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### MOBILE CLEANING ROBOT SUSPENSION

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#### Abstract

A mobile cleaning robot can be movable within an environment, the mobile cleaning robot can include a body, a drive wheel arm, a drive wheel, a cam, and a cam follower. The drive wheel arm can be connected to the body and can be movable with respect to the body between an extended position and a retracted position. The drive wheel can be connected to the drive wheel arm and can be movable therewith. The drive wheel can be operable to move the mobile cleaning robot. The cam can be connected to the drive wheel arm and can be movable therewith. The cam follower can be connected to the body and can be engaged with the cam to move the drive wheel arm toward the extended position.

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## Background/Summary

PRIORITY APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 17/682,021, filed Feb. 28, 2022, the content of which is incorporated herein by reference in its entirety.

### BACKGROUND

[0002] Mobile robots include mobile cleaning robots that can perform cleaning tasks within an environment, such as a home. A mobile cleaning robot can navigate across a floor surface and avoid obstacles while vacuuming the floor surface and operating rotatable members carried by the robot to ingest debris from the floor surface. As the robot moves across the floor surface, the robot can rotate the rotatable members, which can engage the debris and guide the debris toward a vacuum airflow generated by the robot. The rotatable members and the vacuum airflow can thereby cooperate to allow the robot to ingest debris.

### SUMMARY

[0003] Mobile cleaning robots can autonomously navigate through environments to perform cleaning operations, often traversing over, and navigating around, obstacles. Mobile cleaning robots include suspension systems to provide sufficient wheel downforce to overcome obstacles and to provide effective cleaning on various surfaces. Because obstacles can vary in shape and size and because floor types can also vary, a required wheel downforce can vary during operation of the robot. Many robots include suspension systems using an extension or compression spring directly connected to wheel arms, which can effectively deliver downforce; however, the delivered downforce can decay as the drive wheel extends from the body, delivering a less-than-desirable downforce profile.

[0004] This disclosure describes devices and methods that can help to address this problem such as by including a suspension system including a cam and a cam follower. The cam and cam follower can be connected to a biasing element and can indirectly transfer force to the wheel to provide downforce. Because the cam can be designed in a variety of shapes, the suspension system can be tailored to provide a desired wheel downforce over a range of extension of the wheel from the body of the robot, helping to improve object traversal and cleaning efficiency of the mobile cleaning robot and also helping to reduce costs between robot model variations.

[0005] For example, a mobile cleaning robot can include a body, a drive wheel arm, a drive wheel, a cam, and a cam follower. The drive wheel arm can be connected to the body and can be movable with respect to the body between an extended position and a retracted position. The drive wheel can be connected to the drive wheel arm and can be movable therewith. The drive wheel can be operable to move the mobile cleaning robot. The cam can be connected to the drive wheel arm and can be movable therewith. The cam follower can be connected to the body and can be engaged with the cam to move the drive wheel arm toward the extended position.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0006] In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

[0007] FIG. 1 illustrates a plan view of a mobile cleaning robot in an environment.

[0008] FIG. 2A illustrates a bottom view of a mobile cleaning robot.

[0009] FIG. 2B illustrates an isometric view of a mobile cleaning robot.

[0010] FIG. 3 illustrates a cross-section view across indicators 3-3 of FIG. 2A of a mobile cleaning robot.

[0011] FIG. 4A illustrates a cross-section view of a portion of a mobile cleaning robot in a first condition.

[0012] FIG. 4B illustrates a cross-section view of a portion of a mobile cleaning robot in a second condition.

[0013] FIG. 4C illustrates a cross-section view of a portion of a mobile cleaning robot in a third condition.

[0014] FIG. 5A illustrates a schematic view of a mobile cleaning robot suspension system.

[0015] FIG. 5B illustrates a schematic view of a mobile cleaning robot suspension system.

[0016] FIG. 6 illustrates a performance chart for a suspension system.

[0017] FIG. 7 illustrates a performance chart for a suspension system.

## DETAILED DESCRIPTION

### Robot Overview

[0018] FIG. 1 illustrates a plan view of a mobile cleaning robot **100** in an environment **40**. The environment **40** can be a dwelling, such as a home or an apartment, and can include rooms **42a-42e**. Obstacles, such as a bed **44**, a table **46**, and an island **48** can be located in the rooms **42** of the environment. Each of the rooms **42a-42e** can have a floor surface **50a-50e**, respectively. Some rooms, such as the room **42d**, can include a rug, such as a rug **52**. The floor surfaces **50** can be of one or more types such as hardwood, ceramic, low-pile carpet, medium-pile carpet, long (or high)-pile carpet, stone, or the like.

[0019] The mobile cleaning robot **100** can be operated, such as by a user **60**, to autonomously clean the environment **40** in a room-by-room fashion. In some examples, the robot **100** can clean the floor surface **50a** of one room, such as the room **42a**, before moving to the next room, such as the room **42d**, to clean the surface of the room **42d**. Different rooms can have different types of floor surfaces. For example, the room **42e** (which can be a kitchen) can have a hard floor surface, such as wood or ceramic tile, and the room **42a** (which can be a bedroom) can have a carpet surface, such as a medium pile carpet. Other rooms, such as the room **42d** (which can be a dining room) can include multiple surfaces where the rug **52** is located within the room **42d**. The robot **100** can be configured to navigate over various floor types through one or more components such as a suspension. The suspension of the robot can also allow the robot **100** to navigate over obstacles, such as thresholds between rooms or over rugs, such as the rug **52**.

[0020] Also during cleaning or traveling operations, the robot **100** can use data collected from various sensors (such as optical sensors) and calculations (such as odometry and obstacle detection) to develop a map of the environment **40**. Once the map is created, the user **60** can define rooms or zones (such as the rooms **42**) within the map. The map can be presentable to the user **60** on a user interface, such as a mobile device, where the user **60** can direct or change cleaning preferences, for example.

