

ACTUATOR FOR RECONFIGURABLE MOBILE ROBOTS

RELATED APPLICATION

[0001] This application claims the benefit of priority to the Singapore application no. 10202302802R filed September 29, 2023, which is incorporated herein by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] The present disclosure relates to an actuator for locomotion of mobile robots.

BACKGROUND

[0003] Owing to the conflicting requirements for wheeled locomotion and for legged locomotion, different actuators are typically required for different types of locomotion. It has been a technically challenging problem to provide an actuator system that can enable different modes of locomotion and is yet suitably compact for use on a mobile robot. Other considerations such as the payload of the resulting mobile robot and the unique constraints of legged robotic locomotion further add to the complexity of the problem.

SUMMARY

[0004] In one aspect, the present application discloses an actuator. The actuator includes: an input member, a sun gear, a first output member, a first brake device, a ring gear, a second output member, a second brake device, and a plurality of planetary gears. The sun gear is rotatable about a first axis of a first shaft. The first output member is coupled to the first shaft and rotationally drivable by the sun gear. The first brake device is coupled to the first output member. The first brake device is operable to switch between an unbraked state and a braked state. The first brake device in the unbraked state is configured to enable rotation of the first output member. The first brake device in the braked state is configured to prevent rotation of the first output member. The ring gear is rotatable about a second axis of a second shaft. The second output member is coupled to the second shaft and

rotationally drivable by the ring gear. The second brake device is coupled to the second output member. The second brake device is operable to switch between the unbraked state and the braked state. The second brake device in the unbraked state is configured to enable rotation of the second output member. The second brake device in the braked state is configured to prevent rotation of the second output member. The plurality of planetary gears are coupled to the input member and rotationally drivable by the input member. The plurality of planetary gears are concurrently in meshing engagement with the sun gear and in meshing engagement with the ring gear.

[0005] The actuator may be operable in one of a first mode and a second mode. The actuator may be in one of the first mode and the second mode in response to one of the first brake device and the second brake device being in the braked state concurrently with another of the first brake device and the second brake device being in the unbraked state.

[0006] The actuator may be configured to switch from the second mode to the first mode in response to the second brake device changing from the unbraked state to the braked state concurrently with the first brake device changing from the braked state to the unbraked state.

[0007] The actuator may be configured to switch from the first mode to the second mode in response to the first brake device changing from the unbraked state to the braked state concurrently with the second brake device changing from the braked state to the unbraked state.

[0008] A mobile system includes: a body, and a plurality of locomotive assemblies. The plurality of locomotive assemblies are coupled to the body. Each of the plurality of locomotive assemblies includes: a wheel, a leg mechanism, and an actuator. The actuator includes: an input member; a sun gear, a first output member, a first brake device, a ring gear, a second output member, a second brake device, and a plurality of planetary gears. The sun gear is rotatable about a first axis of a first shaft. The first output member is coupled to the first shaft and rotationally drivable by the sun gear. The first brake device is coupled to the first output member. The first brake device is operable to switch between an unbraked state and a braked state. The first brake device in the unbraked state is configured

to enable rotation of the first output member. The first brake device in the braked state is configured to prevent rotation of the first output member. The ring gear is rotatable about a second axis of a second shaft. The second output member is coupled to the second shaft and rotationally drivable by the ring gear. The second brake device is coupled to the second output member. The second brake device is operable to switch between the unbraked state and the braked state. The second brake device in the unbraked state is configured to enable rotation of the second output member. The second brake device in the braked state is configured to prevent rotation of the second output member. The plurality of planetary gears are coupled to the input member and rotationally drivable by the input member. The plurality of planetary gears are concurrently in meshing engagement with the sun gear and in meshing engagement with the ring gear. The first output member is coupled to the wheel, and the second output member is coupled to the leg mechanism.

[0009] The actuator is operable in one of a first mode and a second mode. The actuator may be in one of the first mode and the second mode in response to one of the first brake device and the second brake device being in the braked state concurrently with another of the first brake device and the second brake device being in the unbraked state.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] FIG. 1 is a schematic block diagram illustrating a mobile system including an actuator according to various embodiments of the present disclosure;

[0011] FIG. 2 is a schematic block diagram showing further details of the actuator;

[0012] FIG. 3 is a schematic drawing of a mobile system according to one embodiment, in which the mobile system is legged locomotion;

[0013] FIG. 4 is a schematic drawing of the mobile system having a plurality of locomotive assemblies switchable between a wheeled mode and a legged mode;

