the wheeled chassis and causing rotary movement of the manipulator about the wheeled chassis.

Causing successive relative rotational movements may involve causing rotary movement of both the manipulator and the platform about the wheeled chassis.

Causing rotary movement of both the manipulator and the platform about the wheeled chassis may involve causing the wheeled chassis to be aligned for movement in a direction aligned to pick up or place the plurality of articles along a line, causing rotary movement of the manipulator to orient the manipulator for loading or unloading the plurality of articles, and causing rotary movement of the platform to, after loading each article, dispose an empty location on the platform in reach of the manipulator for loading a subsequent article, or dispose a subsequent article on the platform in reach of the manipulator for unloading.

The method may involve controlling a drive associated with at least one wheel of the wheeled chassis to orient the wheeled chassis to align the manipulator for loading each of the first article and the subsequent articles.

The method may involve operating at least one tool to perform an operation on the articles while transporting the plurality of articles on the wheeled chassis.

Operating the at least one tool may involve causing rotational movement between the at least one tool and the platform to provide access to each article for performing the operation.

Causing rotational movement between the at least one tool and the platform may involve causing rotational movement of the manipulator, the at least one tool being coupled to the manipulator.

In accordance with another disclosed aspect there is provided a method for transporting a plurality of articles between a pickup location and an intended drop-off location on a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis. The method involves positioning a pickup beacon proximate the plurality of articles at the pickup location, positioning a left drop-off beacon and a right drop-off beacon on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the respective location, receiving location signals at transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis, processing the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons, navigating the wheeled chassis using the determined location and orientation of the wheeled chassis to pick up successive articles of the plurality of articles proximate the pickup location, move between the pickup location and the drop-off location, and place articles proximate the drop-off location.

Receiving location signals may involve transmitting ultra-wideband (UWB) signals at the transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis, and receiving the UWB signals at the other transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis.

Navigating may involve using the location signals to determine a real-time location and orientation for steering the wheeled chassis along a path between the pickup location and drop-off location, receiving proximity signals indicative of obstacles in the path of the wheeled chassis, and using the received proximity signals and location signals to modify the path of the wheeled chassis to avoid detected obstacles.

Receiving the proximity signals may involve generating proximity signals using at least one of an optical sensor, an infrared sensor, light detection and ranging (LIDAR) sensor, and an ultrasonic sensor.

Receiving the proximity signals may involve receiving a first proximity signal from an infrared sensor operably configured to indicate close range obstacles, and a second proximity signal from a light detection and ranging (LIDAR) sensor indicating mid and far range obstacles.

The method of may further involve, when the path of the wheeled chassis is within a pre-determined range of the pickup location, processing the received proximity signals to determine whether obstacles in the path of the wheeled chassis correspond to any of the plurality of articles to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles.

The method of may further involve, when path of the wheeled chassis is within a pre-determined range of the drop-off location, causing the wheeled chassis to steer to a first location defined with respect to one of the left drop-off beacon and a right drop-off beacon for unloading of a first article.

The method may involve causing the wheeled chassis to steer to successive locations defined with respect to the one of the left drop-off beacon and a right drop-off beacon beacon for unloading of a second article and subsequent articles in the plurality of articles.

In accordance with another disclosed aspect there is provided a system for transporting a plurality of articles between a pickup location and an intended drop-off location. The system includes a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis, a pickup beacon positioned proximate the plurality of articles at the pickup location, a left drop-off beacon and a right drop-off beacon positioned on either side of the intended drop-off location. The left and right drop-off beacons indicate a desired alignment of the plurality of articles at the respective location, each beacon including a transceiver. The transceivers on the beacons and the pair of transceivers on the wheeled chassis are operably configured to receive location signals and process the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons for navigating the wheeled chassis to pick up articles in the plurality of articles proximate the pickup location, to move between the pickup location and the drop-off location, and to place articles in the plurality of articles proximate the drop-off location.

The transceivers disposed on each beacon and the pair of transceivers on the wheeled chassis may include ultra-wideband (UWB) transceivers.

The system may include at least one proximity sensor disposed on the wheeled chassis, the proximity sensor being operable to provide an indication of obstacles in the path of the wheeled chassis.

Other aspects and features will become apparent to those ordinarily skilled in the art upon review of the following description of specific disclosed embodiments in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In drawings which illustrate disclosed embodiments,

Figure **1** is a perspective view of an apparatus for transporting a plurality of articles according to a first disclosed embodiment;

Figure **2** is a cut-away perspective view of the apparatus shown in Figure **1**;

Figure **3** is a perspective view of a manipulator of the apparatus shown in Figure **1**;

Figure **4** is a perspective view of an alternative manipulator embodiment for the apparatus shown in Figure **1**;

Figure **5** is a partially exploded perspective view of the manipulator shown in Figure **4**;

Figure **6** is a block diagram of a processor circuit for implementing an on-board controller of the apparatus shown in Figure **1**;

Figure **7** is a flowchart depicting blocks of code for directing the processor circuit of Figure **6** to control autonomous loading operations of the apparatus shown in Figure **1**;

Figure **8**A to **8**E are a series of plan views of the apparatus shown in Figure **1** performing the loading process shown in Figure **7**;

Figure **9** is an alternative embodiment of a portion of the process shown in Figure **7**;

Figure **10** is a flowchart depicting blocks of code for directing the processor circuit shown in Figure **6** to control autonomous unloading operations of the apparatus shown in Figure **1**;

Figure **11**A to **11**C are a series of plan views of the apparatus shown in Figure **1** performing the unloading process shown in Figure **10**;

Figure **12** is a perspective view of an apparatus for transporting a plurality of articles according to an alternative disclosed embodiment;

Figure **13** is a plan view of a positioning system for determining a position of the apparatus shown in Figure **1** within an area;

Figure **14** is a flowchart depicting blocks of code for directing a controller to locate arbitrarily positioned beacons of the positioning system shown in Figure **13**; and

Figure **15** is a flowchart depicting blocks of code for directing the controller and the processor circuit shown in Figure **6** to locate arbitrarily positioned beacons of the positioning system.

DETAILED DESCRIPTION

Referring to Figure **1**, an apparatus for transporting a plurality of articles according to a first disclosed embodiment is shown generally at **100**. The apparatus **100** includes a wheeled chassis **102**. In the embodiment shown, the wheeled chassis **102** includes a pair of drive wheels **104**, a pair of front castor wheels **106** (only one of each of the pairs of wheels is visible in Figure **1**), and a further rear castor wheel (not visible in Figure **1** but shown at **108** in Figure **2**). The castor wheels **106** and **108** are able to swivel to permit the wheeled chassis **102** to move in a direction determined by the drive provided to the pair of drive wheels **104**. The wheeled chassis **102** has a rounded shape, but in other embodiments may be otherwise shaped.

The apparatus **100** also includes a platform **110** disposed on the wheeled chassis **102**. The platform **110** has an upper surface **112** for receiving a plurality of articles **114** to be transported. In Figure **1**, two articles **116** and **118** of a plurality of articles **114** have been received on the platform **110** and a third article **120** is about to be loaded onto the platform **110**. The apparatus **100** also includes a manipulator **122** coupled to the wheeled chassis **102**. The manipulator **122** has a pair of end effectors **124** and **126** for grasping the article **120**. The movements of the end effectors **124** and **126** are actuated by actuators housed in an actuator housing **152**. In other applications, the pair of end effectors **124** and **126** may be otherwise configured in accordance with the articles to be loaded and unloaded.

In operation, the apparatus **100** is configured to permit successive relative rotational movements between the manipulator **122** and the platform **110** in a direction indicated by the arrow **128**. The successive relative rotational movements provide access for loading each subsequent article in the plurality of articles **114** onto the platform **110** at successive rotationally spaced apart positions. For example, as shown in Figure **1**, the platform **110** has been positioned to permit access to a position **130** for receiving the article **120**. The platform **110** may have a pair of article supports **131** at each position such as shown for the position **130** in Figure **1**.

In the embodiment shown the plurality of articles **114** are plant pots and the apparatus **100** may be used in a plant nursery. Another application of the apparatus **100** may involve transporting blood samples from one location to another within a health care facility.

The apparatus **100** is shown with the platform **110** partially cut away in Figure **2**. Referring to Figure **2**, in this embodiment the apparatus **100** includes a base **132** coupled to the wheeled chassis. The platform **110** includes a gear **134** coupled to an underside **137** of the platform **110**. The gear **134** and platform are mounted via a shaft **138** to the base **132**. The apparatus **100** also includes a platform actuator **140** for providing a rotation torque to a drive gear **136** that meshes with the gear **134**. The platform actuator **140** includes a rotational encoder (not shown) that measures the angular rotation of the platform **110**. In this embodiment the platform actuator **140** is implemented using an electrical motor that generates a torque for causing rotational movement of the drive gear **136**, which in turn causes the gear **134** and the platform **110** to rotate about the shaft **138** in the direction **128** with respect to the base **132**.

In the embodiment shown, the base **132** is also rotatable with respect to the wheeled chassis **102** and includes a gear **142** coupled to the wheeled chassis. The base **132** includes a base actuator **144** having a drive gear **146** that engages with the gear **142**. In this embodiment the base actuator **144** is implemented using an electrical motor that generates a torque for causing rotational movement of the drive gear **146**, which causes the base **132** to rotate about the gear **142**, and thus the wheeled chassis **102**, in a direction indicated by the arrow **148**. The base actuator **144** is mounted to a cover plate **149** (shown partially cut away in Figure **2**) that covers the base **132**. The base actuator **144** includes a rotational encoder **151** for measuring the angular rotation of the base **132**. The cover plate **149**, which is shown cut away in Figure **2**, extends across and covers the base **132** and carries a plurality of rollers (of which a roller **153** is shown in

Figure **2**). The rollers are distributed peripherally on the cover plate and support the underside **137** platform **110** during loading, transporting, and unloading operations.

In this embodiment, the manipulator **122** is coupled to and moves with the base **132**. Since the platform **110** is also coupled to the base **132**, the platform will move in the direction **148** when the base moves and relative rotational movements of the platform **110** with respect to the base are actuated by causing the platform actuator **140** to drive the drive gear **136**.

In other embodiments the platform **110** and base **132** may be independently rotatable relative to the wheeled chassis **102**. Alternatively, in some embodiments the base **132** may be fixed to the wheeled chassis and not able to rotate independently of the wheeled chassis **102**.

In the embodiment shown in Figure **1** and Figure **2** both of the pair of the wheels **104** are independently driven by a hub drive **150**. The front castor wheels **106** and rear castor wheel **108** are not driven but rather provide stability for the wheeled chassis **102**. In other embodiments the pair of driven wheels **104** may have a common drive and one of the castor wheels **106** and **108** may be steerable.

The apparatus **100** also includes a proximity sensor **154**, which is operable to provide an indication of obstacles in the path of the wheeled chassis **102**. In the embodiment shown the proximity sensor **154** is implemented using an optical light detection and ranging (LIDAR) sensor. Other proximity sensors such as an infrared sensor or ultrasonic sensor may be alternatively or additionally used to implement the proximity sensor **154**.

The manipulator **122** is shown in isolation in Figure **3** with a cover (shown in Figure **2**) of the actuator housing **152** removed to reveal details of actuators for activating movements of the manipulator. Referring to Figure **3**, the manipulator **122** includes a frame **300**, a pair of endplates **302** and **304**. In the embodiment shown, the end effectors **124** and **126** are coupled to respective arms **306** and **308**. Each arm **306** and **308** is mounted for rotation on a respective spline shaft **310** and **312**. The manipulator **122** also includes an arm actuator **314**, which is coupled to the respective spline shafts **310** and **312**. The spline shaft **310** extends between a bearing **316** mounted on the endplate **302** and the actuator housing **152** and is coupled to the arm actuator **314**. Similarly, the spline shaft **312** extends between a bearing **318** mounted on the endplate **304** and the actuator housing **152** and is also coupled to the arm actuator **314**.

The arm actuator **314** is operable to generate a rotational torque on the spline shafts **310** and **312** for causing the arms **306** and **308** to be rotated about the shafts for raising or lowering the respective end effectors **124** and **126**. The arm actuator **314** includes an encoder (not shown) that provides a measurement of the rotational position of the spline shafts **310** and **312** and thus the arms **306** and **308**. In the embodiment shown, the end effectors **124** and **126** are mounted on a pulley belt **320**, which is coupled to between a pulley wheel on the spline shaft **312** (not shown) and a pulley wheel **322**. When the pulley wheel on the spline shaft **312** rotates, the pulley belt **320** causes a corresponding synchronous rotation of the pulley wheel **322** such that the end effector **126** remains in the orientation shown (i.e. generally vertically oriented) when the arm **308** is raised or lowered. The arm **306** is similarly configured.

The manipulator **122** also includes a guide rod **324** extending between the endplate **302** and the actuator housing **152** and a guide rod **326** extending between the endplate **304** and the actuator housing. The arms **306** and **308** are coupled to respective linear guides **328** and **330** that are received on the respective guide rods **324** and **326**. The linear guides **328** and **330** facilitate translational movements of the arms **306** and **308** along the respective guide rods **324** and **326**. The manipulator **122** further includes a leadscrew **332**, a leadscrew **334**, and a translation actuator **336**. The leadscrew **332** extends between a bearing **338** mounted on the endplate **302** and the actuator housing **152** and is coupled to the translation actuator **336**. Similarly, the leadscrew **334** extends between a bearing **340** mounted on the endplate **304** and the actuator housing **152** and is coupled to the translation actuator **336**. Each linear guide **328** and **330** has a leadscrew nut (only the leadscrew nut **342** associated with the guide **328** is visible in Figure **3**), which is received on the respective leadscrews for causing translational movement of the linear guides to reduce or increase a lateral distance between the pair of end effectors **124** and **126** for accommodating different sized articles. In this embodiment the leadscrew **332** and leadscrew **334** have opposite thread directions, such that rotation of the respective leadscrews by the translation actuator **336** causes opposite movements of the respective linear guides **328** and **330** along the guide rods **324** and **326**. The translation actuator **336** includes a rotary encoder (not shown) that provides a measurement of the rotational drive provided to the leadscrews **332** and **334**, which is converted into a linear translation distance based on the leadscrew thread pitch.