[0021] Also, during operation, the robot **100** can detect surface types within each of the rooms **42**, which can be stored in the robot or another device. The robot **100** can update the map (or data related thereto) such as to include or account for surface types of the floor surfaces **50a-50e** of each of the respective rooms **42** of the environment. In some examples, the map can be updated to show the different surface types such as within each of the rooms **42**.

### Components of the Robot

[0022] FIG. 2A illustrates a bottom view of the mobile cleaning robot **100**. FIG. 2B illustrates a bottom view of the mobile cleaning robot **100**. FIG. 3 illustrates a cross-section view across indicators 3-3 of FIG. 2A of the mobile cleaning robot **100**. FIG. 3 also shows orientation indicators Bottom, Top, Front, and Rear. FIGS. 2A-3 are discussed together below.

[0023] The cleaning robot **100** can be a mobile cleaning robot that can autonomously traverse the floor surface **50** while ingesting the debris **75** from different parts of the floor surface **50**. As depicted in FIGS. **2A** and **3**, the robot **100** can include a body **200** movable across the floor surface **50**. The body **200** can include multiple connected structures to which movable components of the cleaning robot **100** can be mounted. The connected structures can include an outer housing to cover internal components of the cleaning robot **100**, a chassis to which drive wheels **210a** and **210b** and the cleaning rollers **205a** and **205b** (of a cleaning assembly **205**) are mounted, and a bumper **138** mounted to the outer housing.

[0024] As shown in FIG. **2A**, the body **200** can include a front portion **202a** that has a substantially semicircular shape and a rear portion **202b** that has a substantially semicircular shape. As shown in FIG. **2A**, the robot **100** can include a drive system including actuators **208a** and **208b**, e.g., motors, operable with drive wheels **210a** and **210b**. The actuators **208a** and **208b** can be mounted in the body **200** and can be operably connected to the drive wheels **210a** and **210b**, which are rotatably mounted to the body **200**. The drive wheels **210a** and **210b** can support the body **200** above the floor surface **50**. The actuators **208a** and **208b**, when driven, can rotate the drive wheels **210a** and **210b** to enable the robot **100** to move across the floor surface **50**.

[0025] The controller (or processor) **212** can be located within the housing **200** and can be a programmable controller, such as a single or multi-board computer, a direct digital controller (DDC), a programmable logic controller (PLC), or the like. In other examples the controller **212** can be any computing device, such as a handheld computer, for example, a smart phone, a tablet, a laptop, a desktop computer, or any other computing device including a processor and communication capabilities. The memory **213** can be one or more types of memory, such as volatile or non-volatile memory, read-only memory (ROM), random-access memory (RAM), magnetic disk storage media, optical storage media, flash-memory devices, and other storage devices and media. The memory **213** can be located within the housing **200** and can be connected to the controller **212** and accessible by the controller **212**.

[0026] The controller **212** can operate the actuators **208a** and **208b** to autonomously navigate the robot **100** about the floor surface **50** during a cleaning operation. The actuators **208a** and **208b** are operable to drive the robot **100** in a forward drive direction, in a backwards direction, and to turn the robot **100**. The robot **100** can include a caster wheel **211** (or alternatively skids) that supports the body **200** above the floor surface **50**. The caster **211** can support the front portion **202b** of the body **200** above the floor surface **50**, and the drive wheels **210a** and **210b** support a middle and rear portion **202a** of the body **200** above the floor surface **50**.

[0027] As shown in FIG. **3**, a vacuum assembly **118** can be located within the body **200** of the robot **100**, e.g., in the middle of the body **200**. The controller **212** can operate the vacuum assembly **118** to generate an airflow that flows through the air gap near the cleaning rollers **205**, through the body **200**, and out of the body **200**. The vacuum assembly **118** can include, for example, an impeller that generates the airflow when rotated. The airflow and the cleaning rollers **205**, when rotated, cooperate to ingest debris **75** into the robot **100**. A cleaning bin **322** can be mounted in the body **200** to contain the debris **75** ingested by the robot **100**, and a filter in the body **200** separates the debris **75** from the airflow before the airflow **120** enters the vacuum assembly **118** and is exhausted out of the body **200**. In this regard, the debris **75** is captured in both the cleaning bin **322** and the filter before the airflow **120** is exhausted from the body **200**.

[0028] The cleaning rollers **205a** and **205b** can operably connected to actuators **214a** and **214b**, e.g., motors, respectively. The cleaning head **205** and the cleaning rollers **205a** and **205b** can be positioned forward of the cleaning bin **322**. The cleaning rollers **205a** and **205b** can be mounted to a housing **124** of the cleaning head **205** and mounted, e.g., indirectly or directly, to the body **200** of the robot **100**. For example, the cleaning rollers **205a** and **205b** can be mounted to an underside of the body **200** so that the cleaning rollers **205a** and **205b** engage debris **75** on the floor surface **50** during the cleaning operation when the underside faces the floor surface **50**.

[0029] The housing **124** of the cleaning head **205** can be mounted to the body **200** of the robot **100**. In this way, the cleaning rollers **205a** and **205b** can also be mounted to the body **200** of the robot **100**, e.g., indirectly mounted to the body **200** through the housing **124**. The cleaning head **205** can also be a removable assembly of the robot **100** where the housing **124** with the cleaning rollers **205a** and **205b** mounted therein is removably mounted to the body **200** of the robot **100**. The housing **124** and the cleaning rollers **205a** and **205b** can be removable from the body **200** as a unit so that the cleaning head **205** is easily interchangeable with a replacement cleaning head **205**.

[0030] The control system can further include a sensor system with one or more electrical sensors. The sensor system, as described herein, can generate a signal indicative of a current location of the robot **100**, and can generate signals indicative of locations of the robot **100** as the robot **100** travels along the floor surface **50**.