- [0014] FIG. 5 is a schematic drawing of the mobile system according to another embodiment, having at least one locomotive assembly in a wheeled mode and at least one other locomotive assembly in a legged mode;
- [0015] FIG. 6 is a perspective view of an actuator according to one embodiment of the present disclosure;
- [0016] FIG. 7 is a perspective view of the actuator of FIG. 6 in assembly with a wheel and a leg mechanism;
- [0017] FIG. 8 is a perspective view of the actuator of FIG. 6 axially exploded to show components of the actuator;
- [0018] FIG. 9 is a cross-sectional view of the actuator of FIG. 6 showing a plurality of planetary gears in meshing engagement with a sun gear and a ring gear, in which the planetary gears are drivable by a belt which is in turn drivable by an input member;
- [0019] FIG. 10 is a schematic perspective view of the actuator in accordance with another embodiment, partially exploded to show a second brake device operable with the ring gear;
- [0020] FIG. 11 is a perspective view of the actuator of FIG. 10;
- [0021] FIG. 12 is a cross-sectional view of the actuator of FIG. 11;
- [0022] FIG. 13 is an exploded schematic perspective view of the actuator in accordance with yet another embodiment;
- [0023] FIG. 14 is a perspective view of the actuator of FIG. 13;
- [0024] FIG. 15 is a cross-sectional view of the actuator of FIG. 14; and
- [0025] FIG. 16 and FIG. 17 are schematic drawing of a tracked robot with flippers, operable in a tracked locomotion mode and in a flipper locomotion mode, respectively, according to another embodiment of the present disclosure.

DETAILED DESCRIPTION

[0026] The following detailed description is made with reference to the accompanying drawings, showing details and embodiments of the present disclosure for the purposes of illustration. Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments, even if not explicitly described in these other

embodiments. Additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0027] The term “and/or” includes any and all combinations of one or more of the associated listed items.

[0028] The terms “about” and “approximately” as applied to a stated numeric value encompasses the exact value and a reasonable variance and the terms “generally” and “substantially” are to be understood in a comparable manner, unless otherwise specified. For example, in the context of various embodiments, the term “about” or “approximately” as applied to a stated numeric value will be generally understood by one skilled in the art to encompass the exact value and a reasonable variance as generally understood in the relevant technical field, e.g., within 10% of the specified value.

[0029] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. As used herein, the singular “a”, “an”, and “the” may be construed as including the plural “one or more” unless apparent from the context to be otherwise.

[0030] Terms such as “first” and “second” are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless required by the context.

[0031] In the present disclosure, the terms “actuator”, “actuator gear box”, “gear train”, “transmission gear train”, etc., may be used interchangeably.

[0032] **FIG. 1** is a schematic block diagram illustrating a mobile system 100 including an actuator 200 according to various embodiments of the present disclosure. The mobile system 100 may include a power source 110, for example, including but not limited to a battery pack. The mobile system 100 may include an input actuator or a motor 130. For example, the motor 130 may be powered by electrical energy drawn from the battery pack (power source 110). In operation, the motor 130 converts the electrical energy to mechanical power to drive a rotational motion of an input member of the actuator 200.

[0033] A controller 120 may be provided as part of the mobile system 100 and/or part of the actuator 200. The motor 130 may be configured to control the speed of the motor 130. The controller 120 may be configured to control a mode of the actuator 200. The controller 120 may be configured to controllably operate the motor 130 and/or the actuator 200 in response to feedback signals (e.g., via one or more sensors) from the actuator 200.

[0034] The actuator 200 may be in the form of a modular unit or a module for “plug-and-play” installation to the motor 130. Once installed, the actuator 200 may be operated in a first mode (e.g., mode 1 as shown in **FIG. 1**) or in a second mode (e.g., mode 2 as shown in **FIG. 1**).

[0035] In some examples, compared to the second mode, the first mode is associated with a higher speed and a lower torque at the output of the actuator 200. For example, the actuator 200 in the first mode may operate a wheel at the output of the actuator 200, to enable the mobile system 100 to move by a wheeled locomotion. In some examples, the mobile system 100 may be a robot with a set of wheels drivable by the actuator 200 in the first mode.

[0036] In some examples, compared to the first mode, the second mode is associated with a lower speed and a higher torque at the output of the actuator 200. For example, the actuator 200 in the second mode may operate one or more leg mechanism at the output of the actuator 200, to enable the mobile system 100 to move by a legged locomotion. A legged locomotion may include any one or a combination of any two or more of a walking locomotion, a running locomotion, a step/stair-climbing locomotion, etc. In some examples, the mobile system 100 may be a robot with a set of legs operable by the actuator 200 in the second mode.

[0037] **FIG. 2** schematically illustrates the actuator 200 in accordance with various embodiments of the present disclosure. Advantageously, the actuator 200 requires only one mechanical power input 134 from the motor 130. In various embodiments a brushless direct current (BLDC) motor may be used. The motor may have a built-in field oriented controller (FOC) enabling control of the position, velocity, and torque of the motor output. Alternatively, a small direct current (DC) motor may be used, e.g., a DC motor controlled by pulse width modulation (PWM) may be used. The controller (which may be built-in or in a separate device) 120

may be configured to provide control signals 122 via a motor control input/output (I/O) interface and/or receive feedback 124 from the motor 130.