An alternative manipulator embodiment is shown in Figure **5** at **450**. Referring to Figure **5**, the manipulator **450** includes a frame **452**, which attaches to the apparatus **100** via a bracket **454**. The manipulator **450** includes a pair of arms **456** and **458** having respective end effectors **460** and **462**. Further details of the manipulator **450** are shown in the partially exploded view of Figure **5**. Referring to Figure **5**, the arms **456** and **458** are similarly configured to the arms **306** and **308** shown in Figure **3**, and include a pulley belt **464** coupled to between pulley wheels **466** and **468** for providing synchronous rotation such that the end effectors **460** and **462** maintain their orientation when the arms are raised or lowered.

The manipulator **450** includes pivots **470** and **472** mounted on the frame **452** for pivotably mounting each of the arms **456** and **458**. In Figure **5**, the arm **456** is shown removed from the pivot **470** to better show details of the manipulator **450**. The pivot **470** has a vertically extending portion **474** for engaging a channel (not shown) in the pulley wheel **466** such that the pulley wheel is able to rotate freely about the vertically extending portion of the pivot in a direction indicated by the arrow **476**. The manipulator **450** also includes an arm actuator **478** operable to raise or lower the arms **456** and **458** by causing rotation of a shaft **480**, which is coupled to arm mounting brackets **482** and **484**. When the shaft **480** causes the arm **456** to be raised or lowered, the vertically extending portion **474** of the pivot **470** prevents the pulley **466** from rotating and the pulley belt **464** is moved causing a rotational movement to the pulley wheel **468** in proportion to the upward or downward movement of the arm. In this manner, the end effector **460** remains oriented as shown in Figure **4** when the arm is raised or lowered. The arm **458** is configured in the same way.

The manipulator **450** also includes respective stepper motors **486** and **488** for causing lateral rotation of the respective arms **456** and **458**. The stepper motor **488** associated with the arm **458** is shown with an outer covering removed in Figure **5**. The stepper motor is coupled via a drive shaft **490** to a beam **492** of the arm **458** and causes lateral rotation of the beam and arm about the drive shaft in a direction shown by the arrow **494**.

The manipulator **450** thus differs from the manipulator **122** in that the arms **456** and **458** are configured for a "pincer" type movement for gripping and releasing articles rather than for a lateral translation as in the case of the arms **306** and **308**.

Referring back to Figure **2**, in the embodiment shown the apparatus **100** further includes an on-board controller **160** for autonomously controlling operations of the apparatus. The controller **160** is shown in more detail in Figure **6** and may be implemented using an embedded processor circuit such as a Microsoft

Windows® industrial PC. Referring to Figure **6**, the controller **160** includes a microprocessor **400**, a memory **402**, and an input output (I/O) **404**, all of which are in communication with the microprocessor **400**. The I/O **404** includes a wireless interface **406** (such as an IEEE **802.11** interface) for wirelessly receiving and transmitting data communication signals between the controller **160** and a network **408**. The I/O **404** also includes a wired network interface **410** (such as an Ethernet interface) for connecting to the LIDAR proximity sensor **154**. The I/O **404** further includes a USB interface **412** for connecting to a digital to analog converter (DAC) **414** and to ultra-wideband transceivers (UWB) **416** and **417**.

The DAC **414** includes a plurality of ports for receiving analog signals and converting the analog signals into digital data representing the signals and/or producing analog control signals. In the embodiment shown the DAC **414** includes a port **418** for producing control signals for controlling the platform actuator **140**. The rotary encoder of the platform actuator **140** produces a signal indicating a rotational position of the platform **110**, which are received at the port **418**. The DAC **414** also includes a port **420** for producing control signals for controlling the base actuator **144**. The rotational encoder **151** of the base actuator **144** produces a signal indicating a rotational position of the base **132**, which are received at the port **420**. The DAC **414** also includes a port **422** for producing control signals for controlling the arm actuator **314** and a port **424** for producing control signals for controlling the translation actuator **336** of the manipulator **122**. Signals from the encoders associated with the actuators **314** and **336** are received at the respective ports **422** and **424**. The DAC **414** also includes a port **426** for producing control signals for controlling the hub drives **150** of the respective drive wheels **104** for moving and steering the wheeled chassis **102** of the apparatus **100**.

Program codes for directing the microprocessor **400** to carry out various functions are stored in a location **430** of the memory **402**, which may be implemented as a flash memory, for example. The program codes **430** direct the microprocessor **400** to implement an operating system (such as Microsoft Windows for example) and to perform various other system functions associated with operation of the apparatus **100**. The memory **402** also includes variable storage locations **432** for storing variable and parameter data associated with operation of the apparatus **100**.

In other embodiments (not shown), the controller **160** may be partly or fully implemented using a hardware logic circuit including discrete logic circuits, an application specific integrated circuit (ASIC), and/or a field-programmable gate array (FPGA), for example.

Referring to Figure **7**, a flowchart depicting blocks of code for directing the controller processor circuit **160** to control autonomous loading operations of the apparatus **100** is shown at **500**. The blocks generally represent codes that may be read from the program codes location **430** of the memory **402** for directing the microprocessor **400** to perform various loading functions. The actual code to implement each block may be written in any suitable program language, such as C, C++, C#, Java, and/or assembly code, for example.

A plan view of the apparatus **100** performing the loading process **500** is provided in Figures **8**A – **8**F as an example of a typical loading operation for the apparatus **100**. The loading process **500** starts at block **502**, which directs the microprocessor **400** to receive signals produced by the LIDAR proximity sensor **154** at the wired network interface **410** of the I/O **404**. Referring to Figure **8**A, a plurality of articles to be loaded at a pickup location **602** is shown generally at **604**. The LIDAR proximity sensor **154** is operable to detect articles within a range of angles indicated by broken lines **608** and **610** in Figure **8**A. In one embodiment, standard dimensions for articles to be loaded are stored in the memory **402** (for example a height *H* and a width *W*) and block **502** directs the microprocessor **400** read the *H* and *W* values and to determine whether the received LIDAR signals include data that corresponds to these dimensions. Articles that generate LIDAR data signals that generally match the standard dimensions are identified as articles to be loaded at the pickup location **602**.

Block **504** directs the microprocessor **400** to output signals at the USB interface **412** of the I/O **404**, which cause the DAC **414** to generate wheel drive signals at the port **426** for controlling the respective hub drives **150** of the drive wheels **104**. The generated drive signals control the respective hub drives **150** for steering the wheeled chassis **102** toward a first detected article **606** of the plurality of articles **604**.

Block **506** then directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **422** for causing the arms **306** and **308** to be positioned for loading by causing the arm translation actuator **336** to translate the arms outwardly to accommodate the width of the detected article. Block **506** also directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **422** for causing the arm rotation actuator **314** rotate the arms **306** and **308** about the spline shafts **310** and **312** until the end effectors **124** and **126** are positioned at height corresponding to the height *H* of the article **604**. Referring to Figure **8**B, in this embodiment the when positioned for loading, the arms **306** and **308** are spaced apart at a distance slightly exceeding the width *W* of the article **606**, either based on the standard dimensions saved in memory **402** or based on a measured dimension of the article from the LIDAR data.

Block **508** then directs the microprocessor **400** to generate wheel drive signals at the port **426** to advance and steer the wheeled chassis **102** to align the arms **306** and **308** such that the respective end effectors **124** and **126** are aligned to grasp the article **606** at diametrically opposing surfaces thereof, as shown in Figure **8**B. Block **510** then directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **422** for causing the arms **306** and **308** to translate inwardly to engage the article **606**.

The loading process **500** then continues at block **512**, which directs the microprocessor **400** to determine whether there is a vacant loading position available on the platform **110**. If there is a vacant loading position available (in the example shown in Figure **8**B the platform is empty), then the microprocessor **400** is directed to block **514**. In one embodiment, the number of positions on the platform **110** than can be occupied by articles **604** is determined based on the width *W* of the articles. A register of the number of positions already filled may also be stored in memory **402**, and used by the microprocessor **400** to determine whether there is a vacant position remaining on the platform **110**.

Block **514** directs the microprocessor **400** to cause the DAC **414** to generate platform actuation signals at the port **418** for causing the platform **110** to rotate to align a vacant position **612** (shown in broken outline) behind the arms **306** and **308** of the manipulator **122**. In the example shown in Figure **8**B, since the platform **110** is empty, no rotational movement of the platform is necessary, but if any articles had already been loaded the platform would need to be rotated to align a vacant position behind the arms **306** and **308** of the manipulator **122**.

While blocks **512** and **514** are depicted as following sequentially after blocks **502** – **510**, in practice the functions of these blocks may be performed in parallel with other functions. Similarly, the functions of blocks **506** and **510** may also be performed in parallel with functions **504** and **508**.

Block **516** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **422** to cause the the arm rotation actuator **314** to rotate the arms **306** and **308** upwardly about the spline shafts **310** and **312** towards the platform **110** (as shown in broken outline in Figure **8**C) and over the center toward the vacant position **612** on the platform **110**.

Block **518** then directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **422** for causing the arm translation actuator **336** to translate the arms **306** and **308** outwardly to disengage the article **606**, as shown in Figure **8**C. Block **518** also direct the microprocessor **400** to return the arms to the loading position by causing the DAC **414** to output signals for causing the arm actuator **314** to rotate the arms **306** and **308** back to the forward oriented position as shown in Figure **8**B. Block **518** may also cause blocks **512** and **514** to be repeated to cause the platform actuator **140** to rotate the platform **110** to align a vacant position for loading the next article behind the arms **306** and **308** of the manipulator.

The loading process **500** then continues at block **520**, which directs the microprocessor **400** to receive signals produced by the LIDAR proximity sensor **154** at the wired network interface **410** of the I/O **404**. Block **522** then directs the microprocessor **400** to determine whether further articles are detected, in which case block **522** directs the microprocessor back to block **504** to repeat blocks **504** – **512**. If no further articles are detected, then block **522** directs the microprocessor **400** to block **526**, which causes the DAC **414** to generate wheel drive signals at the port **426** for steering the wheeled chassis **102** toward a drop-off location (not shown in Figure **8**).

If at block **512**, there is no vacant loading position on the platform **110**, the microprocessor **400** is directed to block **524**. Block **524** directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **422** for causing the arm actuator **314** to elevate the article **606** off the ground and to hold the article in the arms for transport. Advantageously, even though there are no vacant positions on the platform **110**, an additional article may be carried in the pair of end effectors **124** and **126**. Block **526** then directs the microprocessor **400** to cause the DAC **414** to generate wheel drive signals at the port **426** for steering the wheeled chassis **102** toward a drop-off location (not shown in Figure **8**).

In the process **500** as described above, the platform actuator **140** positions the platform **110** such that successive vacant loading positions on the platform are disposed to receive articles **604**. Additionally or alternatively, the base actuator **144** may be actuated together with the platform actuator **140** at block **506** to facilitate efficient movement of loading of articles. An alternative embodiment of the functions implemented at block **506** is shown in Figure **9**. Referring back to Figure **8**C, following loading of the article **606**, the LIDAR proximity sensor **154** may detect an article **614** in the plurality of articles **604** as the next article to be loaded. Referring to Figure **9**, block **700** directs the microprocessor **400** to cause the DAC **414** to generate signals for rotating the arms **306** and **306** to a correct loading height *H* for picking up the article **614** and block **702** directs the microprocessor **400** to cause the DAC **414** to generate signals for translating the arms **306** and **306** to a correct width *W* for engaging the article **614**.

Block **704** then directs the microprocessor **400** to cause the DAC **414** to generate wheel drive signals at the port **426** to move the wheeled chassis toward the article **614**. As shown in Figure **8**C, the wheels remain oriented to move the wheeled chassis **102** in a direction indicated by the arrow **616**. Referring to Figure **8**D, and Figure **9**, block **706** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **420** for causing the base actuator **144** to rotate the base **132** and the attached manipulator **122** in the direction indicated by the arrow **618**. Block **708** then directs the microprocessor **400** to receive proximity signals from the proximity sensor **154** at the wired network interface **410** of the I/O **404**. Block **710** then directs the microprocessor **400** to determine whether the apparatus **100** is aligned for loading of the article **614**. If at block **710** the apparatus **100** is not yet aligned for loading of the article **614**, block **710** directs the microprocessor back to block **704** and blocks **704** – **708** are repeated to perform further movement iterations until at block **710**, it is determined that the apparatus is aligned for loading as shown in Figure **8**D. While blocks **704** and **708** are shown being sequential in Figure **9**, the movement functions could also be performed in parallel. The article **614** is then loaded into a vacant position **620** as described above in connection with blocks **512** – **520** or blocks **524** and **526**. When the platform **110** is rotated to place the vacant position **620** behind the manipulator arms **306** and **308**, the rotation of the base **132** is taken into account and the loading operation thus involves coordinated movements of the wheeled chassis **102**, base **132**, and platform **110**. Block **710** then directs the microprocessor **400** to block **510** of the process **500**, where the microprocessor is directed to cause the DAC **414** to produce signals at the port **422** for causing the arms **306** and **308** to translate inwardly to engage the article.

Referring to Figure **8**E, on completion of the process loading process **500**, the platform **110** has **5** of the plurality of articles **604** loaded on the platform **110** and a sixth article **622** held for transport in end effectors **124** and **126**. As described above, block **526** directs the microprocessor **400** to generate wheel drive signals to steer the wheeled chassis toward a drop-off location **624**. In the embodiment shown in Figure **8**E, two articles **626** have already been dropped off at the drop-off location **624**. The on-board controller **160** monitors signals produced by the LIDAR proximity sensor **154** to avoid colliding with any obstacles, such as the forklift truck.

Referring to Figure **10**, a flowchart depicting blocks of code for directing the controller processor circuit **160** to control autonomous unloading operations of the apparatus **100** is shown at **800**. The process begins at block **802**, which directs the microprocessor **400** to receive LIDAR signals from the proximity sensor **154** at the wired network interface **410** of the I/O **404** and to process the signals to detect already unloaded articles at the drop-off location **624**.