[0031] Cliff sensors **134** (shown in FIG. 2A) can be located along a bottom portion of the housing **200**. Each of the cliff sensors **134** can be an optical sensor that can be configured to detect a presence or absence of an object below the optical sensor, such as the floor surface **50**. The cliff sensors **134** can be connected to the controller **212**. A bumper **138** can be removably secured to the body **200** and can be movable relative to body **200** while mounted thereto. In some examples, the bumper **138** forms part of the body **200**. The bump sensors **139a** and **139b** (the bump sensors **139**) can be connected to the body **200** and engageable or configured to interact with the bumper **138**. The bump sensors **139** can include break beam sensors, capacitive sensors, switches, or other sensors that can detect contact between the robot **100**, i.e., the bumper **138**, and objects in the environment **40**. The bump sensors **139** can be in communication with the controller **212**.

[0032] An image capture device **140** can be a camera connected to the body **200** and can extend through the bumper **138** of the robot **100**, such as through an opening **143** of the bumper **138**. The image capture device **140** can be a camera, such as a front-facing camera, configured to generate a signal based on imagery of the environment **40** of the robot **100** as the robot **100** moves about the floor surface **50**. The image capture device **140** can transmit the signal to the controller **212** for use for navigation and cleaning routines.

[0033] Obstacle following sensors **141** (shown in FIG. 2B) can include an optical sensor facing outward from the bumper **138** and that can be configured to detect the presence or the absence of an object adjacent to a side of the body **200**. The obstacle following sensor **141** can emit an optical beam horizontally in a direction perpendicular (or nearly perpendicular) to the forward drive direction of the robot **100**. The optical emitter can emit an optical beam outward from the robot **100**, e.g., outward in a horizontal direction, and the optical detector detects a reflection of the optical beam that reflects off an object near the robot **100**. The robot **100**, e.g., using the controller **212**, can determine a time of flight of the optical beam and thereby determine a distance between the optical detector and the object, and hence a distance between the robot **100** and the object.

[0034] A side brush **142** can be connected to an underside of the robot **100** and can be connected to a motor **144** operable to rotate the side brush **142** with respect to the body **200** of the robot **100**. The side brush **142** can be configured to engage debris to move the debris toward the cleaning assembly **205** or away from edges of the environment **40**. The motor **144** configured to drive the side brush **142** can be in communication with the controller **112**. The brush **142** can rotate about a non-horizontal axis, e.g., an axis forming an angle between 75 degrees and 90 degrees with the floor surface **50**. The non-horizontal axis, for example, can form an angle between 75 degrees and 90 degrees with the longitudinal axes **126a** and **126b** of the rollers **205a** and **205b**.

[0035] The brush **142** can be a side brush laterally offset from a center of the robot **100** such that the brush **142** can extend beyond an outer perimeter of the body **200** of the robot **100**. Similarly, the brush **142** can also be forwardly offset of a center of the robot **100** such that the brush **142** also extends beyond the bumper **138**. Optionally, the robot **100** can include multiple side brushes, such as one located on each side of the body **200**, such as in line with drive wheels **210a** and **210b**, respectively.

[0036] The robot **100** can also include a button **146** (or interface) that can be a user-operable interface configured to provide commands to the robot, such as to pause a mission, power on, power off, or return to a docking station. The robot **100** can also include a privacy button **148** (or interface) that can be a user-operable interface configured to provide commands to the robot, such as to disable or restrict use of the camera **140**. For example, pressing the privacy button **148** can cut power to the camera **140** or can operate a shutter **152** to close or open. An indicator **150** can optionally be included and can be lit to indicate when the camera **140** is operating. Additional privacy controls and options are discussed in further detail below with respect to FIGS. 4A-6.

### Operation of the Robot

[0037] In operation of some examples, the robot **100** can be propelled in a forward drive direction or a rearward drive direction. The robot **100** can also be propelled such that the robot **100** turns in place or turns while moving in the forward drive direction or the rearward drive direction.

[0038] When the controller **212** causes the robot **100** to perform a mission, the controller **212** can operate the motors **208** to drive the drive wheels **210** and propel the robot **100** along the floor surface **50**. In addition, the controller **212** can operate the motors **214** to cause the rollers **205a** and **205b** to rotate, can operate the motor **144** to cause the brush **142** to rotate, and can operate the motor of the vacuum system **118** to generate airflow. The controller **212** can execute software stored on the memory **213** to cause the robot **100** to perform various navigational and cleaning behaviors by operating the various motors of the robot **100**.

[0039] The various sensors of the robot **100** can be used to help the robot navigate and clean within the environment **40**. For example, the cliff sensors **134** can detect obstacles such as drop-offs and cliffs below portions of the robot **100** where the cliff sensors **134** are disposed. The cliff sensors **134** can transmit signals to the controller **212** so that the controller **212** can redirect the robot **100** based on signals from the cliff sensors **134**.

[0040] In some examples, a bump sensor **139a** can be used to detect movement of the bumper **138** along a fore-aft axis of the robot **100**. A bump sensor **139b** can also be used to detect movement of the bumper **138** along one or more sides of the robot **100**. The bump sensors **139** can transmit signals to the controller **212** so that the controller **212** can redirect the robot **100** based on signals from the bump sensors **139**.

[0041] The image capture device **140** can be configured to generate a signal based on imagery of the environment **40** of the robot **100** as the robot **100** moves about the floor surface **50**. The image capture device **140** can transmit such a signal to the controller **212**. The image capture device **140** can be angled in an upward direction, e.g., angled between 5 degrees and 45 degrees from the floor surface **50** about which the robot **100** navigates. The image capture device **140**, when angled upward, can capture images of wall surfaces of the environment so that features corresponding to objects on the wall surfaces can be used for localization.

[0042] In some examples, the obstacle following sensors **141** can detect detectable objects, including obstacles such as furniture, walls, persons, and other objects in the environment of the robot **100**. In some implementations, the sensor system can include an obstacle following sensor along a side surface, and the obstacle following sensor can detect the presence or the absence an object adjacent to the side surface. The one or more obstacle following sensors **141** can also serve as obstacle detection sensors, similar to the proximity sensors described herein.