[0038] The actuator 200 includes an epicyclic gear train 220. The epicyclic gear train 220 includes a plurality of planetary gears 400 in concurrent meshing engagement with a sun gear 300 and a ring gear 500. According to various embodiments, the planetary gears 400, the sun gear 300, and the ring gear 500 may be disposed co-planarly or substantially co-planarly relative to one another. Each of the gears (e.g., the sun gear 300, the planetary gears 400, the ring gear 500) may be a spur gear or a straight-cut gear.

[0039] Each of the sun gear 300, the planetary carrier 410, the planetary gears 400, and the ring gear 500 may be disposed to rotate about respective shafts (or axes of rotation defined by the respective shafts 301, 401, 411, 501) that are parallel to one another. In some embodiments, two or more of the axes of rotation (defined by the shafts 301, 401, 411, 501 respectively) may be co-axially disposed. For the sake of brevity, reference may be taken with respect to the first shaft 301 of the sun gear 300. For example, a second shaft 501 of the ring gear 500 may be disposed parallel or substantially parallel to the first shaft 301.

[0040] A planetary carrier 410 may be configured to rotate about a carrier shaft 401 as a result of mechanical power input from the motor 130. For example, the planetary carrier 410 may be rotatably driven by the motor 130 such that the planetary carrier 410 rotates about an axis of rotation defined by the carrier shaft 401. Each of the plurality of planetary gears 400 may be supported by the planetary carrier 410. The planetary gears 400 may be spaced apart from one another (e.g., not in direct meshing engagement with one another) and distributed about the carrier axis 401. Each of the plurality of planetary gears 400 may be configured to rotate relative to the planetary carrier 410 and about an axis of rotation defined by the respective planetary gear shaft 411.

[0041] The planetary gears 400 are in meshing engagement with the sun gear 300. The sun gear 300 is fixed to a first shaft 301 which rotates with the sun gear 300. The rotation of the first shaft 301 is transmitted to a corresponding rotation of a first output member 360 (e.g., which may also be referred to as a sun output or a sun gear output).

[0042] The planetary gears 400 are in meshing engagement with the ring gear 500. The ring gear 500 is coupled to a second output member 560 (e.g., which may also be referred to as a ring gear output) such that rotation of the ring gear is transmitted to a corresponding rotation of the second output member 560 (e.g., which may also be referred to as a ring output or a ring gear output).

[0043] The actuator 200 may be configured to operate in one of a plurality of modes.

[0044] The actuator includes a first brake device 370 (e.g., which may also be referred to as a sun gear brake) that can be controllably operated to prevent the sun gear 300 from rotating. For example, the actuator 200 may be configured such that activating or operating the first brake device 370 puts the actuator in a second mode. For example, the controller 120 may control the first brake device 370 via first brake control signals 123 to engage or to disengage the first brake device 370 with/from one of the first output member 360, the first shaft 301, and the sun gear 300. In the second mode, the sun gear 300 is fixed (e.g., relative to a frame of reference such as, but not limited to, a body of the mobile system 100). The input to the actuator 200 is delivered via the planetary carrier 410. The output from the actuator 200 is at the second output member 560. The power transmission from the actuator input to the second output member 560 is via the planetary gears 400 and the ring gear 500. The transmission ratio of such a gear train configuration may be configured to be always greater than one.

[0045] The actuator includes a second brake device 570 (e.g., which may also be referred to as a ring gear brake) that can be controllably operated to prevent the ring gear 500 from rotating. The actuator includes a first brake device 370 (e.g., which may also be referred to as a sun gear brake) that can be controllably operated to prevent the sun gear 300 from rotating. For example, the actuator 200 may be configured such that activating or operating the second brake device 570 puts the actuator in a first mode. For example, the controller 120 may control the second brake device 570 via first brake control signals 125 to engage or to disengage the second brake device 570 with/from one of the second output member 560, the second shaft 501, and the ring gear 500. For example, the actuator 200 may be configured such that activating or operating the second brake device 570 puts the

actuator in a first mode. In the first mode, the ring gear 500 is fixed (e.g., relative to a frame of reference such as, but not limited to, a body of the mobile system 100). The actuator input (e.g., input to the actuator 200) is delivered via the planetary carrier 410. The output from the actuator 200 is at the first output member 360. The power transmission from the actuator input to the first output member 360 is via the planetary gears 400 and the sun gear 300. The transmission ratio of such a gear train configuration may be configured to be always less than one.

[0046] As schematically illustrated in **FIG. 3**, “legged locomotion” of a mobile system 100 may involve having selected ones of the locomotive assemblies 150 in contact with the ground 190 (e.g., for balance or support) and concurrently having at least one other of the locomotive assemblies 150 extending to engage a new part of the intended path of locomotion. Legged locomotion can be useful for traversing irregular terrain.

[0047] **FIG. 3** is a schematic diagram showing an example of the mobile system 100 with a body 140 and a plurality of locomotive assemblies 150. At any one time, each locomotive assembly 150 may operate in one of a plurality of modes. For example, the mobile system 100 may be configured in the first mode in which all the locomotive assemblies 150 are operable in wheeled locomotion. For example, the mobile system 100 may be configured in the second mode in which all the locomotive assemblies 150 are operable in a legged locomotion.

