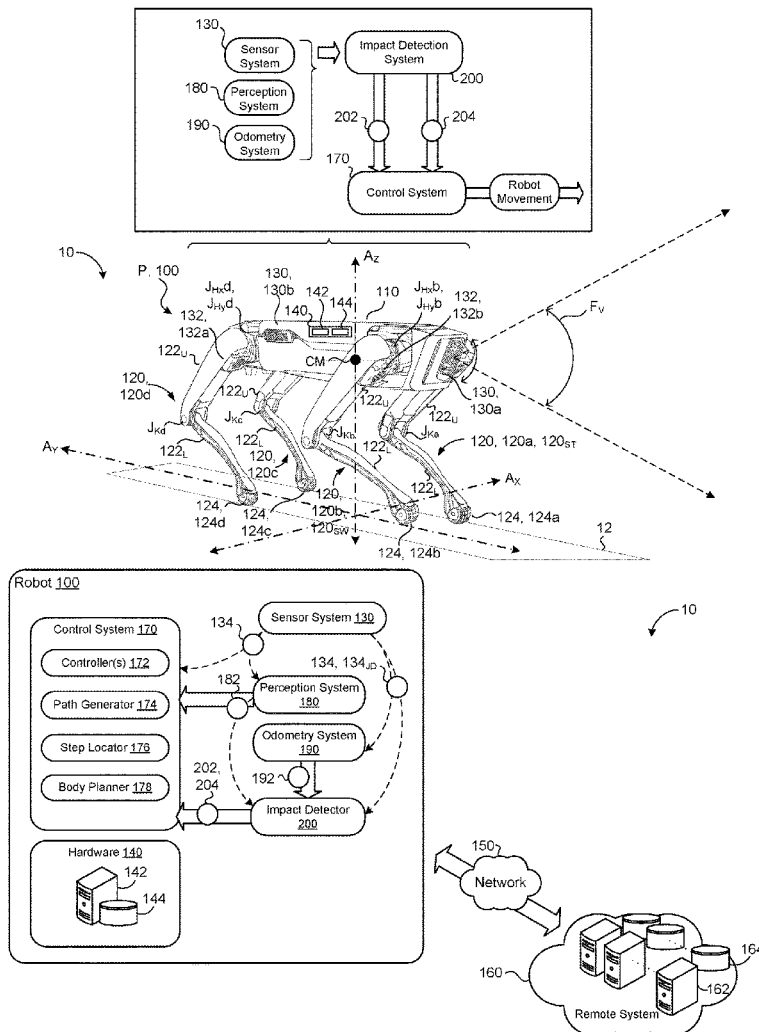(19) **United States**

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(54) **FOOTSTEP CONTACT DETECTION**

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CPC *B25J 9/1633* (2013.01); *B25J 9/162* (2013.01); *B62D 57/032* (2013.01); *B25J 13/085* (2013.01); *B25J 9/1664* (2013.01)

(57) **ABSTRACT**

A method of footstep contact detection includes receiving joint dynamics for a swing leg of the robot where the swing leg performs a swing phase of a gait of the robot. The method also includes receiving odometry defining an estimation of a pose of the robot and determining whether an unexpected torque on the swing leg corresponds to an impact on the swing leg. When the unexpected torque corresponds to the impact, the method further includes determining whether the impact is indicative of a touchdown of the swing leg on a ground surface based on the odometry and the joint dynamics. When the impact is not indicative of the touchdown of the swing leg, the method includes classifying a cause of the impact based on the odometry of the robot and the joint dynamics of the swing leg.
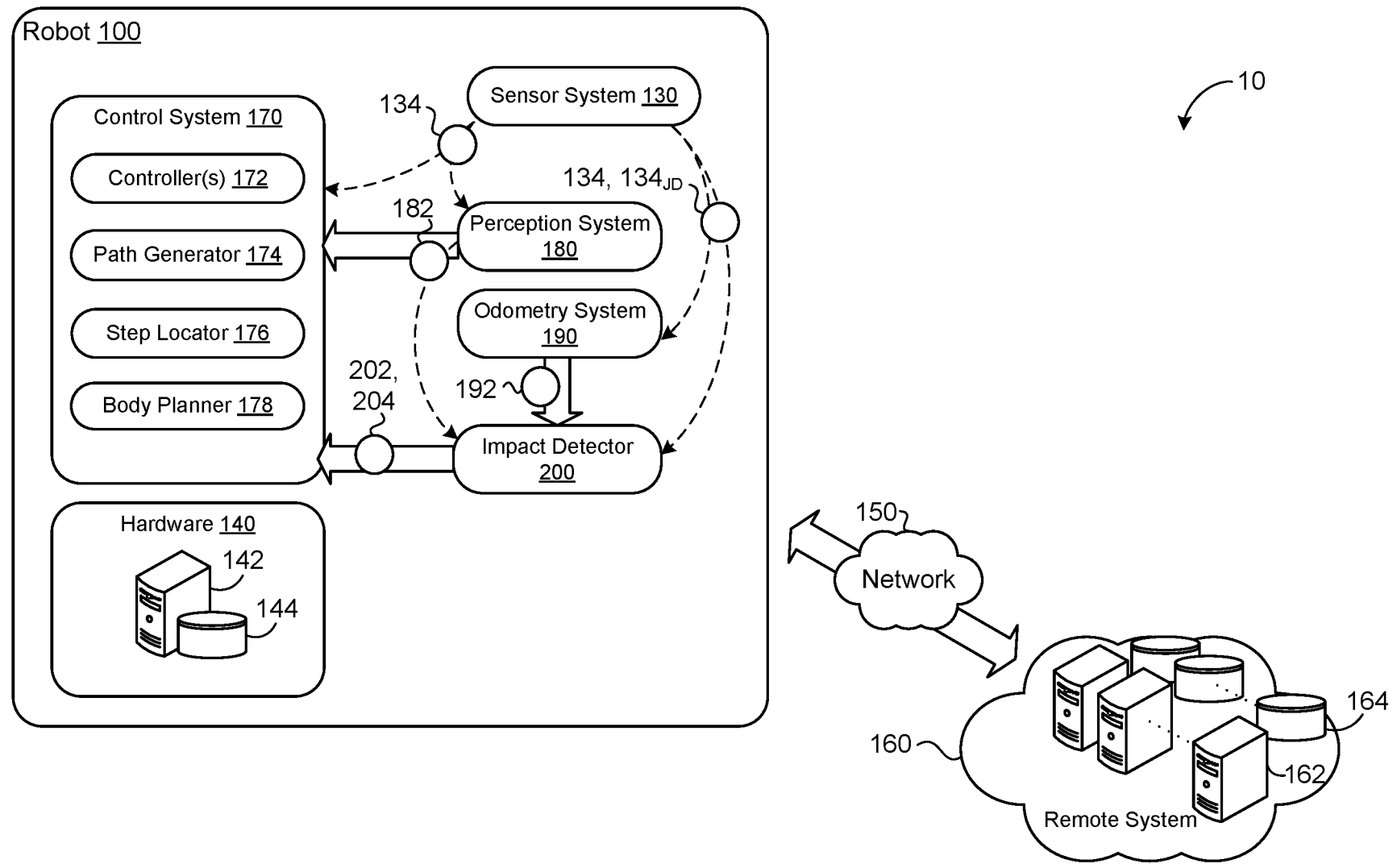
FIG. 1A