[0043] The robot **100** can also include sensors for tracking a distance travelled by the robot **100**. For example, the sensor system can include encoders associated with the motors **208** for the drive wheels **210**, and the encoders can track a distance that the robot **100** has travelled. In some implementations, the sensor can include an optical sensor facing downward toward a floor surface. The optical sensor can be positioned to direct light through a bottom surface of the robot **100** toward the floor surface **50**. The optical sensor can detect reflections of the light and can detect a distance travelled by the robot **100** based on changes in floor features as the robot **100** travels along the floor surface **50**.

[0044] The controller **212** can use data collected by the sensors of the sensor system to control navigational behaviors of the robot **100** during the mission. For example, the controller **212** can use the sensor data collected by obstacle detection sensors of the robot **100**, (the cliff sensors **134**, the bump sensors **139**, and the image capture device **140**) to enable the robot **100** to avoid obstacles within the environment of the robot **100** during the mission.

[0045] The sensor data can also be used by the controller **212** for simultaneous localization and mapping (SLAM) techniques in which the controller **212** extracts features of the environment represented by the sensor data and constructs a map of the floor surface **50** of the environment. The sensor data collected by the image capture device **140** can be used for techniques such as vision-based SLAM (VSLAM) in which the controller **212** extracts visual features corresponding to objects in the environment **40** and constructs the map using these visual features. As the controller **212** directs the robot **100** about the floor surface **50** during the mission, the controller **212** can use SLAM techniques to determine a location of the robot **100** within the map by detecting features represented in collected sensor data and comparing the features to previously stored features. The map formed from the sensor data can indicate locations of traversable and non-traversable space within the environment. For example, locations of obstacles can be indicated on the map as non-traversable space, and locations of open floor space can be indicated on the map as traversable space.

[0046] The sensor data collected by any of the sensors can be stored in the memory **213**. In addition, other data generated for the SLAM techniques, including mapping data forming the map, can be stored in the memory **213**. These data produced during the mission can include persistent data that are produced during the mission and that are usable during further missions. In addition to storing the software for causing the robot **100** to perform its behaviors, the memory **213** can store data resulting from processing of the sensor data for access by the controller **212**. For example, the map can be a map that is usable and updateable by the controller **212** of the robot **100** from one mission to another mission to navigate the robot **100** about the floor surface **50**.

[0047] The persistent data, including the persistent map, helps to enable the robot **100** to efficiently clean the floor surface **50**. For example, the map enables the controller **212** to direct the robot **100** toward open floor space and to avoid non-traversable space. In addition, for subsequent missions, the controller **212** can use the map to optimize paths taken during the missions to help plan navigation of the robot **100** through the environment **40**.

#### Suspension Examples

[0048] FIG. **4A** illustrates a cross-section view of a portion of a mobile cleaning robot **400** in a first condition. FIG. **4B** illustrates a cross-section view of a portion of the mobile cleaning robot **400** in a second condition. FIG. **4C** illustrates a cross-section view of a portion of the mobile cleaning robot **400** in a third condition. FIGS. **4A-4C** are discussed together below. The mobile cleaning robot **400** can be similar to the robot **100** discussed above. FIGS. **4A-4C** show that the mobile cleaning robot **400** can include a cam-based suspension system. Any of the robots discussed above or below can be modified to include such a suspension.

[0049] More specifically, the mobile cleaning robot **400** can include a body **402** supported by drive wheels **412** (only one wheel is visible in FIGS. **4A-4C**) and skids **411**. Optionally, the skids **411** can be substituted with a caster. The mobile cleaning robot **400** can also include a suspension system **454** connected to the body **402** and connected to the drive wheels **412**. The suspension system **454** can be configured to control or determine a downforce applied by the wheels **412**.

[0050] The suspension system **454** can include a drive wheel arm **456**, a cam **458**, a cam follower assembly **460**, and a spring assembly **462** (or biasing assembly). The drive wheel arm **456** can be connected to the body **402** and movable with respect to the body **402** between an extended position (as shown in FIG. **4C**) and a retracted position (as shown in FIG. **4A**). The drive wheel arm **456** can be connected to the body **402** at a pivot **464**, which can allow the drive wheel arm **456** and the drive wheels **412** to pivot with respect to the body **402**. The drive wheel arm **456** can support a

drive train **466** connected to the drive wheel **412** and configured to drive the drive wheel **412** to rotate.

[0051] The cam **458** can be connected to the drive wheel arm **456** and can be movable therewith. The cam **458** can optionally include projections **468** insertable into slots **470** (numbered in FIG. **4A**) of the drive wheel arm **456**, such as in a dovetail configuration. This configuration can allow the cam **458** to be easily replaceable to achieve a different cam profile, as discussed in further detail below. The cam **458** can define a cam surface **472** that can be contoured for engagement with the cam follower assembly **460** to move the drive wheel arm **456** toward the extended position while achieving a desired downforce profile of the drive wheel **412** through such a range of movement.

[0052] The cam follower assembly **460** can include a cam arm **474**, a cam follower **476**, and a pin **478**. The cam arm **474** can be a rigid or semi-rigid member that can be connected to the cam follower **476** via the pin **478** such as to support rolling motion of the cam follower **476** with respect to the cam arm **474**. Rolling motion of the cam follower **476** can allow the cam follower **476** to rotatably follow the cam surface **472**. The cam arm **474** can be connected to the body **402** via a pivot **480** such as to allow the cam follower assembly **460** to pivot with respect to the body **402**.