[0048] In some examples as shown in **FIG. 4**, switching from the first mode to the second mode may include using the same actuator 100 to rotate and extend the leg mechanism, in addition to the second brake device 570 being changed to an unbraked state and the first brake device 370 being changed to a braked state.

[0049] In some examples, switching from the second mode to the first mode may include using the actuator 100 to rotate and tuck up the leg mechanism so that the wheel contacts the ground 190, in addition to the second brake device 570 being changed to a braked state and the first brake device 370 being changed to an unbraked state.

[0050] **FIG. 5** is a schematic drawing of another embodiment of the mobile system 100 showing the versatility of the proposed actuator 200. The mobile system 100 may be fitted with multiple units of the same actuator 200, with selected units

of the actuator 200 being configured in a wheeled mode and other units of the actuator 200 being configured in a legged mode. Despite operating in different modes of locomotion, the same actuator 200 may be used. This advantageously enables the mobile system 100 to adapt itself to a variety of different terrains or environments. Further, the versatility of the actuator 200 enables the wheel or the leg mechanism to be interchangeable attached or detached by the user.

[0051] For example, the mobile system 100 may be manufactured and sold with the body 140 and a plurality of the actuators 200 connected to the body 140. The user may then select from various types of wheels and attach the selected wheel to the first output member 360, and/or select from various types of leg mechanisms and attach the selected leg mechanism to the second output member 560, respectively.

[0052] **FIG. 6** to **FIG. 9** are various views of the actuator 100 according to a prototype fabricated and tested. **FIG. 6** shows the actuator 200 in assembly with the motor 130. The motor 130 may drive the planetary carrier of the actuator 200 via a pulley 138 and a timing belt 139 assembly. **FIG. 7** shows the actuator 200 in assembly with two locomotive assemblies 150, e.g., a wheel 150 and a leg mechanism 152.

[0053] To further aid understanding, in **FIG. 8**, the actuator 200 is shown exploded along a first axis defined by the first shaft 301. In this example, the first brake device 370 and the second brake device 570 are disposed on different sides of the epicyclic gear train 300/400/500. The ring gear 500 may be coupled to a ring hub 510 which is in turn connected to the ring output or the second output member 560. A ring bearing 520 may be provided between the ring gear 500 and a part of the body 140 or a supporting frame 142, for relative motion between the ring bearing 520 and the body 140.

[0054] **FIG. 9** is a cross-sectional view of the actuator 200 showing the planetary gears 400 in concurrent meshing engagement with the sun gear 300 and the ring gear 400. As can be seen, the actuator 200 is relatively compact with the majority of the components aligned axially along the first axis (e.g., as defined by the first shaft 301). The actuator 200 can be relatively compact with only one input member 132 (which in one embodiment includes the output of the motor 130, the pulley 138,

and timing belt 139) disposed at an offset. Since only one motor 130 is required, it would not be required to provide multiple sets of sensors and other sensors for control feedback, as compared to conventional set-ups where each motor would require its own set of sensors for feedback control.

[0055] An exemplary prototype of the actuator 100 was built and mounted with a legged mechanism and a wheel (e.g., as illustrated in **FIG. 7**). The motor 130 used was capable of a nominal speed of 228 rpm (revolutions per minute) with a theoretical peak torque of 48 Nm. The ring gear selected had 120 teeth ($N = 120$), the sun gear 60 teeth ($N = 60$), and the carrier 30 teeth ($N = 30$). The following two alternative outputs could be obtained.

[0056] In one mode (high speed low torque), a torque of 6 Nm (Newton meters) and a speed of about 678 rpm or about 680 rpm was obtained. This would be suitable for wheeled locomotion where speed is preferred. The effective gear ratio was 1:3 (input:output), with the ring gear being stationary.

[0057] In another mode (high torque low speed), an average torque of 12 Nm with a peak torque of 32 Nm could be obtained, with a speed of about 340 rpm. This would be suitable for legged locomotion or for overcoming obstacles. The effective gear ratio was 1:1.5 (input:output), with the sun gear being stationary. In this example, the change in output torque is two times ($2\times$). Advantageously, between high torque mode and the low torque mode, the difference in the output torque in output torque can be as high as ten times ($10\times$) or greater. The present actuator can potentially widen the range of motion of the mobile system for a given payload or performance requirement.

[0058] In the experiments, a method of controlling the actuator 200 includes:

- (i) The motor 130 and associated electronics receiving power from a power source 110.
- (ii) The controller 120, e.g., a microcontroller unit (MCU), which manages the motor 130 and electromagnetic brakes 370/570, receiving a command from either a main controller unit or a computing device.
- (iii) The controller 120 engages one of the electromagnetic brakes based on the command / specified desired output, e.g., ring output or sun output.
- (iv) The controller sends commands to the motor 130, and the motor 130 starts

rotating, providing the mechanical input to the planetary gears.