Two articles **626** have already been unloaded at the drop-off location **624**. Block **804** then directs the microprocessor **400** to identify a next open space with respect to the articles **626**. Referring to Figure **11**A, in the embodiment shown articles are to be spaced apart by a distance *D* and aligned along a datum line **900**. The distance *D* may be calculated based on the width *W* of the articles and such that there remains sufficient space between adjacent articles to permit the end effectors **124** and **126** to be maneuvered. The next open space is identified at **902**, and block **806** directs the microprocessor **400** to cause the DAC **414** to generate wheel drive signals at the port **426** to cause the wheeled chassis **102** to move toward the next open space **902** and to position the article **622** (held in the end effectors **124** and **126**) above the open space. Block **808** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **422** to cause the arms **306** and **308** to rotate to lower the article **622** into the open space **902**. Block **808** also directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **424** to translate the arms **306** and **308** outwardly to disengage the article **622**.

Block **810** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **422** to cause the arms **306** and **308** to be raised to clear the article. Block **812** then directs the microprocessor **400** to cause the DAC **414** to generate wheel drive signals to orient the wheeled chassis **102** for lateral movement in a direction **904** aligned with the datum line **900** along which the already unloaded articles **626** and **622** are aligned. Block **814** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **420** to cause the base actuator **144** to rotate the base **132** to re-orient the manipulator **122** toward the articles **626** as shown in Figure **11**B. Block **814** further directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **418** to cause the platform actuator **140** to rotate the platform **110** in a direction indicated by the arrow **906** to align an article **908** on the platform behind the manipulator **122**. Block **816** then directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **422** to align the arms **306** and **308** such that the respective end effectors **124** and **126** are aligned to grasp the article **908** at diametrically opposing surfaces thereof, as shown in Figure **11**B. Block **816** also directs the microprocessor **400** to cause the DAC **414** to produce signals at the port **424** to cause the end effectors **124** and **126** to grasp the article **908**, and to produce signals at the port **422** to lift the article over the center and lower the article into a next open space **910**. Block **818** then directs the microprocessor **400** to cause the DAC **414** to generate signals at the port **424** to translate the arms **306** and **308** outwardly to disengage the article **908**. The article **906** is again aligned with the datum line **900** and placed a distance *D* from the article **622**.

The process **800** then continues at block **820**, which directs the microprocessor **400** to determine whether there are further articles remaining on the platform to be unloaded. As described above, a register for the number of loaded articles is stored in the memory **402** and is read and updated by the microprocessor each time an article is unloaded from the platform **110**. If at block **820** further articles are still to be unloaded, the microprocessor **400** is directed to block **822**, which directs the microprocessor to cause the DAC **414** to generate wheel drive signals at the port **426** to cause a further lateral movement corresponding to the distance *D* in the direction **904** for unloading the next article into an open space **914**. Block **822** then directs the microprocessor **400** back to block **814** and blocks **814** – **820** are repeated for each remaining article on the platform **110**.

If at block **820**, no further articles remain on the platform, then the unloading process ends at **824**. In the embodiment shown, the combination of the rotatable base **132** and rotatable platform **110** advantageously allow orientation of the wheels **104** for movement in the direction **904**. Subsequent lateral movements of the wheeled chassis **102** by the distance *D* facilitate rapid unloading of articles from the platform. In embodiments having a fixed base **132**, following placement of the article in the open space **902**, each subsequent unload would require a reversing movement of the wheeled chassis **102** to clear the unloaded article followed by a forward movement of the wheeled chassis to align with the next open space.

In the embodiment shown in Figures **11**A – **11**C, the articles are aligned along a single datum line **900**. In other embodiments, articles may be unloaded to align with a plurality of spaced apart datum lines such that articles are placed in several rows. The autonomous unloading operations of the apparatus **100** result in a precise alignment of the articles and also precise spacing *D* between articles. The precise alignment and spacing provided by the autonomous unloading has the advantage of conserving space at the drop-off location **624**, which may accommodate a greater number of articles than if manually placed.

An alternative embodiment of an apparatus for transporting a plurality of articles is shown in Figure **12** at **1000**. Referring to Figure **12**, the apparatus **1000** includes all of the components of the apparatus **100** shown in Figure **1**, including the wheeled chassis **102** having drive wheels **104** and castor wheels **106**, the base **132** and platform **110**, and the manipulator **122**. The apparatus **1000** further includes one or more tools operably configured to perform an operation on the plurality of articles **114** while being transported on the wheeled chassis **102**. In the embodiment shown, a plurality of tool supports **1002**, **1004**, **1006**, and **1008** are coupled to the base **132**. The tool support **1002** has a spraying tool **1010** mounted on the support. The spraying tool **1010** is operable to draw a liquid plant protection product, such as a pesticide, contained in a reservoir **1012** and to spray the liquid onto a plant articles in the plurality of articles **114** disposed in a path of the spray. The tool support **1004** has a robotic arm **1014** mounted on the support. In one embodiment the robotic arm **1014** may be an articulated robot such as a SCARA (Selective Compliance Articulated Robot Arm), which is simple to mount on the tool support **1004** and has a small footprint. In embodiments where the articles **114** are plant pots operations such as trimming, sticking, or other operations may be performed by the articulated robot. The apparatus **1000** also includes a plurality of cameras **1018**, **1020**, **1022**, and **1024** mounted on respective supports **1006** and **1008**, which are operable to generate images facilitating inspection of the plurality of articles **114**. In other embodiments, the apparatus **1000** may only have a single tool and tool support. Alternatively, in some embodiments more than four tools may be provided.

Further examples of tools that me be mounted on one of the plurality of tool supports **1002** – **1008**, include a labeling machine, a **3**D printer head, a drilling and/or milling machine, a cutting and trimming machine, a monitoring apparatus, etc.

Actuation of the platform actuator **140** causes the platform **110** to rotate in the direction **128** to dispose successive articles in the plurality of articles **114** to be operated on by the spraying tool **1010**, robotic arm **1014**, and inspection cameras **1016** – **1022**. In the embodiment shown where the base **132** is rotatable with respect to the wheeled chassis **102**, the plurality of tool supports **1002** – **1008** would thus also move with the base. As an alternative, the platform **110** may be held in a fixed rotational orientation while the base **132** is rotated to cause the tools, **1012**, **1014**, and **1016** – **1022** to be successively disposed to perform operations on each of the plurality of articles **114**. In the embodiment described above where the platform is not rotatable, the rotatable base **132** would thus provide for rotational movement to dispose each tool to operate on the articles. In the other disclosed embodiment, where the base **132** is fixed and the manipulator **122** is thus not moveable w.r.t. the wheeled chassis **102**, rotational movement of the platform **110** thus disposes each of the plurality of articles **114** to be operated on by each tool.

The upper surface **112** of the platform **110** thus accommodates several articles on which operations can be performed while the apparatus **100** is moving between the pickup location **602** and the drop-off location **624**. This has the advantage over prior-art systems that need to transport articles to a fixed station where operations are performed on the plurality of articles **114** before transporting the articles to the drop-off location **624**. The relatively large upper surface **112** of the platform **110** also accommodates several articles (in this case **6** articles) for both transport to the drop-off location **624** and simultaneous performing of operations using the tools **1012**, **1014**, and **1016 – 1022**.

In Figure **1**, the proximity sensor **154** of the apparatus embodiment **100** was disclosed as being implemented using a single LIDAR sensor. In the apparatus embodiment **1000** shown in Figure **12**, the proximity sensor **154** is implemented using a LIDAR sensor **1024** and an infrared sensor **1026**, where the infrared sensor **1026** performs close range proximity detection and the LIDAR sensor performs mid-range and long-range proximity detection. Some LIDAR sensors do not provide sufficient resolution for close range objects, while new LIDAR sensors that have recently become available may provide sufficient resolution at close range. As an example, the infrared sensor **1026** may be used for detection of objects within a range of about **100** cm, while the LIDAR sensor **1024** may be used to cover ranges between about **15** cm and **6** meters.

Referring back to Figure **1**, the apparatus **100** may further include a pair of spaced apart mounts **162** and **164** that carry the respective UWB transceivers **416** and **417** (shown in Figure **6**). The UWB transceivers **416** and **417** are operable to receive and/or transmit radio frequency (RF) positioning signals. Ultra-wideband transceivers use a low energy level RF pulse transmission over a wide bandwidth for short-range communications and are commonly used in precision locating and tracking applications. UWB pulses have low energy and in addition to requiring less operating power, also generally do not conflict with other wireless signals. In the embodiment shown, the UWB transceivers **416** and **417** are implemented using the DWM**1000** UWB wireless transceiver module manufactured by DecaWave of Dublin, Ireland, which facilitates location of objects to a precision of about **10** centimeters indoors over a range of up to about **300** meters. For the UWB transceivers **416** and **417** on the apparatus **100**, the DWM**1000** module is configured as a "tag", for which the position is to be tracked.

Figure **13** shows a plan view of an area **1100** such as a plant nursery floor. A plurality of articles (in this case, plants in pots) are to be transported on the wheeled chassis **102** of the apparatus **100** between a pickup location **1102** and an intended drop-off location **1104** within the area **1100**. Referring to Figure **13**, a positioning system shown generally at **1106** includes a pickup beacon **1108** positioned proximate a plurality of articles **1110** at the pickup location **1102**. The positioning system **1106** also includes a left drop-off beacon **1112** positioned proximate the intended drop-off location **1104** and a right drop-off beacon **1114** positioned proximate drop-off location **1104**. The left drop-off beacon **1112** and right drop-off beacon **1114** define a datum **1116** for indicating a desired alignment of articles at the drop-off location **1104**.

Each of the beacons **1108**, **1112**, and **1114** includes a transceiver for receiving and/or transmitting positioning signals. In one embodiment of the positioning system **1106**, the beacons **1108**, **1112**, and **1114** may also each include a DWM**1000** UWB wireless transceiver module configured as an "anchor", which provides fixed reference points for locating the apparatus **100** within the area **1100**. The UWB transceivers **416** and **417** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** each include a wireless interface, and are able to transmit and receive data signals from each other including timing information. In one embodiment communications between the UWB transceivers **416** and **417** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** may be in accordance with the IEEE **802.15.4** protocol for low-rate wireless personal area networks. The UWB transceivers **416** and **417** on the apparatus **100** are in communication with the on-board controller **160** via a USB interface **412**, as shown in Figure **6**. Advantageously, the UWB transceivers **416** and **417** and the UWB transceivers on the beacons **1108**, **1112**, and **1114** provide accurate real time positioning of the apparatus **100** within a workspace that does not rely on tracking movements of the drive wheels **104** or hub drive **150**.

The pickup beacon **1108** is used to generally indicate the pickup location **1104** where the plurality of articles **1110** are located. In this embodiment the datum **1116** provided by the left drop-off beacon **1112** and right drop-off beacon **1114** indicate a desired alignment of a plurality of articles **1122** at the drop-off location **1106**. In Figure **13** articles in the plurality of articles **1122** that have already been unloaded have been aligned along a line **1124**, which is spaced apart from the datum **1116** by a distance *S*.

In order to determine the position of the UWB transceivers **416** and **417** it is necessary to first establish the location of each of the beacons **1108**, **1112**, and **1114** in a local coordinate frame **1126**. In one embodiment, the beacons **1108**, **1112**, and **1114** may be placed at arbitrary fixed positions and the UWB transceivers **416** and **417** and on-board controller **160** may be configured to locate each of the beacons within the local coordinate frame **1126**.

Referring to Figure **14**, a flowchart depicting blocks of code for directing the controller **160** to locate arbitrarily positioned beacons **1108**, **1112**, and **1114** in the local coordinate frame **1126** is shown generally at **1200**. The process **1200** begins at block **1202**, which directs the controller **160** to cause the UWB transceivers **416** and **417** on the apparatus **100** to initiate transmission of positioning signals, which are received by the UWB transceivers on each beacon **1108**, **1112**, and **1114**. The UWB transceivers transmit signals over a wide bandwidth, which is equivalent to transmission of a very precise narrow pulse (about **1** nanosecond) in the time domain and facilitates accurate determination of a time of flight (*TOF*) for each transmitted pulse. In one embodiment the UWB transceivers may implement two-way ranging in which the transceivers exchange timing information over several transmissions between the transceivers to provide for precise *TOF* measurements. Signals received back at the transceivers **416** and **417** from the beacons **1108**, **1112**, and **1114** are processed to calculate distances d_i corresponding to the determined *TOF* for each pulse transmission. The distances between each beacon are given by:

$$d_i = TOF * c; \qquad \text{Eqn } \mathbf{1}$$

where d_i is the calculated distance and c is the speed of light. When two-way ranging is implemented, each distance d_i is calculated based on several transmissions between transceivers, and thus provides an improved distance measurement between beacons. As described above in connection with Figure **6**, the UWB transceivers **416** and **417** are in communication with the microprocessor **400** of the on-board controller **160** and the *TOF* and/or the distances d_i are thus made available to the controller **160** for further processing via the USB interface **412** to the transceivers. In some embodiments the on-board controller **160** may receive *TOF* information and calculate the distances at the controller. In other embodiments received position data may already be converted into distances.

Block **1206** then directs the controller **160** to establish the local coordinate frame **1126** with respect to the beacons **1108**, **1112**, and **1114**. This involves designating one beacon as an origin of the local coordinate frame **1126** (in this case the left drop-off beacon **1112**), designating another beacon as defining a direction of the positive x-axis (in this case the right drop-off beacon **1114**), and establishing the y-axis perpendicular to the x-axis. Block **1208** then directs the controller **160** to use the calculated distances to determine the position of the remaining beacons (i.e. in this case the right drop-off beacon **1114** and the right drop-off beacon **1114** right drop-off beacon **1114**) within the local coordinate frame **1126**. The beacons **1108**, **1112**, and **1114**, while placed in arbitrary positions thus facilitate establishment of a fixed frame of reference **1126** for the positioning system **1106**.