FIG. 1B

130

134_{JD},
134_{JD}a-c

180

182

190

192

Impact Detector System 200

Detector 210

$\text{Abs}(\tau_{comp})$

T_{TH}

212

Time

Y

Sum of 212 for all
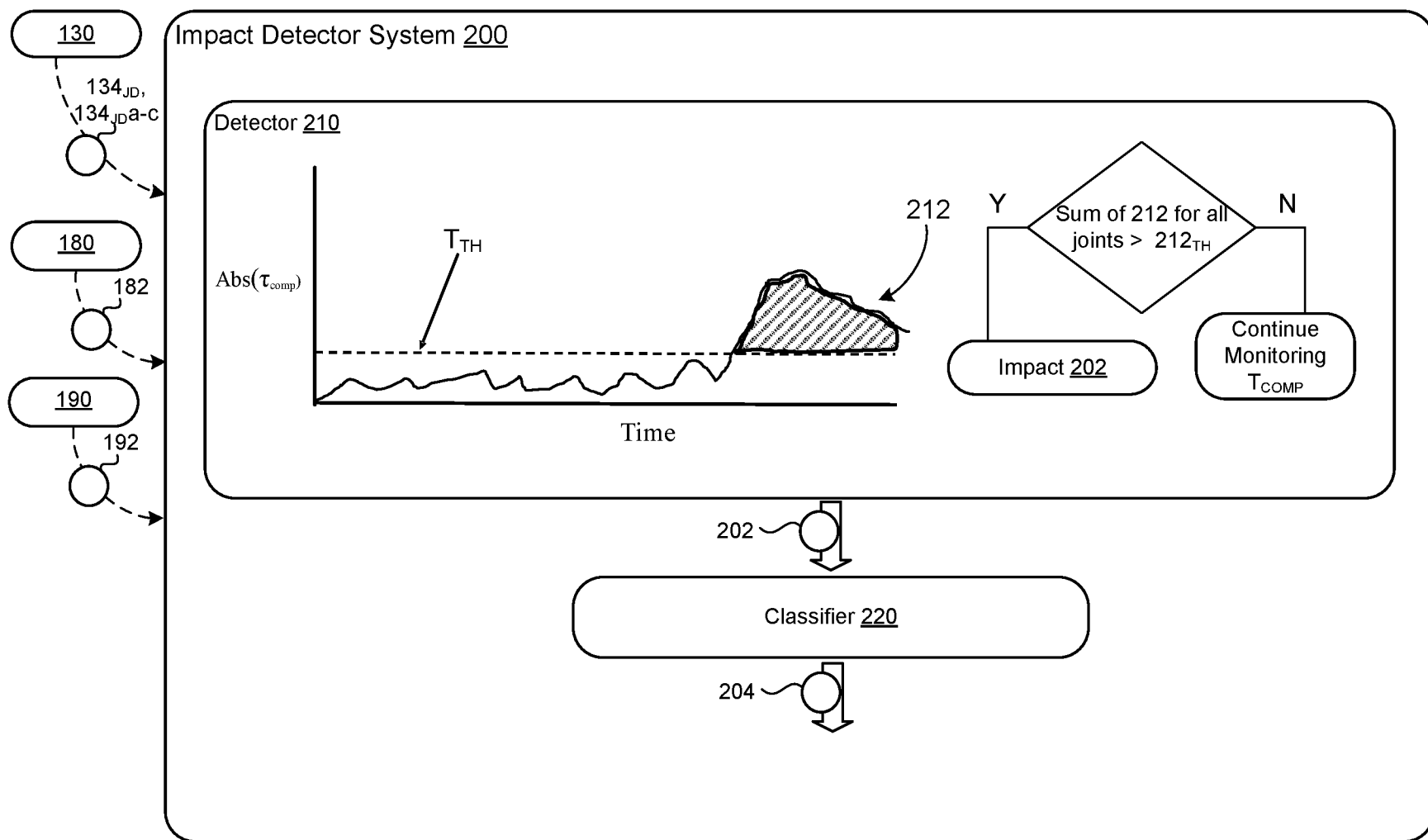joints > 212_{TH}

N

Impact 202

Continue
Monitoring
T_{COMP}

202

Classifier 220

204

FIG. 2A
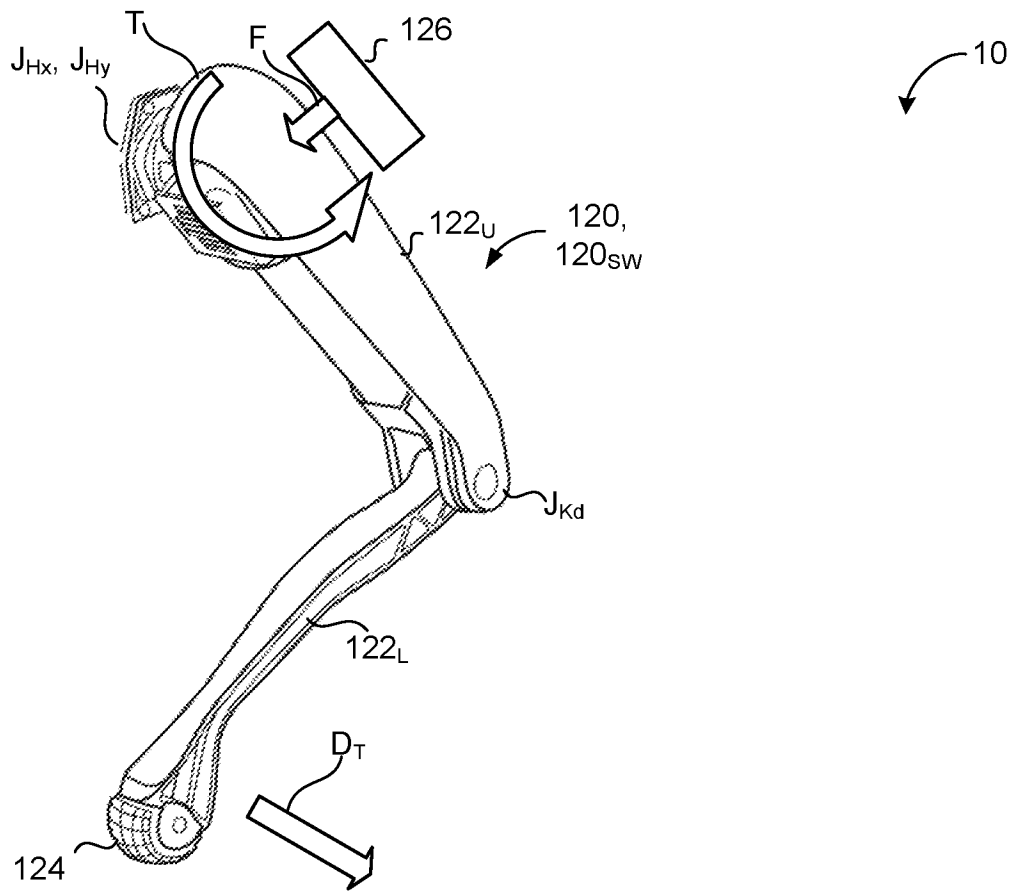
FIG. 2B

FIG. 2C

FIG. 2D

FIG. 2E

FIG. 2F

FIG. 2G

FIG. 2H

P, 100

10

$J_{Hx}a,$
$J_{Hy}a$

$J_{Hx}b,$
$J_{Hy}b$

J_{Ka}

$120_{ST},$
$120_{CL},$
120b

J_{Kb}

124a

$120_{SW},$
120a

124b

FIG. 2I

10

$J_{Hx}a,$
$J_{Hy}a$

P, 100

110

$120_{SW},$
$120a$

J_{Ka}

J_{Kb}

$120_{ST},$
$120b$

124a

124b

FIG. 2J

FIG. 2K

FIG. 2L

300

Receiving Joint Dynamics For A Swing Leg Of The Robot, The Swing Leg Performing A Swing Phase Of A Gait The Robot

302

Receiving Odometry Defining An Estimation Of A Pose Of The Robot Relative To A World Reference Frame

304

Determining Whether A Torque On The Swing Leg Corresponds To An Impact On The Swing Leg

306

When The Torque On The Swing Leg Corresponds To The Impact:

Determining Whether The Impact Is Indicative Of A Touchdown Of The Swing Leg On A Ground Surface About The Robot Based On The Odometry Of The Robot And The Joint Dynamics Of The Swing Leg

308a

When The Impact Is Not Indicative Of The Touchdown Of The Swing Leg, Classifying A Cause Of The Impact Based On The Odometry Of The Robot And The Joint Dynamics Of The Swing Leg