- (v) By engaging one of the two electromagnetic brakes 370/570, the epicyclic gear train is now fully constrained, and the actuator 200 transmits the input power to the desired output.
- (vi) Each of the two possible outputs has predetermined torque and speed characteristics for the respective application or use case, with the two possible outputs being distinct from one another.
- (vii) The motor 130 provides real-time data feedback to the controller 120, allowing for continuous monitoring and adjustments, if necessary, to maintain the desired performance.

[0059] In general, conventional legged robots tend to reach an inherent speed limit, as well as generally having relatively lower efficiency while “running”, as compared to an equivalent (by net actuation power) wheeled robot, due to the physical limitation of actuation speed in combination with legged kinematics & dynamics. Conventional wheel-legged robot attempts to overcome these physical limitation by adding an additional wheel and motor to the foot of the robot, to try to bridge the efficiency gap between legged and wheeled systems. These limitations are no longer issues in a mobile system 100 using the proposed actuator 200.

[0060] One other potential use of the proposed actuator system is to replace one of the legged joints, for example, the “elbow joint”. This allows a hybrid legged platform to operate in two “modes”, e.g., (i) as a conventional legged robot, with the wheels locked, or (ii) as a hybrid-wheeled platform where the joint is locked, and operates as a wheeled system.

[0061] **FIG. 10** is an exploded perspective view of another embodiment of the actuator 200. **FIG. 11** is a perspective view of the actuator 200 of **FIG. 10**. **FIG. 12** is a cross-sectional view of the actuator 200 of **FIG. 11**. As illustrated, the actuator 200 includes an epicyclic gear train 300/400/500 configured to receive one mechanical power input 134 at the planetary carrier 410 with two possible outputs enabled by operating a first brake device 370 and a second brake device 570. In this example, the second brake device 570 is formed by a ring brake component 571 and a ring disk brake caliper 572. The second brake device 570 may be disposed in a brake housing 573. As shown in **FIG. 11** and **FIG. 12**, despite the

ability to enable different modes of locomotion, the actuator 200 can be relatively compact and modular, e.g., suitable for interchangeable installation which advantageously enable a greater degree of versatility in the configuration of the mobile system 100.

[0062] **FIG. 13** is an exploded perspective view of yet another embodiment of the actuator 200. **FIG. 14** is a perspective view of the actuator 200 of **FIG. 12**. **FIG. 15** is a cross-sectional view of the actuator 200 of **FIG. 14**. In this example, the actuator 200 is similarly configured with one mechanical power input 134. The actuator 200 includes an epicyclic gear train that can be configured to transmit the rotational torque to a ring output (e.g., second output member 560) and/or output shaft (e.g., second shaft 501). The actuator 200 may include a second brake device 570. The second brake device 470 may be configured to engage the second output member 560 in a braked state.

[0063] The rotational torque may alternatively be transmitted to the planetary carrier 410 and/or an output shaft 406 connected thereto. The actuator 200 may include a carrier brake device 470. The carrier brake device 470 may be configured to engage the planetary carrier 410 and/or the planetary gears 400 in a braked state relative to the sun gear 300.

[0064] As shown in **FIG. 14** and **FIG. 15**, despite the ability to enable different modes of locomotion, the actuator 200 can be relatively compact and modular, e.g., suitable for interchangeable installation which advantageously enable a greater degree of versatility in the configuration of the mobile system 100.

[0065] The proposed actuator 200 may be described as a hybrid actuator or an all-in-one actuator that is suited for both high-speed wheeled locomotion as well as high torque legged locomotion at a lower speed. Additionally, the actuator has been shown to be relatively compact while being configurable to provide mechanical power to wheel-legged hybrid mechanisms (e.g., mechanisms that integrate a wheel with legged mechanisms). The actuator 200 includes a planetary differential transmission (300/400/500) that connects the one input (e.g., input member) to two possible outputs (e.g., first output member 360 and second output member 560), a braking mechanism (e.g., first brake device 370 and second brake device 570) that can selectively lock one of the two possible outputs, and a mode switching

mechanism that enables the actuator 200 to switch between two modes of operation (e.g., locomotion) such as a wheel mode and a legged mode. The proposed approach involves one input and two selectable (mutually exclusive) outputs. This is done through securing two distinct sets of output by locking separate components, thus obtaining outputs from both the sun gear 300 and the ring gear 500, for example. These two outputs showcase distinct gear ratios and speed-torque characteristics stemming from one input shaft (e.g. input member).

[0066] The mobile system 100 may include the controller 120, the epicyclic gear train (300/400/500), and a set of electromagnetic brakes (370, 570) that takes in one mechanical input and outputs two mutually exclusive coaxial outputs using electromagnetic brakes to selectively constrain the under-constrained epicyclic gear train. The braking mechanism also enables control of the output torque and output speed of the actuator 200. Advantageously, this allows a single actuator to be used in place of conventional set-ups which require two actuators to achieve a similar result. The complexity of the mobile system 100 can therefore be simplified by use of the actuator 200.