Referring to Figure **15**, a flowchart depicting blocks of code for directing the on-board controller **160** of the apparatus **100** determine its position within the area **1100** is shown generally at **1300**. The process **1300** begins at block **1302**, which directs the microprocessor **400** of the on-board controller **160** to cause the UWB transceivers **416** and **417** to transmit positioning pulses, generally as described above. The transmission of the positioning pulses, when received at the beacons **1108**, **1112**, and **1114** cause transmission of return positioning pulses from the beacons including data related to the *TOF* associated with the pulse transmission. The process **1300** then continues at block **1304**, where the positioning pulses are received back at the UWB transceivers **416** and **417** and three distances d_i are calculated for each of the UWB transceivers based on the determined *TOF* as described above.

At block **1306**, the distances d_i are provided to the microprocessor **400** for further processing. Block **1308** then directs the microprocessor **400** to uniquely locate the UWB transceivers **416** and **417** in the local coordinate frame **1126** with respect to the beacons **1108**, **1112**, and **1114**. The location process generally involves finding the intersection between circles centered at each of the beacons **1108**, **1112**, and **1114** and having a respective radius of d_i. In practice, noise and other errors will likely not yield a unique intersection point, but probabilistic methods such as a least squares approximation may be used to provide a relatively precise estimate of the location of each sensor. If a more a precise estimation of the location of the sensors **416** and **418** is required, an additional beacon (not shown) may be added to further reduce uncertainties associated with the position calculation. The process **1300** will generally be repeated at a repetition rate sufficient to locate the apparatus **100** in real-time or near-real time, while reducing the power consumption of the transceivers that may be powered by batteries.

The apparatus **100** may use the positional information for navigating the wheeled chassis to pick up articles from the plurality of articles **1110** at the pickup location **1104** and to move between the pickup location and the drop-off location **1106**, and to place articles in the plurality of articles proximate the destination location. The position of the apparatus **100** may be derived from the positions of the UWB transceivers **416** and **417**, for example by taking a midpoint between the positions for each of the UWB transceivers **416** and **417** or some other reference point on the wheeled chassis **102**. Additionally, the respective positions provided for the spaced apart mounts **162** and **164** provide sufficient separation between the UWB transceivers **416** and **417** to permit determination of an orientation or heading of the apparatus **100** within the local coordinate frame **1126** for the positioning information provided by the respective transceivers.

In one embodiment, the real-time location and orientation provided by the positioning system may be used for steering the wheeled chassis along a path **1224** between the pickup location **1104** and drop-off location **1106**. Additionally, the LIDAR proximity sensor **154** may simultaneously receive proximity signals indicative of obstacles in the path of the wheeled chassis **102**. The microprocessor **400** may use the received proximity signals from the LIDAR proximity sensor **154** and the positional information provided by the positioning system to modify the path **1224** of the wheeled chassis to avoid detected obstacles.

When the wheeled chassis **102** is within a pre-determined range of the pickup location **1104**, the proximity signals received from the proximity sensor **154** may be processed by the microprocessor **400** to determine whether obstacles in the path of the wheeled chassis **102** correspond to any of the plurality of articles **1110** to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles. In general, LIDAR and/or other proximity signals provided by the proximity sensor **154** may be used in combination with data provided by the UWB transceivers **416**, **417** on the apparatus **100** and the UWB transceivers on each beacon **1108**, **1112**, and **1114** to provide details of the environment, articles **1110** and **1122**, obstacles, and the position of the apparatus **100** within the area **1100**. Based on this information, the apparatus **100** may determine the path **1224** and make necessary adjustments to the path during movement.

Similarly, when path **1224** of the wheeled chassis **100** is within a pre-determined range of the drop-off location **1106**, the microprocessor **400** may cause the wheeled chassis **102** to steer to a first location defined with respect to the second beacon **1112** (and/or the first beacon **1112**) for unloading a first article at the **1106**. Subsequently, for additional articles in the plurality of articles **1110** the microprocessor **400** may cause the wheeled chassis to steer to successive locations (for example the location **1226**) defined with respect to the first and second beacons **1112** and **1114** for unloading of subsequent articles in the plurality of articles.

While specific embodiments have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.

What is claimed is:

1. An apparatus for transporting a plurality of articles, the apparatus comprising:

a wheeled chassis;

a platform disposed on the wheeled chassis;

a manipulator coupled to the wheeled chassis and operably configured to:

load a first article of the plurality of articles at a first position on the platform; or

unload the first article of the plurality of articles from the first position on the platform; and

at least one actuator operably configured to cause successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform for loading or unloading each subsequent article in the plurality of articles.

2. The apparatus of claim **1** wherein the at least one actuator is operably configured to cause one of a rotary movement of the platform about the wheeled chassis and a rotary movement of the manipulator about the wheeled chassis.

3. The apparatus of claim **1** wherein the manipulator is coupled to base rotatable with respect to the wheeled chassis and wherein the at least one actuator comprises:

a base actuator operably configured to cause rotary movement of the base and the manipulator about the wheeled chassis;

a platform actuator operably configured to cause rotary movement of the platform about the wheeled chassis; and

wherein the base actuator and the platform actuator are operable to cause successive relative rotational movements of both the manipulator and the platform about the wheeled chassis for providing access for loading or unloading each subsequent article in the plurality of articles.

4. The apparatus of claim **3** wherein the manipulator is coupled to the wheeled chassis via a support and wherein the base actuator is operably configured to cause rotary movement of the support about the wheeled chassis.

5. The apparatus of claim **3** wherein the wheeled chassis comprises at least one drive for driving wheels of the wheeled chassis and further comprising a controller operably configured to:

cause the at least one drive to orient the wheeled chassis for movement in a direction aligned to pick up or place the plurality of articles in a line;

cause the base actuator to cause rotary movement of the manipulator about the wheeled chassis to orient the manipulator for loading or unloading the plurality of articles; and

cause the platform actuator to cause rotary movement of the platform to:

after loading each article, dispose an empty location on the platform in reach of the manipulator for loading a subsequent article; or

dispose a subsequent article on the platform in reach of the manipulator for unloading.

6. The apparatus of claim **1** wherein the wheeled chassis comprises a drive for driving at least one wheel of the wheeled chassis and further comprising a controller operably configured to control the drive to orient the wheeled chassis to align the manipulator for loading or unloading each of the first article and the subsequent articles.

7. The apparatus of claim **1** wherein the manipulator comprises:

a pair of outwardly directed spaced apart arms operably configured to grasp the article;

an arm actuator, operably configured to vertically rotate the arms toward the platform while the article is suspended between the arms; and an end effector distally disposed on each respective arm and wherein the end effectors are operably configured to grasp the article and suspend the article during vertical movement of the arms.

8. The apparatus of claim **7** wherein the arms are mounted for vertical rotation on a driven shaft and wherein the end effectors are coupled to the shaft via a belt such that rotation of the arms causes a respective rotation of the end effectors for maintaining an orientation of the end effectors while grasping the article.

9. The apparatus of claim **7** wherein the pair of outwardly directed spaced apart arms are mounted for one of lateral movement and rotational movement about a pivot to cause the pair of end effectors to move to grasp or release the article.

10. The apparatus of claim **1** further comprising at least one tool operably configured to perform an operation on the articles while transporting the plurality of articles on the wheeled chassis.

11. The apparatus of claim **10** wherein the at least one tool is coupled to the manipulator such that causing rotary movement between the manipulator and the platform provides access to each article for performing the operation.

12. The apparatus of claim **11** wherein the manipulator and the at least one tool are respectively coupled to a common base mounted for rotation on the wheeled chassis such that rotary movement of the common base causes rotary movement of each of the manipulator and the at least one tool.

13. The apparatus of claim **10** wherein the at least one tool is coupled to the wheeled chassis such that causing rotary movement between the wheeled chassis and the platform provides access to each article for performing the operation.

14. A method of transporting a plurality of articles on a wheeled chassis, the method comprising:

causing a manipulator coupled to the wheeled chassis to:

load a first article of the plurality of articles at a first position on a platform disposed on the wheeled chassis; or unload the first article of the plurality of articles from the first position on the platform; and

causing successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform; and

causing the manipulator to load or unload each subsequent article of the plurality of articles to or from the successive rotationally spaced apart positions on the platform.

15. The method of claim **14** wherein causing successive relative rotational movements comprises one of causing rotary movement of the platform about the wheeled chassis and causing rotary movement of the manipulator about the wheeled chassis.

16. The method of claim **15** wherein causing successive relative rotational movements comprises causing rotary movement of both the manipulator and the platform about the wheeled chassis.

17. The method of claim **16** wherein causing rotary movement of both the manipulator and the platform about the wheeled chassis comprises:

causing the wheeled chassis to be aligned for movement in a direction aligned to pick up or place the plurality of articles along a line;

causing rotary movement of the manipulator to orient the manipulator for loading or unloading the plurality of articles; and

causing rotary movement of the platform to:

after loading each article, dispose an empty location on the platform in reach of the manipulator for loading a subsequent article; or

dispose a subsequent article on the platform in reach of the manipulator for unloading.

18. The method of claim **14** further comprising controlling a drive associated with at least one wheel of the wheeled chassis to orient the wheeled chassis to align the manipulator for loading each of the first article and the subsequent articles.

19. The method of claim **16** further comprising operating at least one tool to perform an operation on the articles while transporting the plurality of articles on the wheeled chassis.

20. The method of claim **19** wherein operating the at least one tool comprises causing rotational movement between the at least one tool and the platform to provide access to each article for performing the operation.

21. The method of claim **20** wherein causing rotational movement between the at least one tool and the platform comprises causing rotational movement of the manipulator, the at least one tool being coupled to the manipulator.

22. A method for transporting a plurality of articles between a pickup location and an intended drop-off location on a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis, the method comprising:

positioning a pickup beacon proximate the plurality of articles at the pickup location;

positioning a left drop-off beacon and a right drop-off beacon on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the respective location;

receiving location signals at transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis;

processing the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons;

navigating the wheeled chassis using the determined location and orientation of the wheeled chassis to:

pick up successive articles of the plurality of articles proximate the pickup location;

move between the pickup location and the drop-off location; and

place articles proximate the drop-off location.

23. The method of claim **22** wherein receiving location signals comprises:

transmitting ultra-wideband (UWB) signals at the transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis; and

receiving the UWB signals at the other transceivers disposed on each of the beacons and at the pair of transceivers on the wheeled chassis.

24. The method of claim **22** wherein navigating comprises:

using the location signals to determine a real-time location and orientation for steering the wheeled chassis along a path between the pickup location and drop-off location;

receiving proximity signals indicative of obstacles in the path of the wheeled chassis; and

using the received proximity signals and location signals to modify the path of the wheeled chassis to avoid detected obstacles.

25. The method of claim **24** wherein receiving the proximity signals comprises generating proximity signals using at least one of an optical sensor, an infrared sensor, light detection and ranging (LIDAR) sensor, and an ultrasonic sensor.

26. The method of claim **24** wherein receiving the proximity signals comprises receiving:

a first proximity signal from an infrared sensor operably configured to indicate close range obstacles; and

a second proximity signal from a light detection and ranging (LIDAR) sensor indicating mid and far range obstacles.

27. The method of claim **24** further comprising, when the path of the wheeled chassis is within a pre-determined range of the pickup location, processing the received proximity signals to determine whether obstacles in the path of the wheeled chassis correspond to any of the plurality of articles to be transported, and in response causing the wheeled chassis to steer towards one of the articles in the plurality of articles.

28. The method of claim **24** further comprising, when path of the wheeled chassis is within a pre-determined range of the drop-off location, causing the wheeled chassis to steer to a first location defined with respect to one of the left drop-off beacon and the right drop-off beacon for unloading of a first article.

29. The method of claim **28** further comprising causing the wheeled chassis to steer to successive locations defined with respect to the one of the left drop-off beacon and the right drop-off beacon for unloading of a second article and subsequent articles in the plurality of articles.

30. A system for transporting a plurality of articles between a pickup location and an intended drop-off location, the system comprising:

a wheeled chassis having a pair of transceivers disposed in spaced apart relation on the wheeled chassis;

a pickup beacon positioned proximate the plurality of articles at the pickup location;

a left drop-off beacon and a right drop-off beacon positioned on either side of the intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the respective location, each beacon including a transceiver; and

wherein the transceivers on the beacons and the pair of transceivers on the wheeled chassis are operably configured to receive location signals and process the location signals to determine a location and orientation of the wheeled chassis with respect to the beacons for navigating the wheeled chassis to pick up articles in the plurality of articles proximate the pickup location, to move between the pickup location and the drop-off location, and to place articles in the plurality of articles proximate the drop-off location.

31. The system of claim **30** wherein the transceivers disposed on each beacon and the pair of transceivers on the wheeled chassis comprise ultra-wideband (UWB) transceivers.

32. The system of claim **30** further comprising at least one proximity sensor disposed on the wheeled chassis, the proximity sensor being operable to provide an indication of obstacles in the path of the wheeled chassis.