308b

308

FIG. 3

FIG. 4
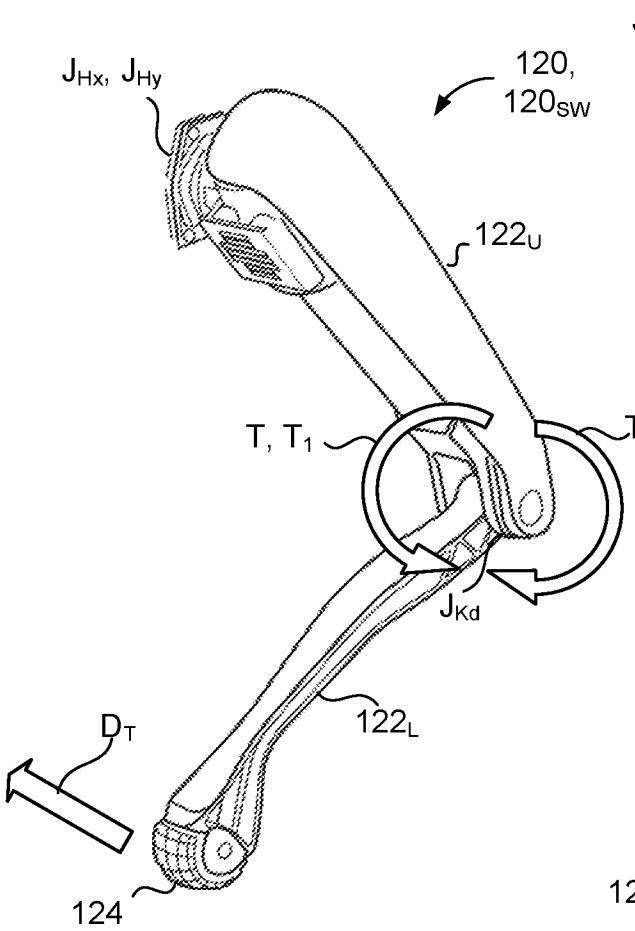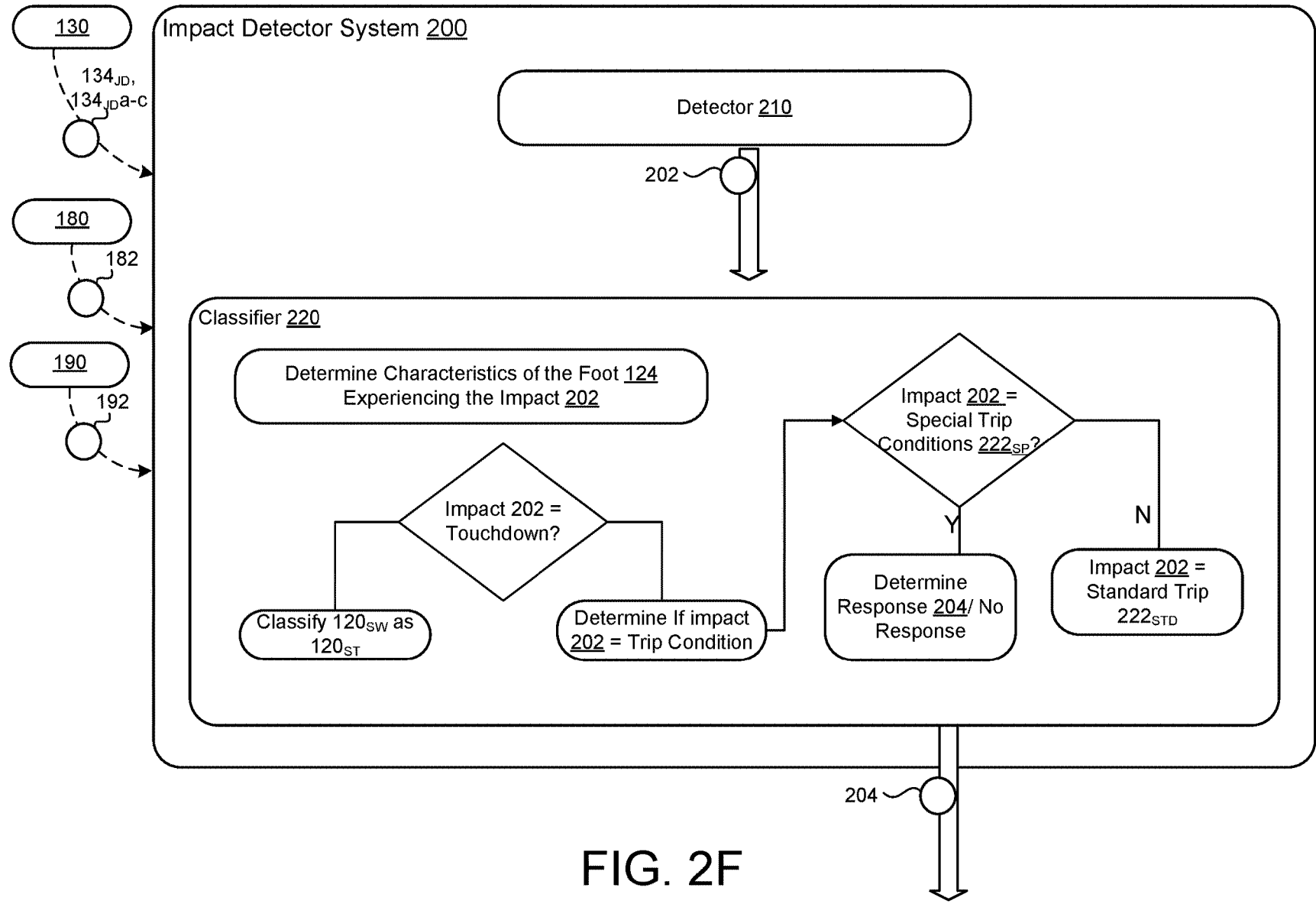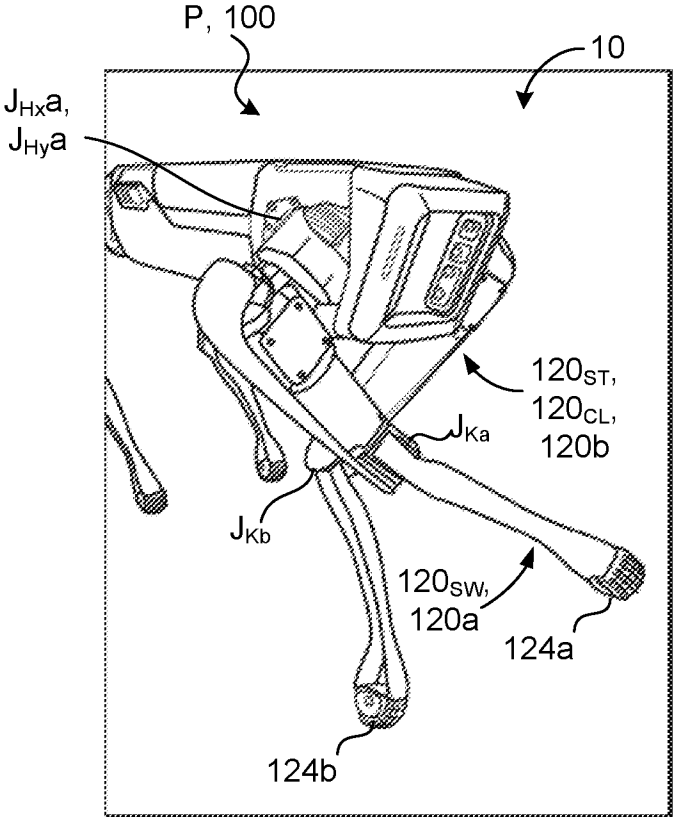
FOOTSTEP CONTACT DETECTION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This U.S. patent application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application 62/883, 636, filed on Aug. 6, 2019. The disclosure of this prior application is considered part of the disclosure of this application and is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] This disclosure relates to footstep contact detection.