[0067] The dual configuration allows the actuator 200 to have two mutually exclusive outputs that can be controlled. At any time, the actuator 200 may be operable in only one of the two mutually exclusive outputs. The planetary differential transmission (300/400/500) allows the actuator 200 to split the torque and speed to achieve different outputs. The braking mechanism (370/570) allows the actuator 200 to lock one of the outputs to achieve a higher torque or speed output from the other output.

[0068] The actuator 200 can be used as a modular unit that can be quickly connected to other similar or different units to form reconfigurable and modular mobile robots. The actuator 200 can also be equipped with sensors and communication devices to enable coordination and collaboration among a plurality of the actuators 200 installed on a mobile system 100. In other words, this is a scalable concept that can be adapted to various mobile systems 100 of different sizes and power requirements, making it suitable for various applications with similar constraints. The mobile system 100 can also be adapted for the specific applications, such as a locomotion system that can perform on flat ground and

overcome obstacles such as steps or stairs.

[0069] The actuator 200 has a wide range of potential applications. The actuator 200 can conceivably be used to reduce the total number of motors required to operate a tracked robot with flippers. Conventionally, tracks 150 and flippers 155 are such different types of mechanisms that operating tracks 150 and flippers 155 on the same robot would require a dedicated motor for each track 150 and each flipper 155. **FIG. 16** and **FIG. 17** schematically illustrate a tracked robot with flippers 155 according to another embodiment of the present disclosure in which the robot can be alternately operable in a tracked locomotion mode or in a flipper locomotion mode. Using the actuator 200 proposed herein, one track and one flipper can share a motor, thereby reducing the number of motors required from four to two. The robot can conceivably be used as an amphibious vehicle with the tracks operable on land and the flippers operable in water.

[0070] It is also envisioned that the actuator 200 can be used for a mobile system in the form of a vehicle with wheels, in which the wheels can be reoriented to serve as tracks. For example, when the vehicle is traversing flat ground, wheels can be deployed to speed up search and rescue operations. When overcoming rough or uneven terrain, the tracks can be deployed.

[0071] The actuator 200 can also be used with transformable wheels or “whegs” (e.g., a wheel that can unfold to form four spiral legs). Using the proposed actuator, the performance of the robot with transformable legs need not be compromised to suit only the wheel mode or the legged mode, even without adding more motors to the robot.

[0072] An actuator includes: an input member, a sun gear, a first output member, a first brake device, a ring gear, a second output member, a second brake device, and a plurality of planetary gears. The sun gear is rotatable about a first axis of a first shaft. The first output member is coupled to the first shaft and rotationally drivable by the sun gear. The first brake device is coupled to the first output member. The first brake device is operable to switch between an unbraked state and a braked state. The first brake device in the unbraked state is configured to enable rotation of the first output member. The first brake device in the braked state is configured to prevent rotation of the first output member. The ring gear is rotatable

about a second axis of a second shaft. The second output member is coupled to the second shaft and rotationally drivable by the ring gear. The second brake device is coupled to the second output member. The second brake device is operable to switch between the unbraked state and the braked state. The second brake device in the unbraked state is configured to enable rotation of the second output member. The second brake device in the braked state is configured to prevent rotation of the second output member. The plurality of planetary gears are coupled to the input member and rotationally drivable by the input member. The plurality of planetary gears are concurrently in meshing engagement with the sun gear and in meshing engagement with the ring gear.

[0073] The actuator may be operable in one of a first mode and a second mode. The actuator may be in one of the first mode and the second mode in response to one of the first brake device and the second brake device being in the braked state concurrently with another of the first brake device and the second brake device being in the unbraked state.

[0074] The actuator may be configured to switch from the second mode to the first mode in response to the second brake device changing from the unbraked state to the braked state concurrently with the first brake device changing from the braked state to the unbraked state.

[0075] The actuator may be configured to switch from the first mode to the second mode in response to the first brake device changing from the unbraked state to the braked state concurrently with the second brake device changing from the braked state to the unbraked state.

[0076] The first mode may be characterized by the first brake member being in the unbraked state and the second brake member being in the braked state, in which the first output member is characterized by a first torque and a first rotational speed, the first torque being a non-zero torque in the first mode.

[0077] The second mode may be characterized by the second brake member being in the unbraked state and the first brake member being in the braked state, in which the second output member is characterized by a second torque and a second rotational speed, the second torque being a non-zero torque in the second mode.

[0078] The first torque in the first mode may be less than the second torque in the second mode.

[0079] The first rotational speed in the first mode may be greater than the second rotational speed in the second mode.

[0080] The first shaft and the second shaft are parallel to one another.

[0081] The first shaft and the second shaft may be coaxial with one another.