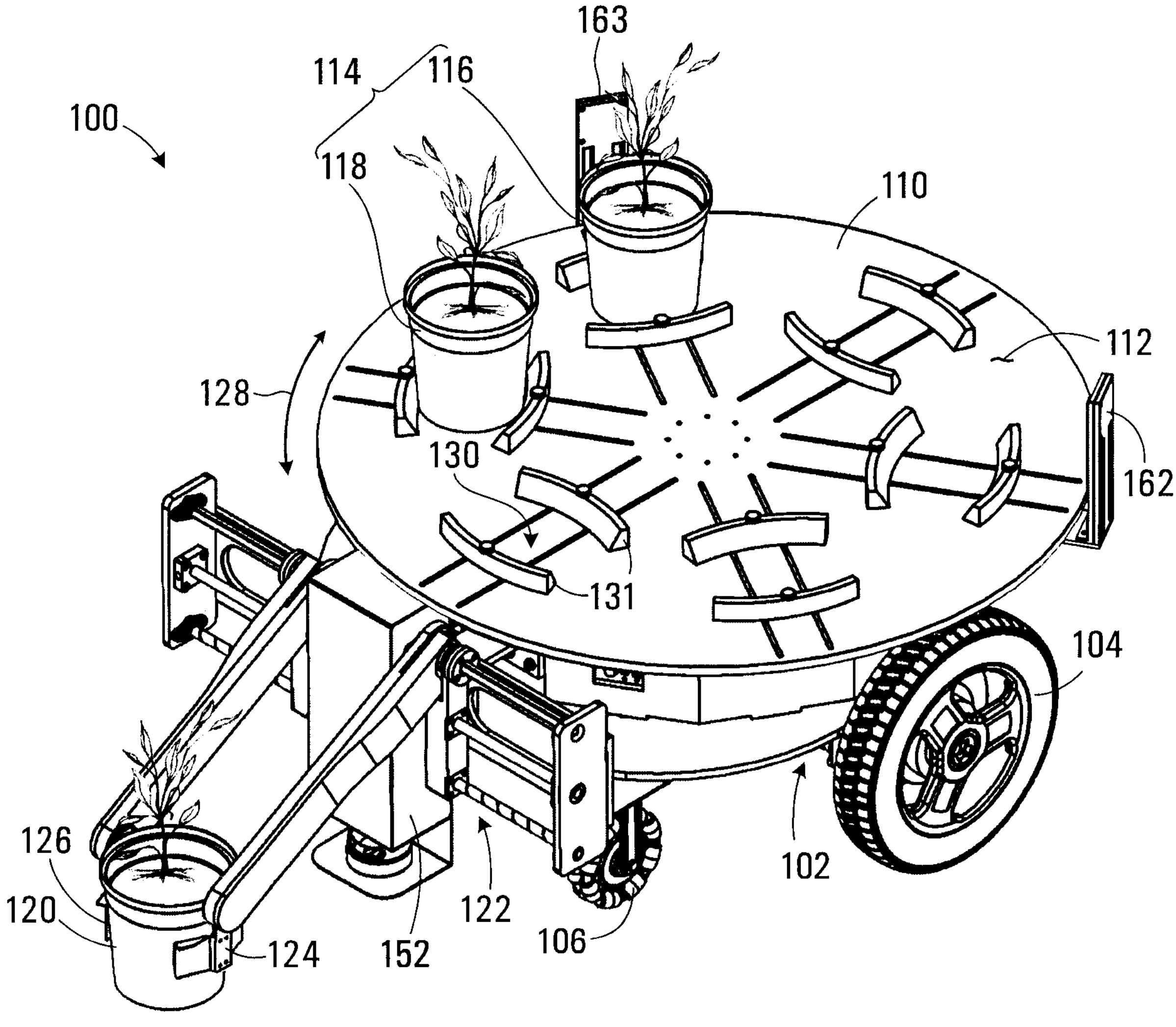
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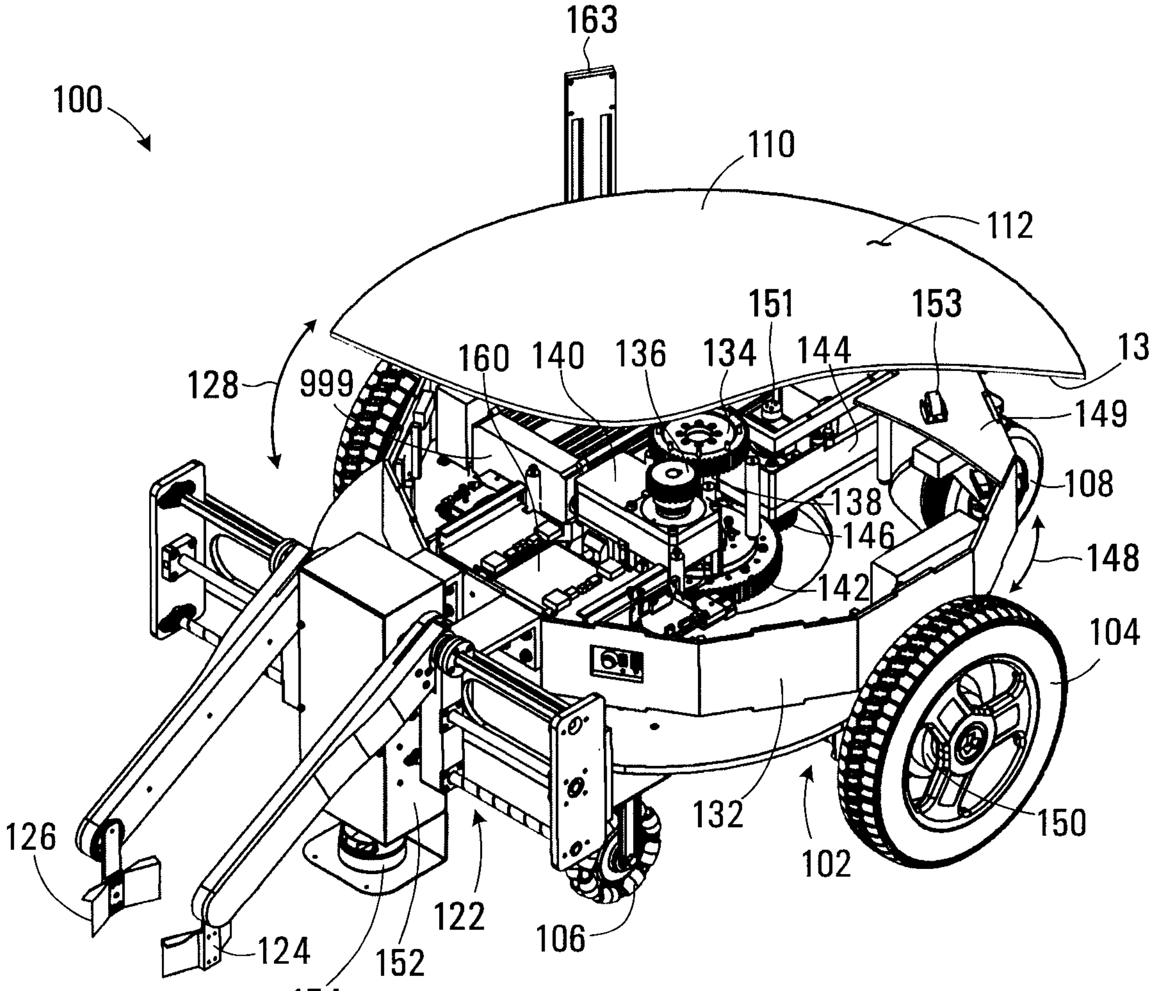
FIG. 1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154

FIG. 2

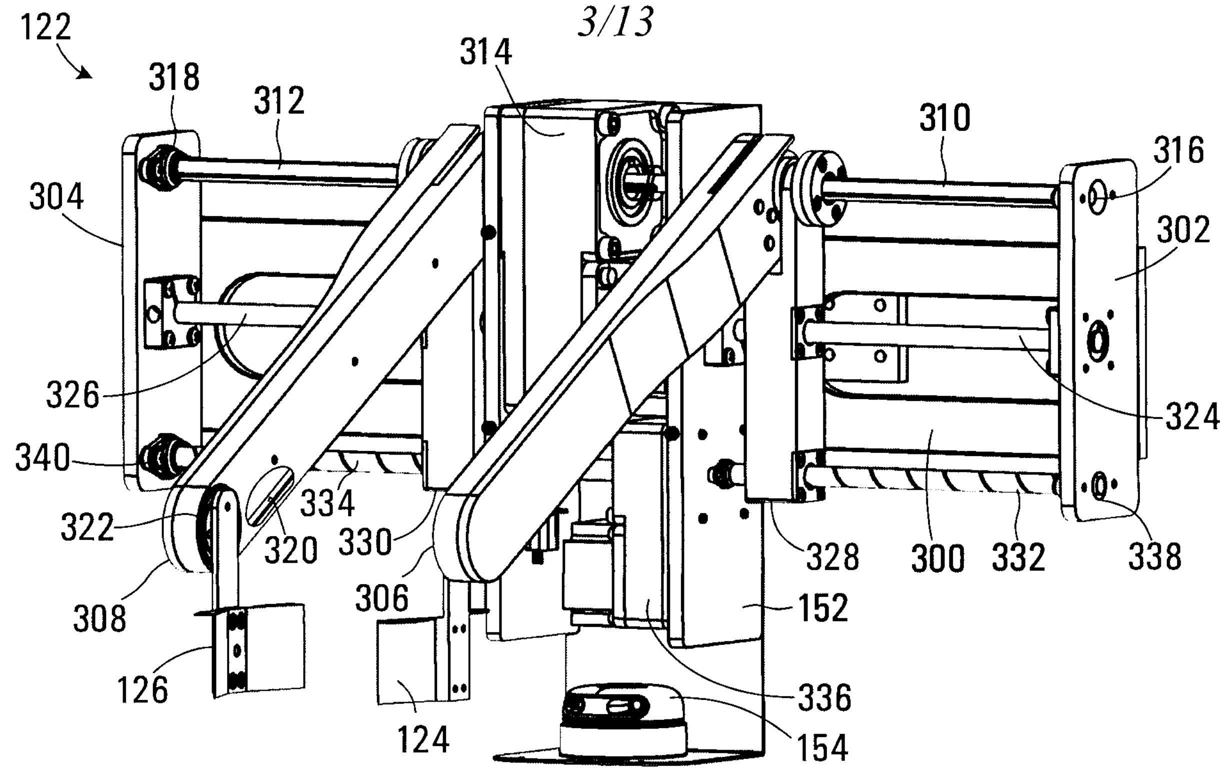
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FIG. 3

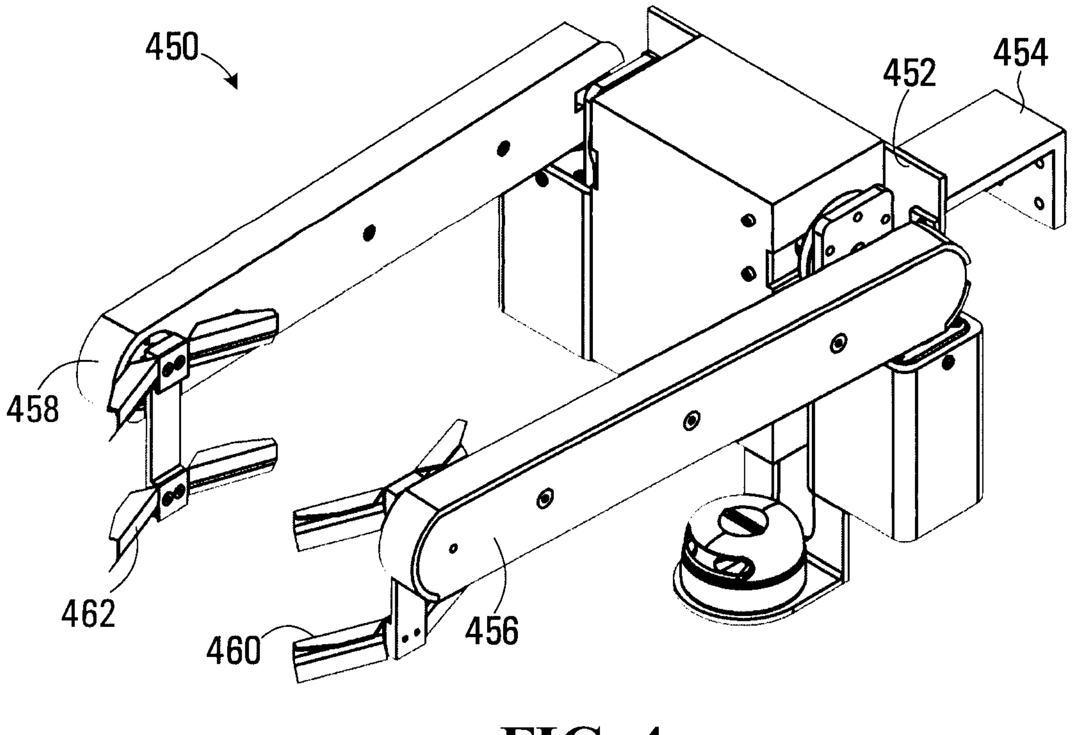
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FIG. 4