BACKGROUND

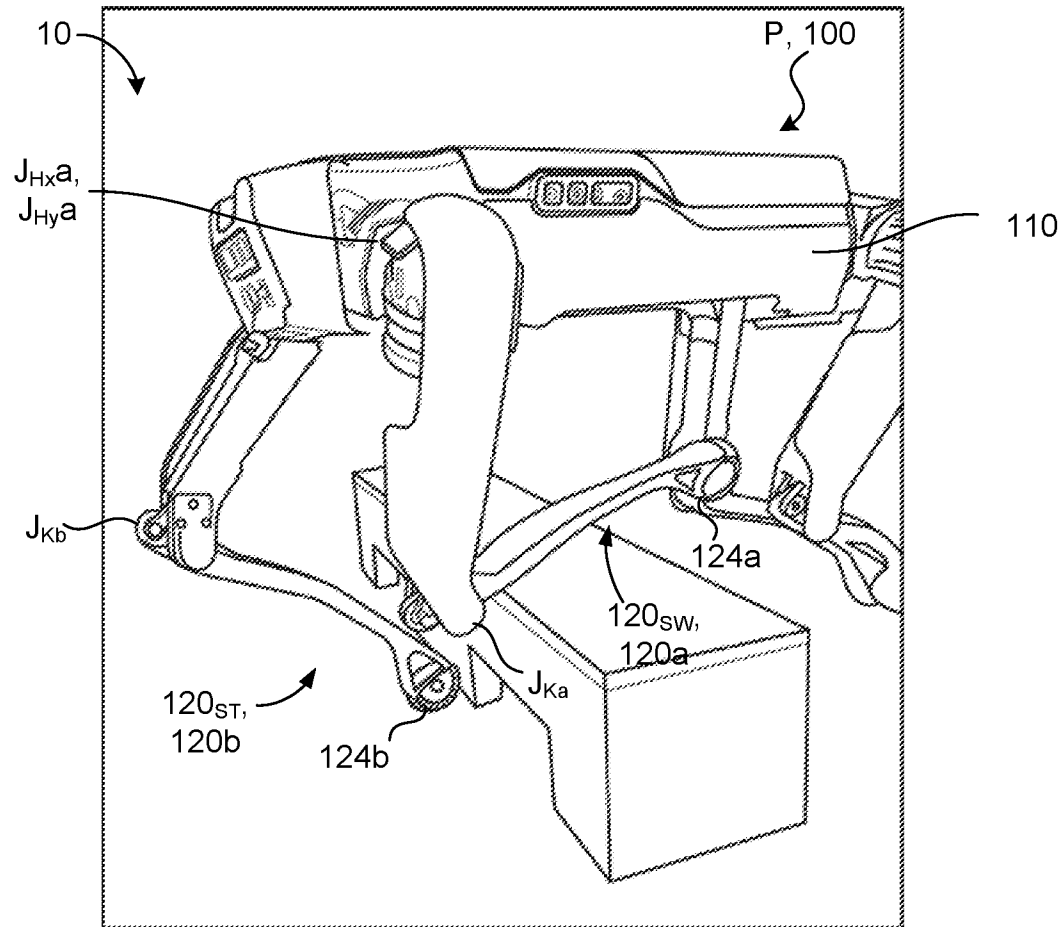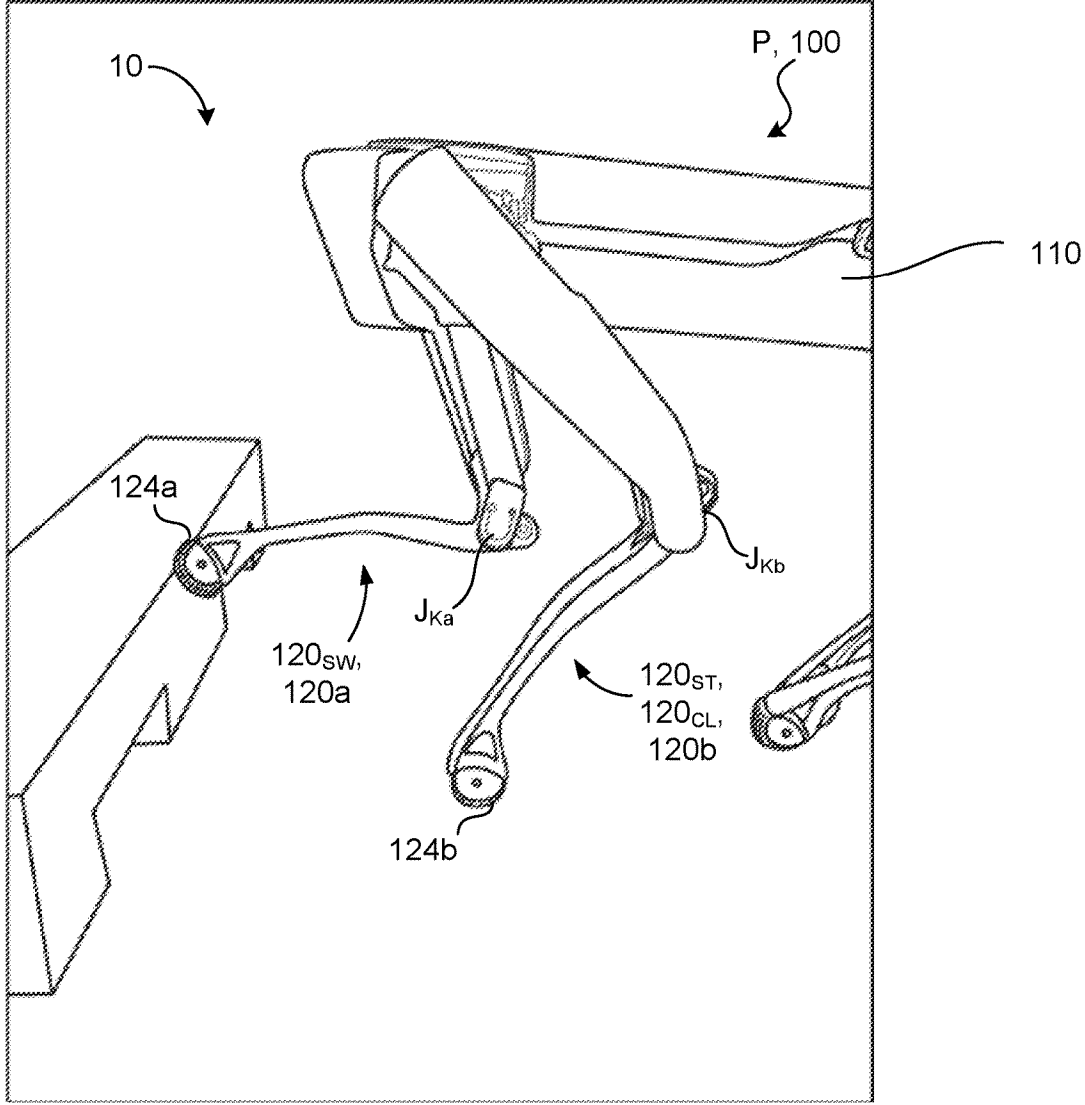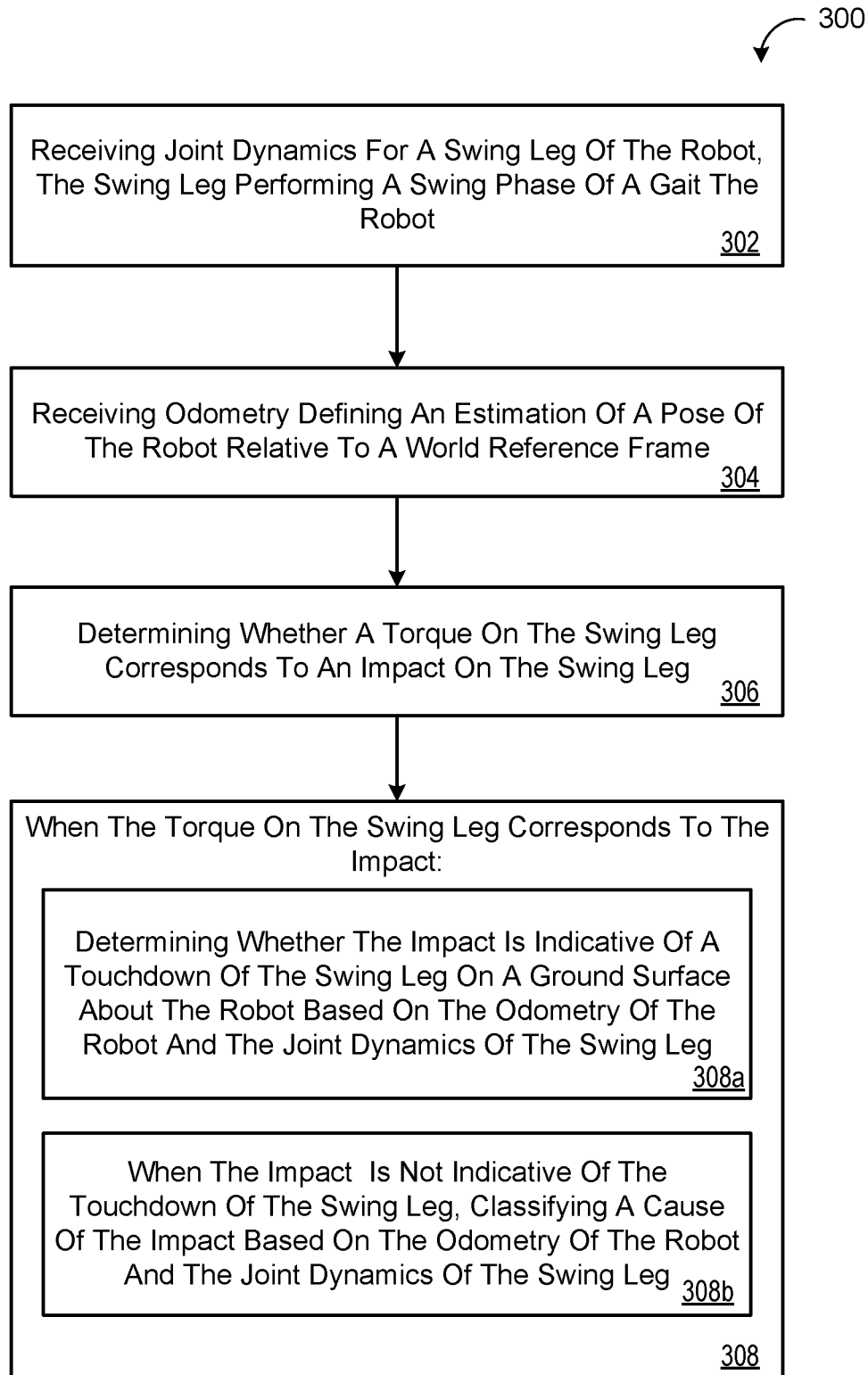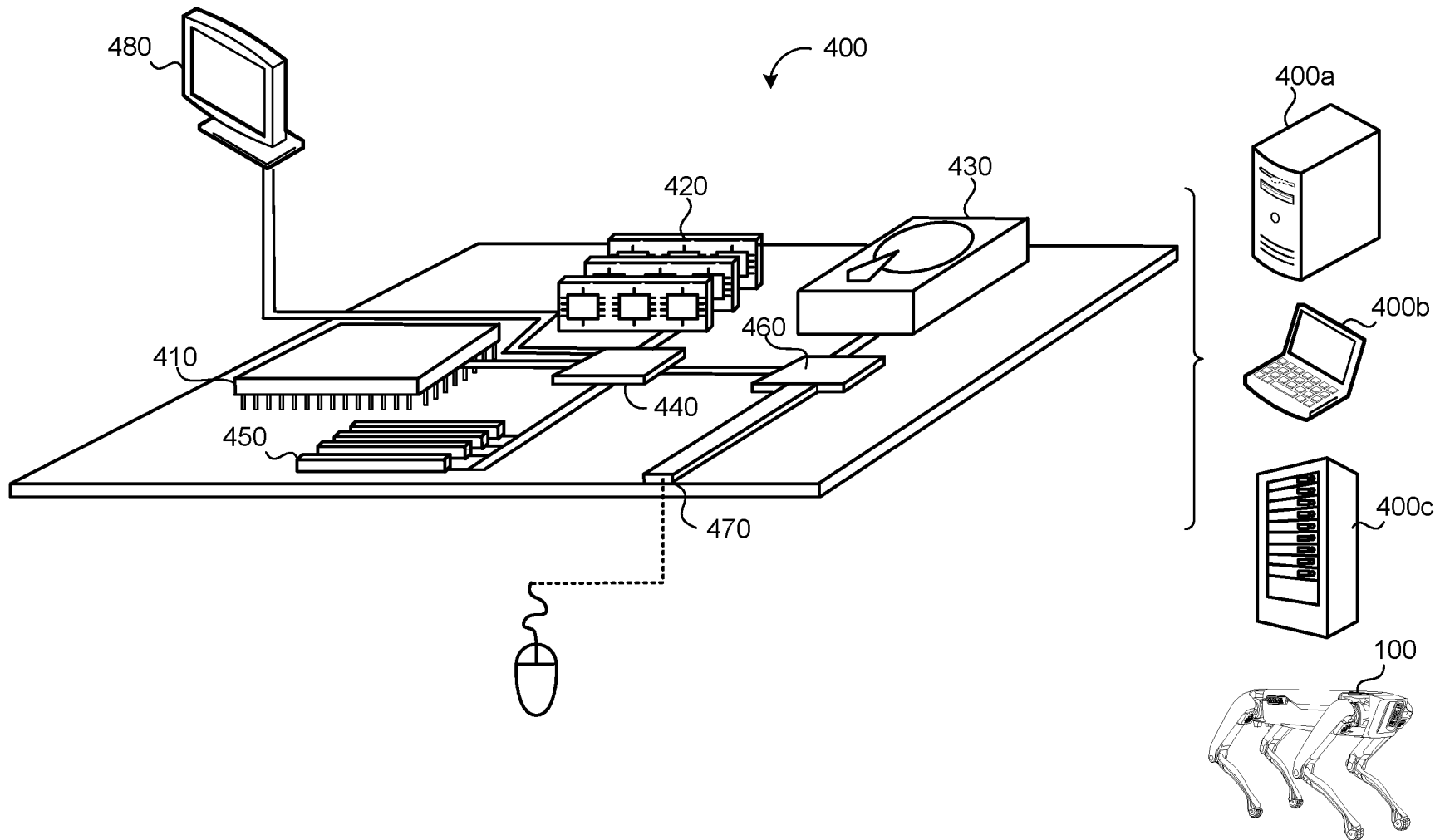[0003] A robot is generally defined as a reprogrammable and multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for a performance of tasks. Robots may be manipulators that are physically anchored (e.g., industrial robotic arms), mobile robots that move throughout an environment (e.g., using legs, wheels, or traction based mechanisms), or some combination of a manipulator and a mobile robot. Robots are utilized in a variety of industries including, for example, manufacturing, transportation, hazardous environments, exploration, and healthcare. As such, the ability of robots to traverse environments with obstacles or features requiring various means of coordinated leg movement provides additional benefits to such industries.