[0082] The actuator may be configured to controllably operate each of the first brake device and the second brake device, in response to a control signal.

[0083] The first brake device and the second brake device may be operable independently of one another.

[0084] The first brake device includes an electromagnetic brake.

[0085] The second brake device includes an electromagnetic brake.

[0086] A mobile system includes: a body, and a plurality of locomotive assemblies. The plurality of locomotive assemblies are coupled to the body. Each of the plurality of locomotive assemblies includes: a wheel, a leg mechanism, and an actuator. The actuator includes: an input member; a sun gear, a first output member, a first brake device, a ring gear, a second output member, a second brake device, and a plurality of planetary gears. The sun gear is rotatable about a first axis of a first shaft. The first output member is coupled to the first shaft and rotationally drivable by the sun gear. The first brake device is coupled to the first output member. The first brake device is operable to switch between an unbraked state and a braked state. The first brake device in the unbraked state is configured to enable rotation of the first output member. The first brake device in the braked state is configured to prevent rotation of the first output member. The ring gear is rotatable about a second axis of a second shaft. The second output member is coupled to the second shaft and rotationally drivable by the ring gear. The second brake device is coupled to the second output member. The second brake device is operable to switch between the unbraked state and the braked state. The second brake device in the unbraked state is configured to enable rotation of the second output member. The second brake device in the braked state is configured to prevent rotation of the second output member. The plurality of planetary gears are coupled to the input member and rotationally drivable by the input member. The

plurality of planetary gears are concurrently in meshing engagement with the sun gear and in meshing engagement with the ring gear. The first output member is coupled to the wheel, and the second output member is coupled to the leg mechanism.

[0087] The actuator is operable in one of a first mode and a second mode. The actuator may be in one of the first mode and the second mode in response to one of the first brake device and the second brake device being in the braked state concurrently with another of the first brake device and the second brake device being in the unbraked state.

[0088] The mobile system may further include a motor. The motor in operation may be coupled to the input member to rotationally drive the input member. The motor may be controllable to operate each of the plurality of locomotive assemblies in one of the first mode and the second mode, in which the wheel is operable in the first mode, and in which the leg mechanism is operable in the second mode.

[0089] The actuator may be configured to switch from the second mode to the first mode in response to the second brake device changing from the unbraked state to the braked state concurrently with the first brake device changing from the braked state to the unbraked state. The actuator may be configured to switch from the first mode to the second mode in response to the first brake device changing from the unbraked state to the braked state concurrently with the second brake device changing from the braked state to the unbraked state.

[0090] The first mode may be characterized by the first brake member being in the unbraked state and the second brake member being in the braked state, the first output member being characterized by a first torque and a first rotational speed, the first torque being a non-zero torque in the first mode, in which the second mode is characterized by the second brake member being in the unbraked state and the first brake member being in the braked state, the second output member being characterized by a second torque and a second rotational speed, the second torque being a non-zero torque in the second mode.

[0091] The first torque and the second torque are mutually exclusive outputs of the actuator.

[0092] It can be appreciated from the above description that one unit of the

actuator 200 may operate in the first mode to drive one or more wheels, and the same unit of the actuator 200 may operate in the second mode to drive one or more legs. The same unit of the actuator 200 may switch between the first mode and the second mode without the need to uninstall a set of wheels and install a set of legs, or vice versa, every time there is a need to use a different locomotion. This may be useful in situations where the mobile system 100 (such as a robot or a vehicle) may encounter a change in terrain, obstacles, and/or environment, etc. This may be particularly useful in situations where it may be impractical to stop the mobile system 100 in its motion, uninstall one set of locomotive assembly, install another set of locomotive assembly, and restart the mobile system in its movement.

[0093] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding, and are not intended to be limiting or exhaustive. Modifications may be made by one of ordinary skill in the art without departing from the scope of the claimed invention.

CLAIMS

1. An actuator comprising:
 - an input member;
 - a sun gear, the sun gear being rotatable about a first axis of a first shaft;
 - a first output member, the first output member being coupled to the first shaft and rotationally drivable by the sun gear;
 - a first brake device, the first brake device being coupled to the first output member, the first brake device being operable to switch between an unbraked state and a braked state, the first brake device in the unbraked state being configured to enable rotation of the first output member, the first brake device in the braked state being configured to prevent rotation of the first output member;
 - a ring gear, the ring gear being rotatable about a second axis of a second shaft;
 - a second output member, the second output member being coupled to the second shaft and rotationally drivable by the ring gear;
 - a second brake device, the second brake device being coupled to the second output member, the second brake device being operable to switch between the unbraked state and the braked state, the second brake device in the unbraked state being configured to enable rotation of the second output member, the second brake device in the braked state being configured to prevent rotation of the second output member; and
 - a plurality of planetary gears, the plurality of planetary gears being coupled to the input member and rotationally drivable by the input member, the plurality of planetary gears being concurrently in meshing engagement with the sun gear and in meshing engagement with the ring gear.
2. The actuator as recited in claim 1, wherein the actuator is operable in one of a first mode and a second mode, the actuator being in one of the first mode and the second mode in response to one of the first brake device and the second brake device being in the braked state concurrently with another of the first brake device and the second brake device being in the unbraked state.