[0053] The pin **478** can be a solid pin configured to act as a journal bearing for the cam follower **476** (optionally the pin **478** can be rolled or hollow). The pin **478** can be other bearings in other examples, such as a ball bearing system. The pin **478** can have an outer diameter between 0.5 millimeters (mm) and 10 mm and can be, for example between 1 mm and 3 mm. The pin **478** can be made of one or more of metal, polymer, ceramic, or the like. For example the pin **478** can be a polished steel pin. The pin **478** can optionally be coated to reduce friction between the cam follower **476**, the pin **478**, and the cam arm **474**. The pin **478** can be supported by bores in the cam arm **474** and can be secured thereto, such as in a press fit arrangement, to form a rolling interface or engagement between the pin **478** and the cam follower **476**. Optionally, the pin **478** can be secured to the cam follower **476** to form a rolling interface or engagement between the pin **478** and the cam arm **474**. Optionally, the pin **478** can be secured in various other manners such that the pin **478** can rotate with respect to the cam arm **474** and such that the cam follower **476** can rotate with respect to the pin **478**.

[0054] Optionally, the pin **478**, the bores of the cam arm **474**, or the cam follower **476** can be coated to reduce friction between the components, such as with polytetrafluoroethylene (PTFE) or the like. Similarly, the cam surface **472** can optionally be coated with or made of a low-friction material such as a polymer-based material (such as nylon), ceramic, or the like.

[0055] The cam follower **476** can be a wheel, disc, roller, or the like configured to form a rolling interface between the cam surface **472** and the cam follower **476**. The cam follower **476** can be made of a low-friction material such as a polymer-based material (such as polyoxymethylene (POM), for example Delrin or other POMs), ceramic, or the like. The cam follower **476** can have an outer diameter that is relatively larger than the pin **478** to reduce rolling friction. For example, the outer diameter of the cam follower **476** can be between 5 mm and 30 mm. Optionally, the outer diameter of the cam follower **476** can be between 10 mm and 20 mm, such as 13, 14, or 15 mm. The outer diameter of the cam follower **476** can be maximized or optimized based on contact between the cam surface **472** and a portion of the body **402** when the drive wheel **412** is in the fully retracted or stored position.

[0056] The spring assembly **462** can include a biasing element **482** and optionally an extension tube **484**. The biasing element **482** can be any biasing element such as an extension spring, compression spring, spring bar, torsion spring, or the like. The biasing element **482** can be connected to a pivot **488** to connect the spring assembly **462** to the body **402** such that the spring assembly **462** can pivot with respect to the body **402**. The biasing element **482** can also be connected to the cam arm **474** directly or indirectly. For example, the biasing element **482** can connect to the extension tube **484** at a spring connection **486**. The extension tube **484** can then be connected to the **474** via a tube post **490** to pivotably connect the extension tube **484** to the cam



arm **474** such as to bias the drive wheel arm **412** toward the extended position and to allow rotation of the spring assembly **462** with respect to the cam arm **474**.

[0057] In operation of some examples, the suspension system **454** can apply a force to move the drive wheel **412** to extend from the body **402** and to maintain a downforce on the drive wheel **412**, for example as the drive wheel **412** moves between the retracted position shown in FIG. **4A**, to the partially extended position of FIG. **4B**, to the fully extended position of FIG. **4C**. Use of springs connected to wheel arms (without a cam) can effectively deliver downforce; however, the delivered downforce can decay as the drive wheel extends from the body, delivering a less-than-desirable downforce profile for many operating conditions, such as navigating through high-pile carpet. Components and methods of the designs of the present application can help to address these issues, such as by using the cam follower assembly **460** and cam **458** to vary the mechanical advantage as the drive wheel **412** is extended and retracted to achieve a desired downforce profile. For example, the spring decay that results as the drive wheel **412** moves toward an extended position can be canceled (or compensated for) by increasing mechanical advantage between the cam follower assembly **460** and the cam **458** as the suspension system **454** moves with the drive wheel **412**. Further operational details are discussed below.

[0058] As shown in FIG. **4A**, the drive wheel **412** can be in the retracted position. In the retracted position, the cam follower **476** can be pivoted upward and can be engaged with a rear portion of the cam surface **472** of the cam **458**. In such a condition or position, the biasing element **482** can be maximally or near maximally extended as the extension tube **484** is nearly in contact with (or is in contact with) an upper portion of the body **402** of the mobile cleaning robot **400**. However, due to the contact position of the cam follower **476** with the cam surface **472** the mechanical advantage between the cam follower assembly **460** and the cam **458** (which deliver the force generated by the biasing element **482**) can be relatively low.

[0059] As shown in FIG. **4B**, the drive wheel **412** can be moved to a partially extended position, such as where the drive wheel **412** engages the floor along with the skids **411**, which can be a hard floor surface configuration or condition, for example. In this position, the suspension system **454** can be rotated downward from its position in FIG. **4A**, causing the cam follower **476** to roll forward on the cam surface **472**, increasing a mechanical advantage between the cam arm **474** and the cam **458**, helping to more effectively deliver force from the biasing element **482** to the drive wheel **412**. This increase in mechanical advantage can balance out the force decay in the biasing element **482** caused by the reduction in length **L1** of the biasing element **482** from FIG. **4A** to FIG. **4B**.

[0060] As shown in FIG. **4C**, the drive wheel **412** can be moved to a fully extended position, such as where the drive wheel **412** engages the floor **50** but the skids **411** are elevated from the floor **50**, which can be a configuration or condition where the mobile cleaning robot **400** is navigating on high-pile carpeting or traversing an obstacle. In this position of FIG. **4C**, the suspension system **454** can be rotated downward further from its position in FIG. **4B**, causing the cam follower **476** to roll further forward on the cam surface **472**, increasing a mechanical advantage between the cam arm **474** and the cam **458**, helping to more effectively deliver force from the biasing element **482** to the drive wheel **412**. This increase in mechanical advantage between the positions of FIGS. **4B** and **4C** can further help to balance the force decay in the biasing element **482** caused by the reduction in length **L1** of the biasing element **482** from FIG. **4B** to FIG. **4C**, which can help maintain a constant or near constant downforce between the positions of FIGS. **4A-4C**.