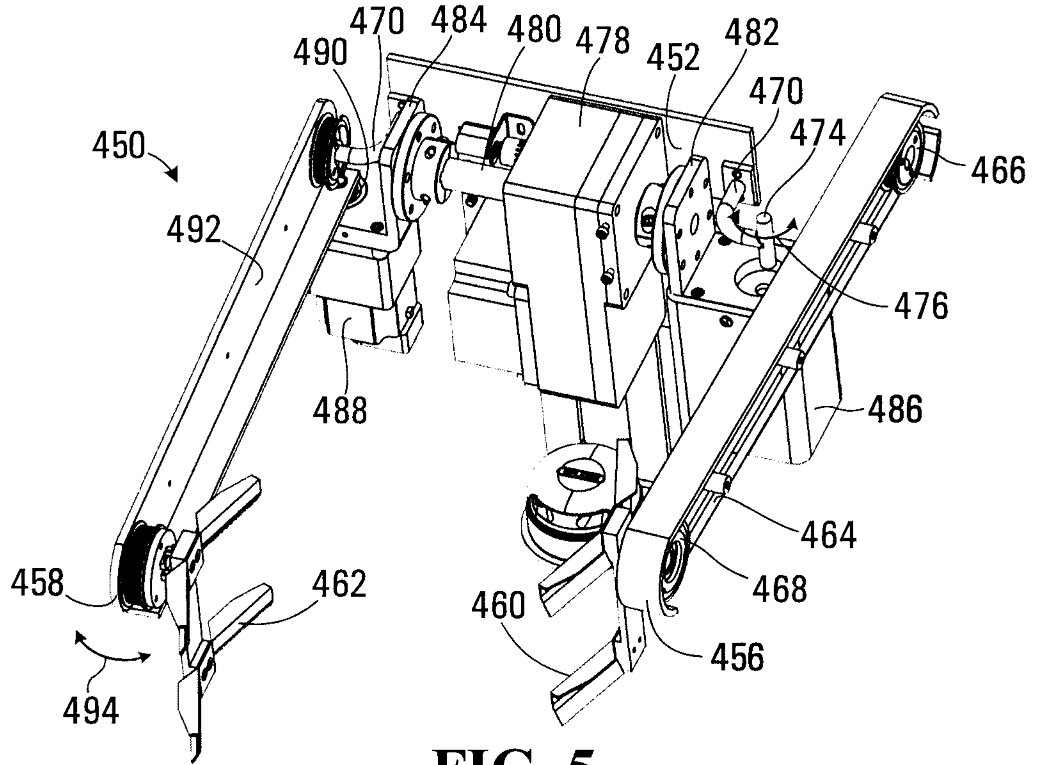
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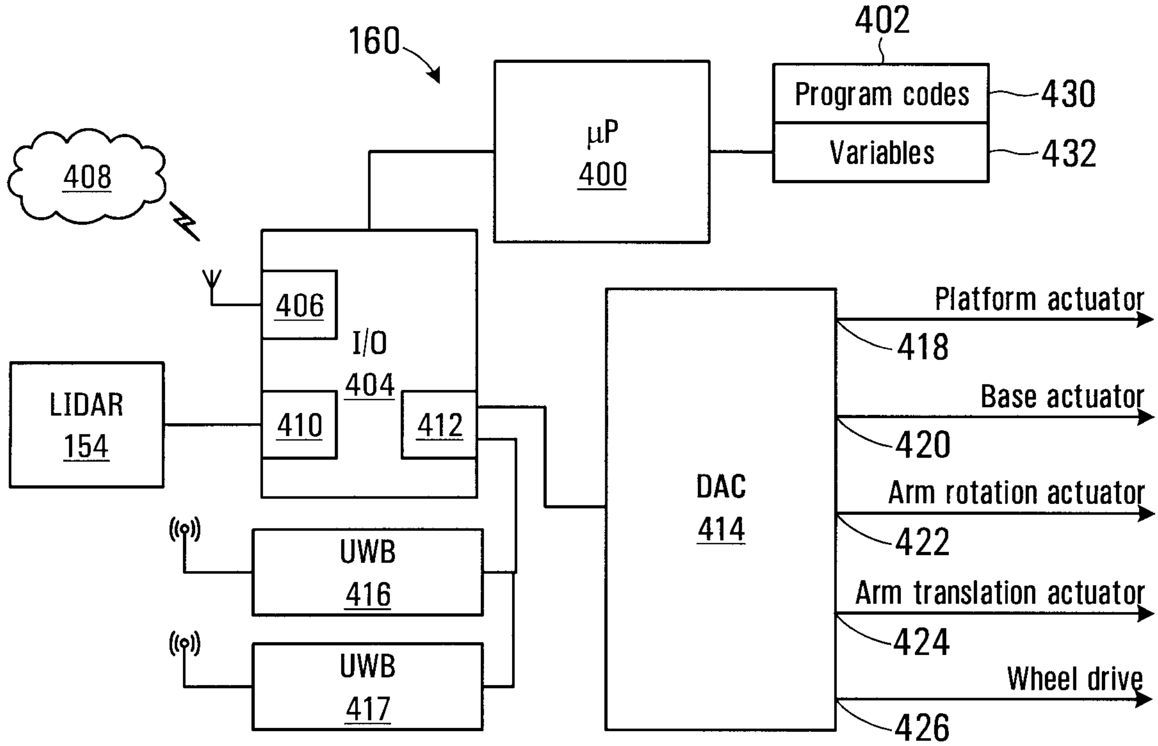
FIG. 5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402
Program codes
430
Variables
432
μP
400
408
406
I/O
404
LIDAR
154
410
412
UWB
416
UWB
417
DAC
414
Platform actuator
418
Base actuator
420
Arm rotation actuator
422
Arm translation actuator
424
Wheel drive
426

FIG. 6

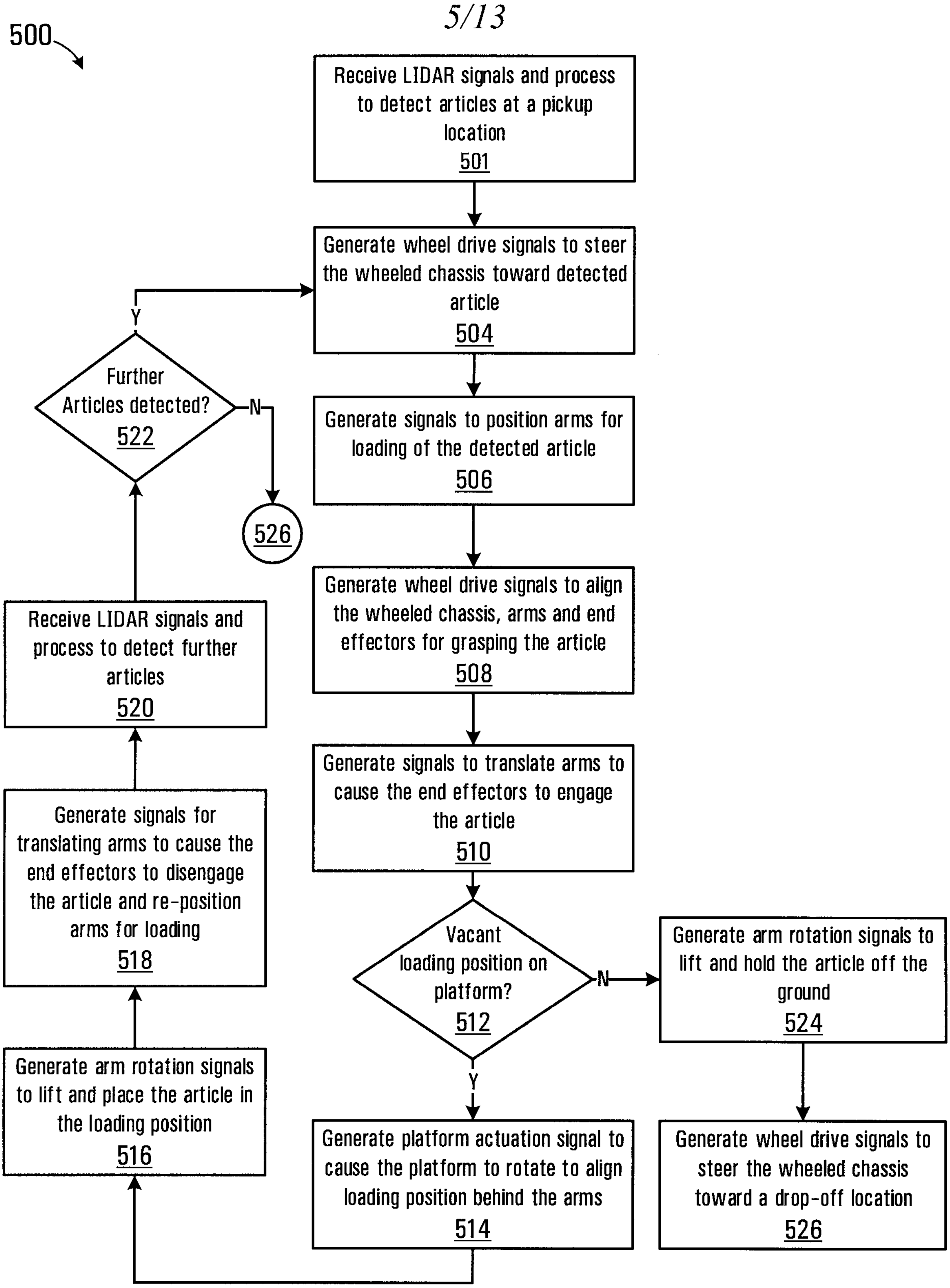

500
Receive LIDAR signals and process to detect articles at a pickup location
501
Generate wheel drive signals to steer the wheeled chassis toward detected article
504
Generate signals to position arms for loading of the detected article
506
Generate wheel drive signals to align the wheeled chassis, arms and end effectors for grasping the article
508
Generate signals to translate arms to cause the end effectors to engage the article
510
Vacant loading position on platform?
512
Y
N
Generate arm rotation signals to lift and hold the article off the ground
524
Generate wheel drive signals to steer the wheeled chassis toward a drop-off location
526
Generate platform actuation signal to cause the platform to rotate to align loading position behind the arms
514
Generate arm rotation signals to lift and place the article in the loading position
516
Generate signals for translating arms to cause the end effectors to disengage the article and re-position arms for loading
518
Receive LIDAR signals and process to detect further articles
520
Further Articles detected?
522
Y
N
526

FIG. 7

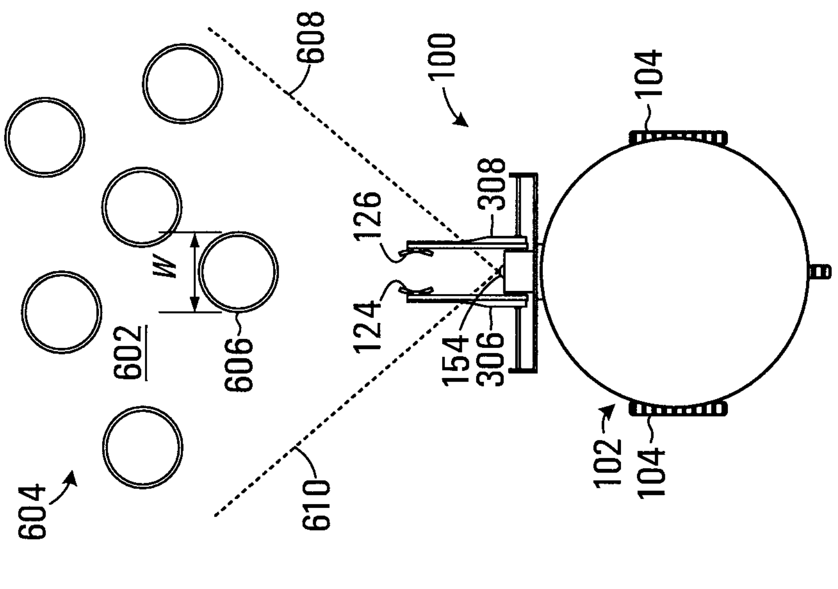


FIG. 8A

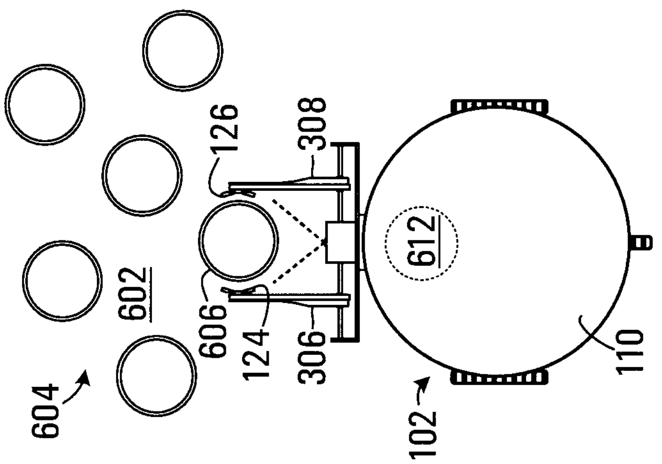


FIG. 8B

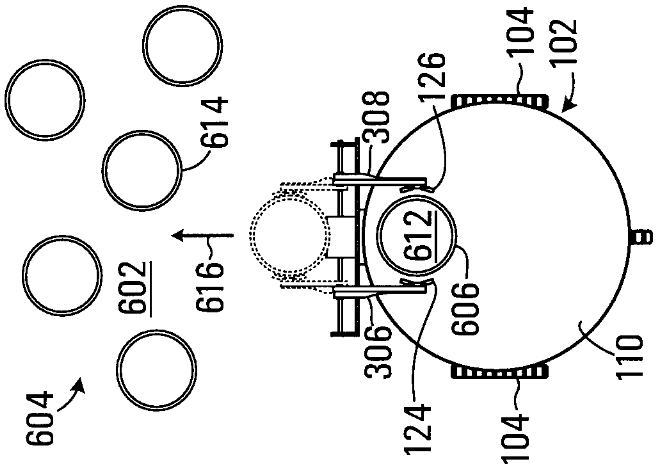
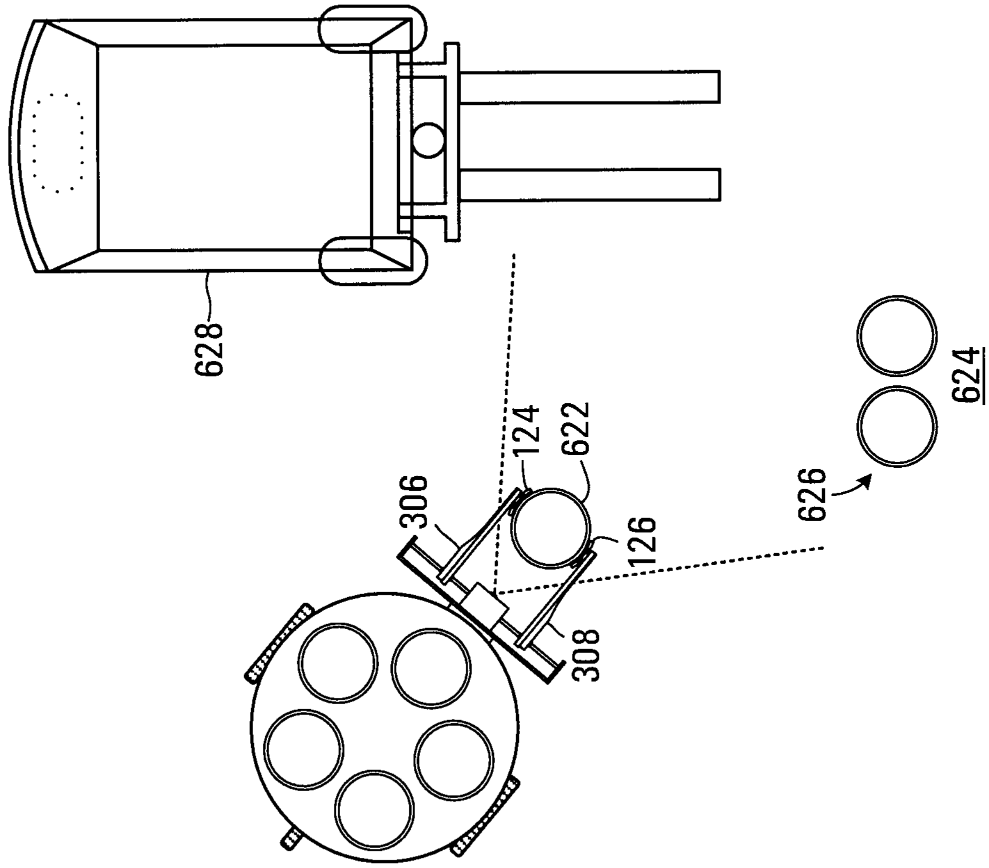