3. The actuator as recited in claim 2, wherein the actuator is configured to switch from the second mode to the first mode in response to the second brake device changing from the unbraked state to the braked state concurrently with the first brake device changing from the braked state to the unbraked state.

4. The actuator as recited in claim 2, wherein the actuator is configured to switch from the first mode to the second mode in response to the first brake device changing from the unbraked state to the braked state concurrently with the second brake device changing from the braked state to the unbraked state.

5. The actuator as recited in claim 2, wherein the first mode is characterized by the first brake member being in the unbraked state and the second brake member being in the braked state, and wherein the first output member is characterized by a first torque and a first rotational speed, the first torque being a non-zero torque in the first mode.

6. The actuator as recited in claim 5, wherein the second mode is characterized by the second brake member being in the unbraked state and the first brake member being in the braked state, and wherein the second output member is characterized by a second torque and a second rotational speed, the second torque being a non-zero torque in the second mode.

7. The actuator as recited in claim 6, wherein the first torque in the first mode is less than the second torque in the second mode.

8. The actuator as recited in claim 6, wherein the first rotational speed in the first mode is greater than the second rotational speed in the second mode.

9. The actuator as recited in claim 1, wherein the first shaft and the second shaft are parallel to one another.

10. The actuator as recited in claim 1, wherein the first shaft and the second shaft are coaxial with one another.

11. The actuator as recited in claim 1, wherein the actuator is configured to controllably operate each of the first brake device and the second brake device, in response to a control signal.

12. The actuator as recited in claim 11, wherein the first brake device and the second brake device are operable independently of one another.

13. The actuator as recited in claim 11, wherein the first brake device comprises an electromagnetic brake.

14. The actuator as recited in claim 11, wherein the second brake device comprises an electromagnetic brake.

15. A mobile system comprising:

a body;

a plurality of locomotive assemblies, the plurality of locomotive assemblies being coupled to the body, each of the plurality of locomotive assemblies including:

a wheel;

a leg mechanism; and

an actuator, the actuator including:

an input member;

a sun gear, the sun gear being rotatable about a first axis of a first shaft;

a first output member, the first output member being coupled to the first shaft and rotationally drivable by the sun gear;

a first brake device, the first brake device being coupled to the first output member, the first brake device being operable to switch between an unbraked state and a braked state, the first brake device in the unbraked state being configured to enable rotation of the first output member, the first brake device in the braked

state being configured to prevent rotation of the first output member;

a ring gear, the ring gear being rotatable about a second axis of a second shaft;

a second output member, the second output member being coupled to the second shaft and rotationally drivable by the ring gear;

a second brake device, the second brake device being coupled to the second output member, the second brake device being operable to switch between the unbraked state and the braked state, the second brake device in the unbraked state being configured to enable rotation of the second output member, the second brake device in the braked state being configured to prevent rotation of the second output member; and

a plurality of planetary gears, the plurality of planetary gears being coupled to the input member and rotationally drivable by the input member, the plurality of planetary gears being concurrently in meshing engagement with the sun gear and in meshing engagement with the ring gear,

wherein the first output member is coupled to the wheel,

and wherein the second output member is coupled to the leg mechanism.

16. The mobile system as recited in claim 15, wherein the actuator is operable in one of a first mode and a second mode, the actuator being in one of the first mode and the second mode in response to one of the first brake device and the second brake device being in the braked state concurrently with another of the first brake device and the second brake device being in the unbraked state.

17. The mobile system as recited in claim 16, further comprising:

a motor, the motor in operation being coupled to the input member to rotationally drive the input member, the motor being controllable to operate each of the plurality of locomotive assemblies in one of the first

mode and the second mode, wherein the wheel is operable in the first mode, and wherein the leg mechanism is operable in the second mode.

18. The mobile system as recited in claim 16,

wherein the actuator is configured to switch from the second mode to the first mode in response to the second brake device changing from the unbraked state to the braked state concurrently with the first brake device changing from the braked state to the unbraked state,

wherein the actuator is configured to switch from the first mode to the second mode in response to the first brake device changing from the unbraked state to the braked state concurrently with the second brake device changing from the braked state to the unbraked state.

19. The mobile system as recited in claim 16,

wherein the first mode is characterized by the first brake member being in the unbraked state and the second brake member being in the braked state, the first output member being characterized by a first torque and a first rotational speed, the first torque being a non-zero torque in the first mode,

wherein the second mode is characterized by the second brake member being in the unbraked state and the first brake member being in the braked state, the second output member being characterized by a second torque and a second rotational speed, the second torque being a non-zero torque in the second mode.

20. The mobile system as recited in claim 19, wherein the first torque and the second torque are mutually exclusive outputs of the actuator.