[0061] The suspension system **454** can thereby deliver a constant (or non-decaying) downforce over a full range of travel of the drive wheel **412**. Though a constant downforce is discussed as being delivered by the suspension system **454**, the suspension system **454** can also be tailored or designed to deliver a desired downforce profile by altering, for example, a shape or profile of the cam surface **472** to alter the mechanical advantage. For example, the cam surface **472** can be shaped to deliver a non-linear downforce to the drive wheel **412** as the drive wheel **412** moves

between the extended position and the retracted position. In other words, the cam surface **472** can be shaped to deliver a desired force profile over a range of movement of the drive wheel arm **456** between the extended position and the retracted position.

[0062] Advantageously, because the cam follower **476** can be separated from the cam **458**, the drive wheel arm **456** and drive wheel **412** can be rotated out of the body without disconnecting components of the suspension system **454**. This can help to simplify replacement of components of the suspension system **454** or the drive wheel **412**, such as a tire tread.

[0063] Optionally, as shown in FIG. **4C**, the body **402** can include a stop **492** engageable with the cam arm **474** to limit downward movement of the cam arm **474**, which can effectively limit application of downward force on the drive wheel arm **456** and therefore to the drive wheel **412**. Downward movement or travel of the drive wheel **412** can optionally be limited by engagement between the drive wheel arm **456** and a lower portion of the drive wheel **412**.

[0064] The extension tube **484** can allow for a biasing element **482** that is longer than the connection between the pivot **488** and the tube post **490** to be used. That is, the biasing element **482** and the extension tube **484** can extend beyond the connection point (the tube post **490**) between the extension tube **484** and the cam arm **474**. In other words, the biasing element **482** can have a length  $L_1$  that is greater than a distance or length  $L_2$  between a connection point (the pivot **488**) of the cam arm **474** to the body **402** and the connection point (the tube post **490**) between the extension tube **484** and the cam arm **474**.

[0065] Optionally, as discussed above, the cam **458** can be removable from the drive wheel arm **456** (via the slots **470** and the projections **468**, as shown in FIG. **4A**). Also, as discussed above, because the suspension system **454** is separated (not rigidly connected), the drive wheel arm **456** and drive wheel **412** can be rotated out from the body **402** easily, such as for maintenance. These features can allow a user, designer, customer, or the like to remove the cam **458** and install a cam with a different cam surface to alter the downforce profile of the suspension system **454**, such as to optimize for floor type or to address traversal issues. These features can also allow a user (or the like) to replace a tread of the drive wheel **412** or the drive wheel **412** itself. Optionally, multiple cams can be connected to the drive wheel arm **456** and the cam arm **474** can be positionable to engage the cam follower **476** with the desired cam.

[0066] FIGS. **5A** and **5B** illustrate schematic views of a mobile cleaning robot suspension system **554** of a robot **500** in a stored or retracted position and an extended position. FIGS. **5A** and **5B** are discussed together below. The suspension system **554** can be similar to the suspension system **454** discussed above, FIGS. **5A** and **5B** shows the components schematically.

[0067] More specifically, FIGS. **5A** and **5B** show schematic views of connection of a biasing element **582** to a body **502** at a pivot **588**. The biasing element **582** can be connected to a cam arm **574** at a tube post **590** (acting as a pivot). The cam arm **574** can be connected to the body **502** at a pivot **580** and the cam arm **574** can be connected to a cam follower **576** via a pin **578**. On the other end, a drive wheel arm **556s** (a schematic representation of the effective drive wheel arm) can be connected to the body **502** at a pivot **564** and can be connected to a drive wheel **512** at a wheel center **594**. The drive wheel arm **556s** can be separated from, but engaged with, the cam arm **574** via the cam follower **576**. FIGS. **5A** and **5B** also shows various forces produced by component interaction, where  $N$  is a normal force, normal to or tangential to a contact point between a cam surface **572** of a cam **558** and the cam follower **576**.  $M_1$  can be a moment arm of the biasing element **582** and the cam arm **574** and  $M_2$  can be a moment arm of the drive wheel arm **556s**.

[0068] FIG. **5A** shows that when the drive wheel **512** is in the stored position, the biasing element **582** is relatively long such that it produces a large spring force  $S_1$  is applied to the cam arm **574**. However, because the contact angle between the cam follower **576** and the **572** is relatively horizontal, the moment arm  $M_1$  is relatively small (or similarly sized) to the moment arm  $M_2$ , resulting in a first mechanical advantage and a first wheel downforce  $D_1$ .

[0069] FIG. **5B** shows that when the drive wheel **512** is in the extended position, the biasing

element **582** is relatively shorter than in the stored position of FIG. 5A, thereby applying a smaller force on the cam arm **574**. However, because the contact angle between the cam follower **576** and the cam surface **572** is relatively vertical and because the cam follower **576** has moved forward, the moment arm **M1** of FIG. 5B is large relative to the moment arm **M2** (and relative to the moment arm **M1** of FIG. 5A), resulting in a second mechanical advantage that is larger than the first mechanical advantage. Because the second mechanical advantage is larger than the first mechanical advantage and because the second spring force **S2** is smaller than the first spring force **S1**, the second wheel downforce **D2** can be about the same as the first wheel downforce **D1**, helping to achieve a relatively consistent wheel downforce throughout a range of travel of the drive wheel **512** with respect to the body **502**.

[0070] Though the downforces **D1** and **D2** are discussed and shown as being relatively constant (due at least in part to the shape of the cam surface **572**), the cam surface **572** can be designed, shaped, or configured to provide a desired downforce at any position over the range of travel of the drive wheel **512**. In this way, the robot **500** (and the robots **100** and **500**) can include a passive suspension system including a tailored wheel downforce profile.

[0071] In some examples, the downforce applied by the suspension system **554** or the robot suspension system **554** can be between 2 and 3.2 pounds (4.9 Newtons (N) to 14.25N). In other examples, the suspension system **554** or the mobile cleaning robot suspension system **554** can provide between 1N and 30N.

#### Suspension Performance

[0072] FIG. 6 illustrates a performance chart **600** for a suspension system, such as the mobile cleaning robot **400** or robot **500** where the suspension system has a first cam profile. FIG. 7 illustrates a performance chart **700** for a suspension system, such as the mobile cleaning robot **400** or robot **500** where the suspension system has a second cam profile. FIGS. 6 and 7 are discussed together below.