FIG. 8C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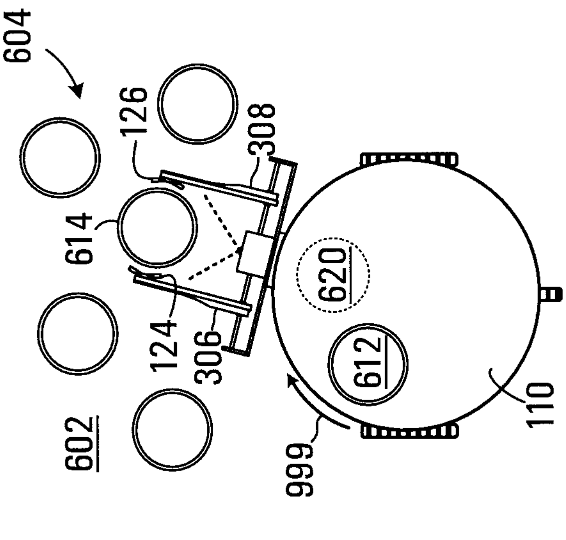
624

FIG. 8E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602

FIG. 8D

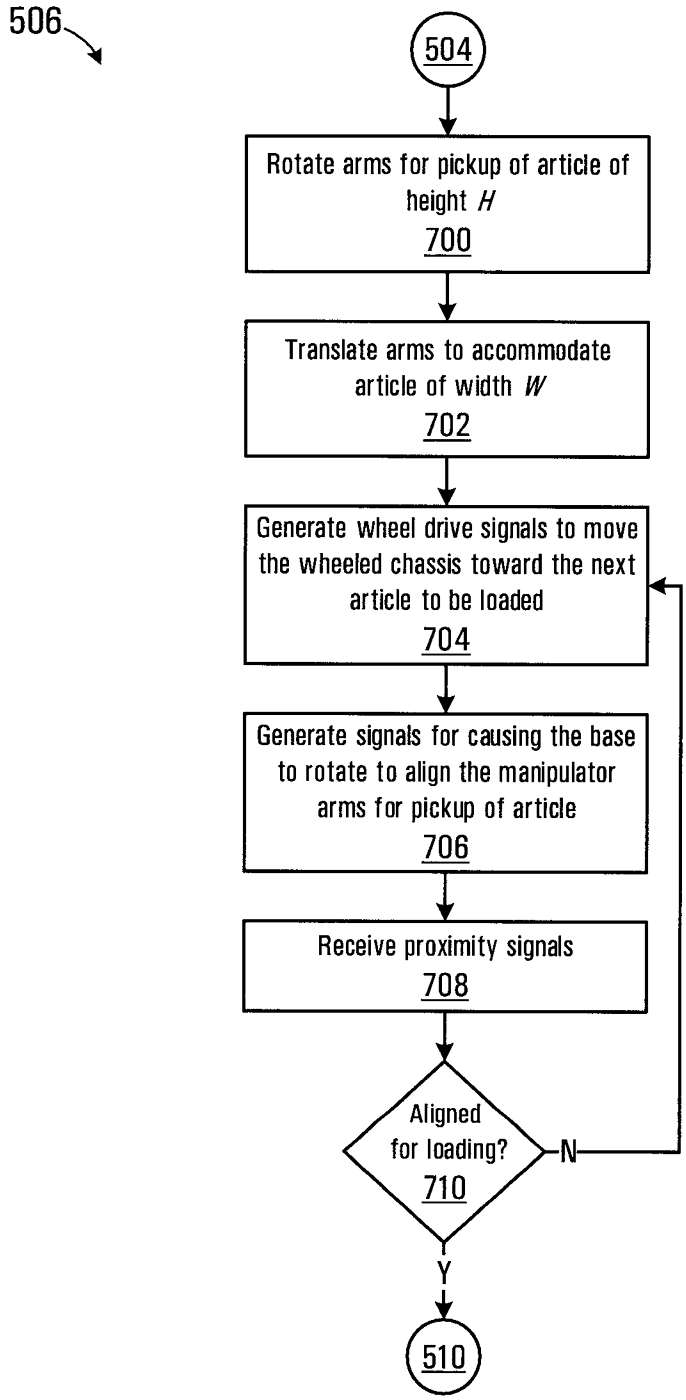

506
504
Rotate arms for pickup of article of height H
700
Translate arms to accommodate article of width W
702
Generate wheel drive signals to move the wheeled chassis toward the next article to be loaded
704
Generate signals for causing the base to rotate to align the manipulator arms for pickup of article
706
Receive proximity signals
708
Aligned for loading?
710
N
Y
510

FIG. 9

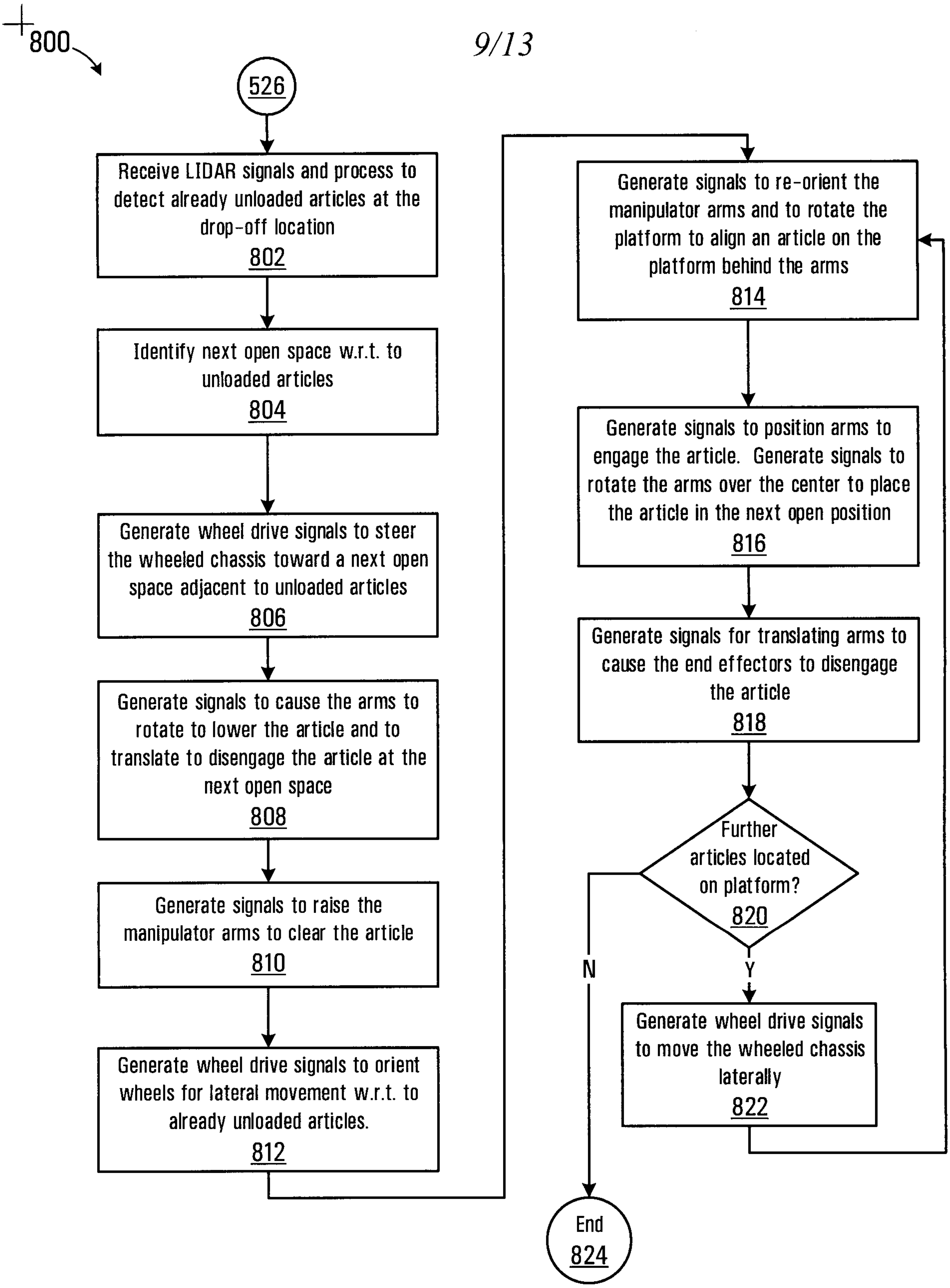

800
526
Receive LIDAR signals and process to detect already unloaded articles at the drop-off location
802
Identify next open space w.r.t. to unloaded articles
804
Generate wheel drive signals to steer the wheeled chassis toward a next open space adjacent to unloaded articles
806
Generate signals to cause the arms to rotate to lower the article and to translate to disengage the article at the next open space
808
Generate signals to raise the manipulator arms to clear the article
810
Generate wheel drive signals to orient wheels for lateral movement w.r.t. to already unloaded articles.
812
Generate signals to re-orient the manipulator arms and to rotate the platform to align an article on the platform behind the arms
814
Generate signals to position arms to engage the article. Generate signals to rotate the arms over the center to place the article in the next open position
816
Generate signals for translating arms to cause the end effectors to disengage the article
818
Further articles located on platform?
820
N
Y
Generate wheel drive signals to move the wheeled chassis laterally
822
End
824

FIG. 10

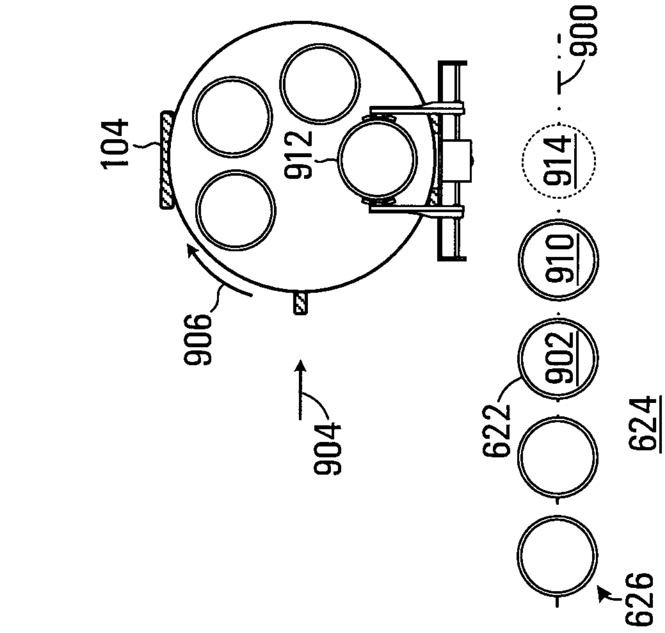


FIG. 11C

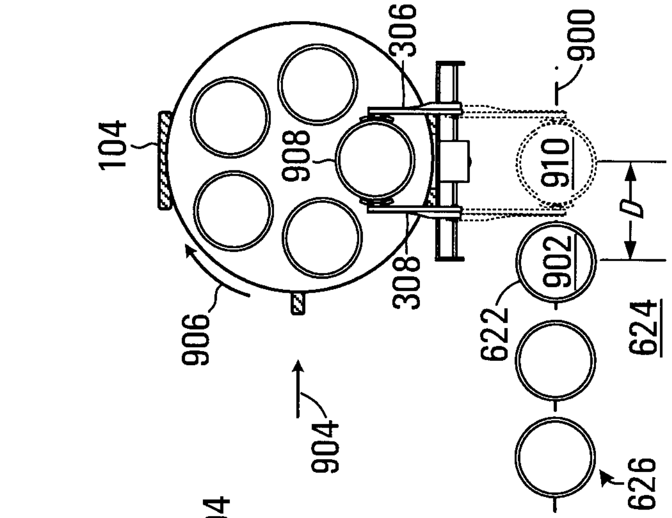


FIG. 11B

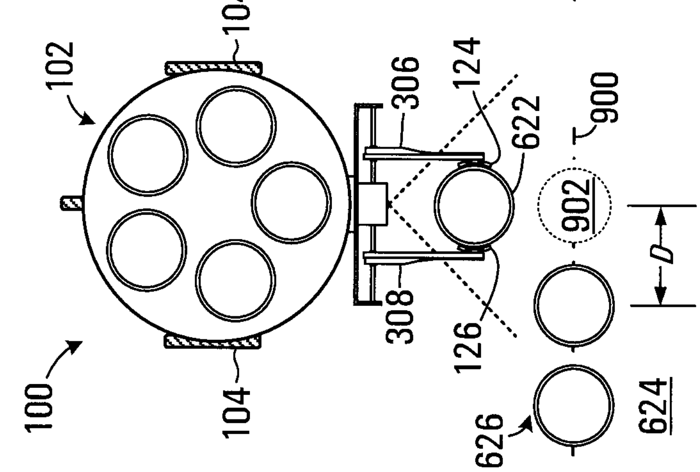
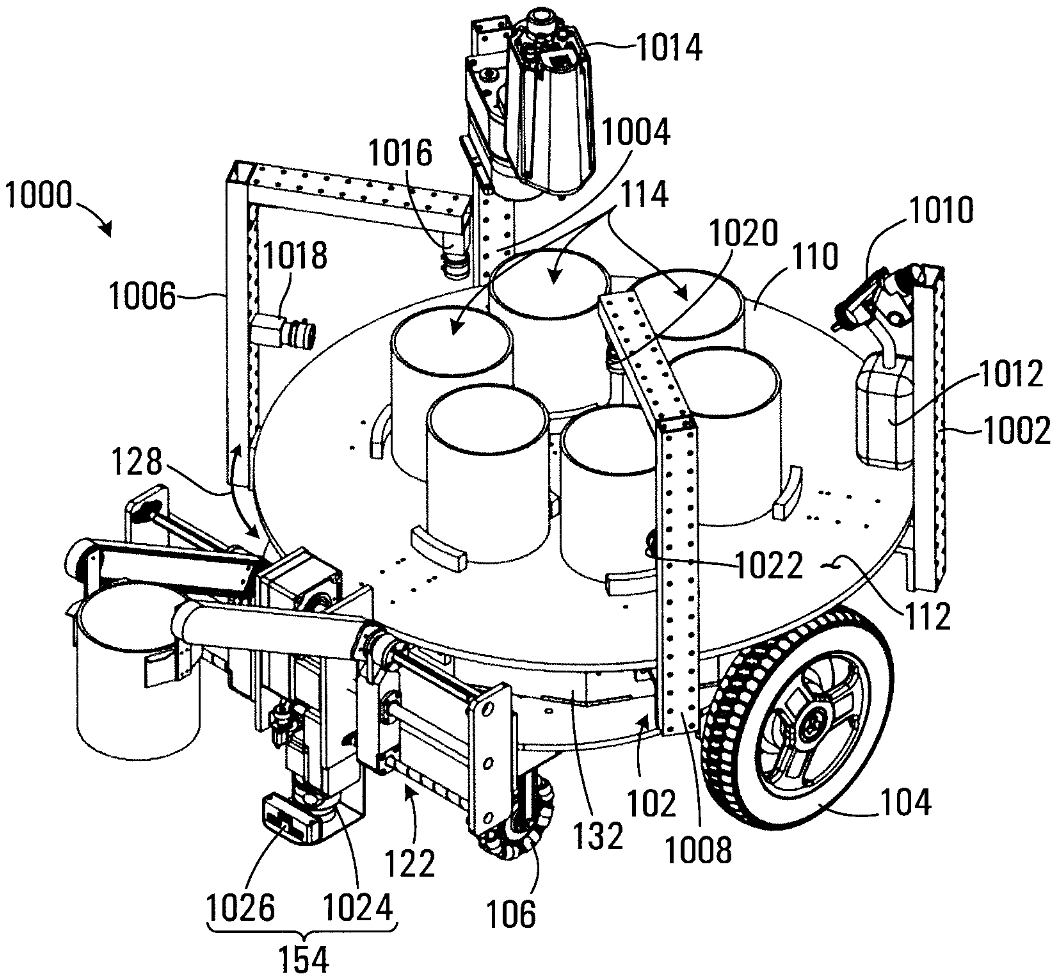


FIG. 11A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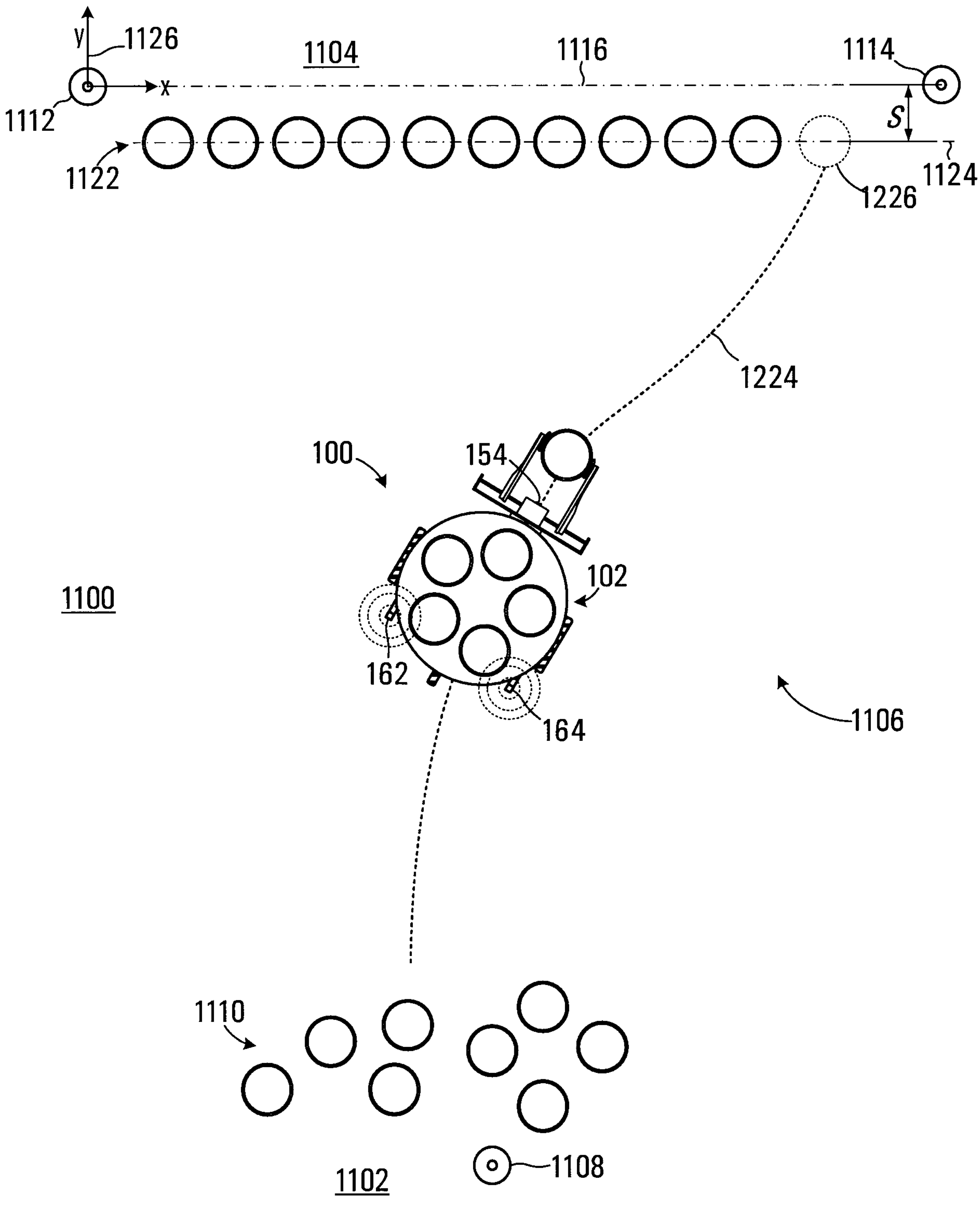
106
1026
1024
154

FIG. 12


y
1126
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1116
1114
x
1112
S
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1224
100
154
102
1100
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164
1106
1110
1102
1108

FIG. 13

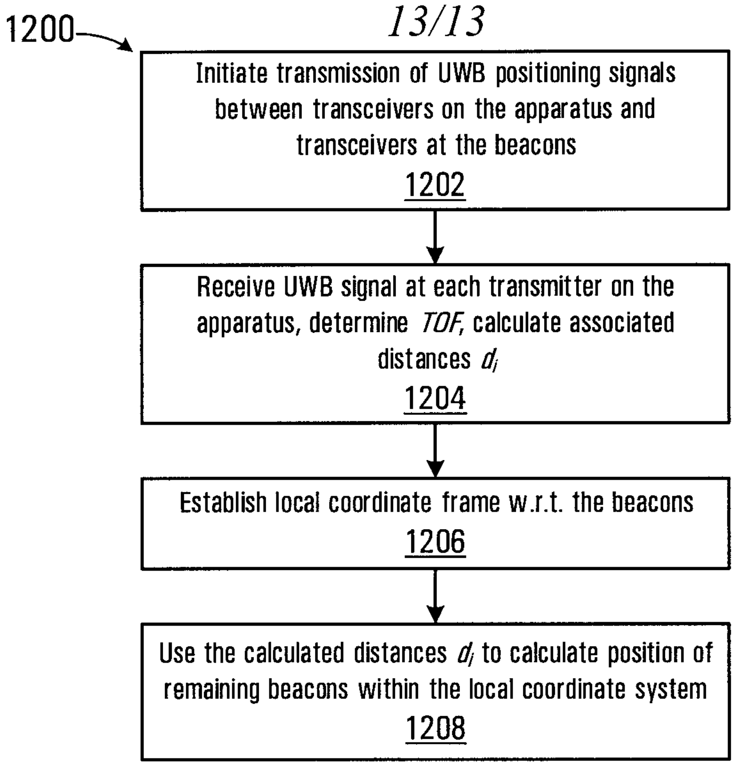
1200
Initiate transmission of UWB positioning signals between transceivers on the apparatus and transceivers at the beacons
1202
Receive UWB signal at each transmitter on the apparatus, determine *TOF*, calculate associated distances d_i
1204
Establish local coordinate frame w.r.t. the beacons
1206
Use the calculated distances d_i to calculate position of remaining beacons within the local coordinate system
1208

FIG. 14

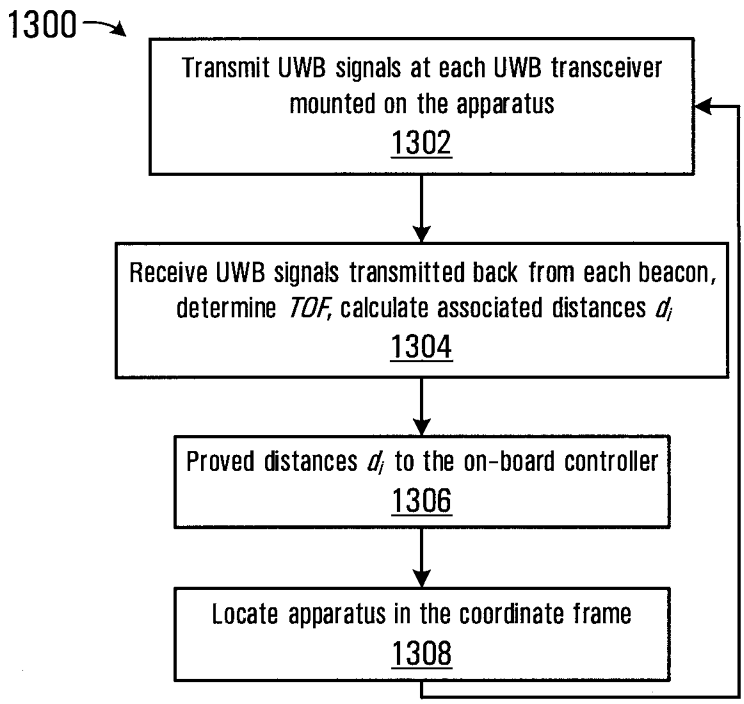
1300
Transmit UWB signals at each UWB transceiver mounted on the apparatus
1302
Receive UWB signals transmitted back from each beacon, determine *TOF*, calculate associated distances d_i
1304
Proved distances d_i to the on-board controller
1306
Locate apparatus in the coordinate frame
1308

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2017/000057

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***B25J 5/00*** (2006.01) , ***B25J 19/02*** (2006.01) , ***B25J 9/00*** (2006.01) , ***B60P 1/48*** (2006.01)

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)
IPC: ***B25J 5/00*** (2006.01) , ***B25J 19/02*** (2006.01) , ***B25J 9/00*** (2006.01) , ***B60P 1/48*** (2006.01)

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

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
FAMPAT (Questel Orbit)
Keywords: platform, load, cargo, article, manipulator, arm, autonomous, robot, mobile, wheel, turntable, unload, unmanned, carousel, transport, track, beacon, mark, tag, transceiver, navigat+, guid+, location, position, signal, and similar terms.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,698,775 A (KOCH, G.R. et al.) 06 October 1987 (06-10-1987) * whole document *	1-32
A	US 2016/0075014 A1 (BRUEMMER, D.) 17 March 2016 (17-03-2016) * paragraphs 73-74 *	22-32
A	EP 0 304 342 A2 (BARRY, R.F.) 22 February 1989 (22-02-1989) * whole document *	1-32
P, A	CN 106272415 A (ZHOU, M. et al.) 04 January 2017 (04-01-2017) * figures 1-2 *	1-32
A	CN 205219095 U (FAN, Z. et al.) 11 May 2016 (11-05-2016) * figure 1 *	1-32

☑ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

*	Special categories of cited documents:	"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
"A"	document defining the general state of the art which is not considered to be of particular relevance	"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
"E"	earlier application or patent but published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search
23 June 2017 (23-06-2017)

Date of mailing of the international search report
25 July 2017 (25-07-2017)

Name and mailing address of the ISA/CA
Canadian Intellectual Property Office
Place du Portage I, C114 - 1st Floor, Box PCT
50 Victoria Street
Gatineau, Quebec K1A 0C9
Facsimile No.: 819-953-2476

Authorized officer

Iain Baxter (819) 635-8829

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2009-196381 A (HORIKIRI, G. et al.) 03 September 2009 (03-09-2009) * figures 1 and 6A-6D *	1-32
A	CA 2 622 940 A1 (ECHELMEYER, W. et al.) 29 March 2007 (29-03-2007) * figures 1-6 *	1-32
A	US 2012/0029697 A1 (KAWABE, K. et al.) 02 February 2012 (02-02-2012) * paragraphs 33 and 36-39; claims 15, 16, and 18; figures 1-12 *	1-32
A	US 5,682,313 A (EDLUND, L. et al.) 28 October 1997 (28-10-1997) * whole document *	22-32
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Box No. II **Observations where certain claims were found unsearchable (Continuation of item 2 of the first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claim Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claim Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claim Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III **Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

See extra sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☑ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claim Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Continuation of Box No. III

The claims are directed to a plurality of inventive concepts as follows:

Group A - Claims 1-21 are directed to an apparatus and method for transporting a plurality of articles, the apparatus comprising, *inter alia*, a wheeled chassis; a platform; a manipulator; and at least one actuator operably configured to cause successive relative rotational movements between the manipulator and the platform to provide access to successive rotationally spaced apart positions on the platform for loading or unloading each subsequent article in the plurality of articles; and

Group B - Claims 22-32 are directed to a method and system for transporting a plurality of articles, the method comprising, *inter alia*, positioning a left drop-off beacon and a right drop-off beacon on either side of an intended drop-off location, the left and right drop-off beacons indicating a desired alignment of the plurality of articles at the respective location.

The claims must be limited to one inventive concept as set out in PCT Rule 13.

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