[0073] The performance charts **600** and **700** each show wheel downforce on the Y-axis or vertical axis and shows wheel elevation from ground or wheel travel on the X-axis or horizontal axis. The chart **600** shows a first cam profile calculated (or theoretical) downforce **602**, measured downforce **604** provided by the drive wheel (e.g., **412**) as the drive wheel extends from the robot, and measured downforce **606** provided by the drive wheel as the drive wheel retracts into the robot. The theoretical plot **602** does not fall about halfway between the two hysteresis plots **604** and **606** likely because the “actual” spring force can be slightly lower than the “theoretical” spring force (and the same spring was used to collect the data for both cam configurations). The chart **700** shows a second cam profile calculated (or theoretical) downforce **702**, measured downforce **704** provided by the drive wheel (e.g., **412**) as the drive wheel extends from the robot, and measured downforce **706** provided by the drive wheel as the drive wheel retracts into the robot.

[0074] The first cam profile (or cam surface shape) of the chart **600** shows a calculated force **602** that has a slight inclining slope as the elevation approaches 0 mm elevation (from -30 mm), peaks around 0 mm wheel elevation, and decreases following retraction into the body (from 0 to 10 mm wheel elevation). This cam profile can provide a relatively consistent wheel downforce (such as 60-75% weight of the robot on the wheels) throughout the range of motion of the drive wheel and wheel arm, where hysteresis causes a differential in extension downforce **604** versus retraction downforce **606**.

[0075] The second cam profile (or cam surface shape) of the chart **700** shows a calculated force **702** that is relatively flat with a large increase in force around 0 mm of wheel elevation, with measured extension and retraction forces on either side accounting for hysteresis. The second cam profile can be designed to deliver such a force profile to help reduce robot vaulting issues as the robot traverses thresholds or other obstacles. Vaulting is a phenomenon that can occur when a robot traverses an obstacle, such as a threshold or small step, because the step is at a front portion of the drive wheel (closer to the pivot), a large down force can be generated, causing the robot to lift off

the ground substantially. This phenomenon can be limited or prevented by altering the cam profile such that downforce is reduced at specific extension distances of the drive wheel.

[0076] Though this profile addresses only some issues, it highlights that the cam profile (e.g., the cam surface **472**) along with the other components of the suspension (e.g., the biasing element **482**, the extension tube **484**, and all of the pivot points), can be tunable or designed to provide a passive suspension system with a varied wheel down force profile to address navigation issues or to help optimize navigation or cleaning performance.

[0077] Because the cam can be designed in a variety of shapes, the cam system can be tailored to provide a desired wheel downforce for a robot of any weight and desired force profile, such that the cam system can be used in a variety of mobile cleaning robots, helping to communize suspension components and helping to reduce costs between robot model variations.

#### NOTES AND EXAMPLES

[0078] The following, non-limiting examples, detail certain aspects of the present subject matter to solve the challenges and provide the benefits discussed herein, among others.

[0079] Example 1 is a mobile cleaning robot movable within an environment, the mobile cleaning robot comprising: a body; a drive wheel arm connected to the body and movable with respect to the body between an extended position and a retracted position; a drive wheel connected to the drive wheel arm and movable therewith, the drive wheel operable to move the mobile cleaning robot; a cam connected to the drive wheel arm and movable therewith; and a cam follower connected to the body, and engaged with the cam to move the drive wheel arm toward the extended position.

[0080] In Example 2, the subject matter of Example 1 optionally includes a biasing member connected to the body and the cam follower to bias the drive wheel arm toward the extended position.

[0081] In Example 3, the subject matter of Example 2 optionally includes a cam arm connecting the cam follower to the body, the biasing member connected to the cam arm.

[0082] In Example 4, the subject matter of Example 3 optionally includes wherein the cam follower is rotatable with respect to the cam arm to rotatably follow the cam.

[0083] In Example 5, the subject matter of Example 4 optionally includes an extension tube connected to the biasing member and the cam arm to connect the biasing member to the cam arm.

[0084] In Example 6, the subject matter of Example 5 optionally includes wherein the biasing member and the extension tube extend beyond a connection point between the extension tube and the cam arm.

[0085] In Example 7, the subject matter of any one or more of Examples 5-6 optionally include wherein the drive wheel arm is pivotably connected to the body, the cam arm is pivotably connected to the body, and the biasing member is pivotably connected to the body.

[0086] In Example 8, the subject matter of Example 7 optionally includes wherein the extension tube is pivotably connected to the cam arm.

[0087] In Example 9, the subject matter of any one or more of Examples 3-8 optionally include wherein the body includes a stop engageable with the cam arm to limit application of downward force on the drive wheel arm.

[0088] In Example 10, the subject matter of any one or more of Examples 1-9 optionally include wherein the cam is shaped to deliver a non-linear downforce from the drive wheel as the drive wheel moves between the extended position and the retracted position.

[0089] In Example 11, the subject matter of any one or more of Examples 1-10 optionally include wherein the cam is shaped to deliver a desired force profile over a range of movement of the drive wheel arm between the extended position and the retracted position.

[0090] Example 12 is a suspension assembly of a mobile cleaning robot, suspension assembly comprising: a drive wheel operable to move the mobile cleaning robot; a drive wheel arm connected a body of the mobile cleaning robot and supporting the drive wheel, the drive wheel arm movable with respect to the body between an extended position and a retracted position; a cam

connected to the drive wheel arm and movable therewith; and a cam follower connected to the body and engaged with the cam to move the drive wheel arm toward the extended position.

[0091] In Example 13, the subject matter of Example 12 optionally includes a biasing member connected to the body and the cam follower to bias the drive wheel arm toward the extended position.

[0092] In Example 14, the subject matter of Example 13 optionally includes a cam arm connecting the cam follower to the body, the biasing member connected to the cam arm.

[0093] In Example 15, the subject matter of Example 14 optionally includes an extension tube connected to the biasing member and the cam arm to connect the biasing member to the cam arm.

[0094] In Example 16, the subject matter of Example 15 optionally includes wherein the biasing member has a length that is greater than a distance between a connection point of the biasing member to the body and a connection point of the extension tube to the cam arm.

[0095] In Example 17, the subject matter of Example 16 optionally includes wherein the drive wheel arm is pivotably connected to the body, the cam arm is pivotably connected to the body, and the biasing member is pivotably connected to the body.

[0096] In Example 18, the subject matter of Example 17 optionally includes wherein the extension tube is pivotably connected to the cam arm.

[0097] Example 19 is a mobile cleaning robot movable within an environment, the mobile cleaning robot comprising: a body; a drive wheel operable to move the mobile cleaning robot; a drive wheel arm connected the body and supporting the drive wheel, the drive wheel arm movable with respect to the body between an extended position and a retracted position; and a cam assembly connected to the body and the drive wheel arm to deliver a desired force profile over a range of movement of the drive wheel arm between the extended position and the retracted position.

[0098] In Example 20, the subject matter of Example 19 optionally includes a biasing member connected to the body and the cam follower to bias the drive wheel arm toward the extended position.

[0099] In Example 21, the subject matter of Example 20 optionally includes a cam arm connecting the cam follower to the body, the biasing member connected to the cam arm.

[0100] In Example 22, the subject matter of Example 21 optionally includes wherein the cam follower is rotatable with respect to the cam arm to rotatably follow the cam.

[0101] In Example 23, the subject matter of Example 22 optionally includes an extension tube connected to the biasing member and the cam arm to connect the biasing member to the cam arm.

[0102] In Example 27, the apparatuses or method of any one or any combination of Examples 1-23 can optionally be configured such that all elements or options recited are available to use or select from.

[0103] The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to herein as “examples.” Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

[0104] In the event of inconsistent usages between this document and any documents so incorporated by reference, the usage in this document controls. In this document, the terms “including” and “in which” are used as the plain-English equivalents of the respective terms “comprising” and “wherein.” Also, in the following claims, the terms “including” and “comprising” are open-ended, that is, a system, device, article, composition, formulation, or process that includes elements in addition to those listed after such a term in a claim are still

deemed to fall within the scope of that claim.

[0105] The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to comply with 37 C.F.R. § 1.72(b), to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description as examples or embodiments, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

## Claims

1. A mobile cleaning robot movable within an environment, the mobile cleaning robot comprising: a body; a drive wheel arm connected to the body and movable with respect to the body between an extended position and a retracted position; a drive wheel connected to the drive wheel arm and movable therewith, the drive wheel operable to move the mobile cleaning robot; a cam connected to the drive wheel arm and movable therewith; a cam follower connected to the body and engaged with the cam to move the drive wheel arm toward the extended position; a biasing member connected to the cam follower to bias the drive wheel arm toward the extended position; and an extension tube connected to the biasing member and the body.
2. The mobile cleaning robot of claim 1, comprising: a cam arm connected to the cam follower, connected to the body, and connected to the extension tube.
3. The mobile cleaning robot of claim 2, wherein the cam follower is rotatable with respect to the cam arm to rotatably follow the cam.
4. The mobile cleaning robot of claim 3, wherein the cam arm is pivotably connected to the body.
5. The mobile cleaning robot of claim 4, wherein the cam arm is pivotably connected to the extension tube.
6. The mobile cleaning robot of claim 5, wherein the biasing member and the extension tube extend beyond a connection point between the extension tube and the cam arm.
7. The mobile cleaning robot of claim 2, wherein the body includes a stop engageable with the cam arm to limit application of downward force on the drive wheel arm.
8. The mobile cleaning robot of claim 1, wherein the cam is shaped to deliver a non-linear downforce from the drive wheel as the drive wheel moves between the extended position and the retracted position.
9. The mobile cleaning robot of claim 1, wherein the cam is shaped to deliver a force corresponding to a specified force profile over a range of movement of the drive wheel arm between the extended position and the retracted position.
10. A suspension assembly of a mobile cleaning robot, suspension assembly comprising: a drive wheel arm connectable to a body of a mobile cleaning robot and movable with respect to the body between an extended position and a retracted position; a drive wheel connected to the drive wheel arm and movable therewith, the drive wheel operable to move the mobile cleaning robot; a cam connected to the drive wheel arm and movable therewith; a cam follower connectable to the body and engaged with the cam to move the drive wheel arm toward the extended position; a biasing

- member connected to the cam follower to bias the drive wheel arm toward the extended position; and an extension tube connected to the biasing member and connectable to the body.
- 11.** The suspension assembly of claim 10, further comprising: a cam arm configured to connect the cam follower to the body, the biasing member connected to the cam arm.
- 12.** The suspension assembly of claim 11, wherein the biasing member has a length that is greater than a distance between a connection point of the biasing member to the body and a connection point of the extension tube to the cam arm.
- 13.** The suspension assembly of claim 11, wherein the cam follower is rotatable with respect to the cam arm to rotatably follow a cam.
- 14.** The suspension assembly of claim 13, wherein the cam arm is pivotably connected to the body.
- 15.** The suspension assembly of claim 14, wherein the cam arm is pivotably connected to the extension tube.
- 16.** The suspension assembly of claim 15, wherein the biasing member and the extension tube extend beyond a connection point between the extension tube and the cam arm.
- 17.** The suspension assembly of claim 12, wherein the body includes a stop engageable with the cam arm to limit application of downward force on the drive wheel arm.
- 18.** The suspension assembly of claim 10, wherein the cam is shaped to deliver a non-linear downforce from the drive wheel as the drive wheel moves between the extended position and the retracted position.
- 19.** The suspension assembly of claim 10, wherein the cam is shaped to deliver a force corresponding to a specified force profile over a range of movement of the drive wheel arm between the extended position and the retracted position.
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