SUMMARY

[0004] One aspect of the disclosure provides a method for footstep contact detection. The method includes receiving, at data processing hardware of a robot, joint dynamics for a swing leg of the robot. The swing leg performs a swing phase of a gait of the robot. The method also includes receiving, at the data processing hardware, odometry defining an estimation of a pose of the robot relative to a world reference frame. The method further includes determining, by the data processing hardware, whether an unexpected torque on the swing leg corresponds to an impact on the swing leg. When the unexpected torque on the swing leg corresponds to the impact, the method includes determining, by the data processing hardware, whether the impact is indicative of a touchdown of the swing leg on a ground surface about the robot based on the odometry of the robot and the joint dynamics of the swing leg. When the impact is not indicative of the touchdown of the swing leg, the method includes classifying, by the data processing hardware, a cause of the impact based on the odometry of the robot and the joint dynamics of the swing leg.

[0005] Implementations of the disclosure may include one or more of the following optional features. In some implementations, the method includes generating, by the data processing hardware, a response for the swing leg of the robot based on the classified cause of the impact. When the impact is indicative of the touchdown of the swing leg, the method may include changing, by the data processing hardware, a classification of the swing leg to a stance leg. The method may include elevating the swing leg as a response to the respective impact when the cause of the impact is classified as a trip.

[0006] In some examples, classifying the cause of the impact includes determining that a percent completion of the swing phase for the swing leg of the robot satisfies a swing phase threshold based on the joint dynamics of the swing leg, the swing phase threshold indicating that the swing leg is early in the swing phase. In this example, classifying the cause of the impact also includes classifying the cause of the impact on the swing leg as a liftoff scuffing. Here, the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the liftoff scuffing.

[0007] In some configurations, classifying the cause of the impact includes determining that a hip joint of the swing leg exceeds a pre-determined motion limit based on the joint dynamics of the swing leg. Here, the joint dynamics include an abduction-adduction component of the hip joint relative to the ground surface and a flexion-extension component of the hip joint relative to the ground surface and the abduction-adduction component includes the pre-determined motion limit as a function of the flexion-extension component. In this configuration, classifying the cause of the impact also includes classifying the cause of the impact on the swing leg as the swing leg contacts a body of the robot. Here, the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the swing leg contacts the body of the robot.

[0008] In some implementations, classifying the cause of the impact includes determining that a vector distance between a first closest point of the swing leg to a contralateral leg and a second closest point of the contralateral leg to the swing leg indicates the swing leg crossed the contralateral leg. Here, classifying the cause of the impact also includes determining that a distal end of the swing leg crossed a respective distal end of the contralateral leg, determining that a first knee joint of the swing leg crossed a second knee joint of the contralateral leg, classifying the condition causing the respective impact for the swing leg of the robot as the swing leg crossed the contralateral leg of the robot, and moving the swing leg to uncross with the contralateral leg of the robot.

[0009] In some examples, classifying the condition for the leg of the robot corresponding to the respective impact includes determining that the swing leg is positioned near a contralateral leg of the robot, determining that the torque corresponding to the respective impact results from joint dynamics predominantly from a lateral component of a hip joint of the swing leg, classifying the condition causing the respective impact for the swing leg of the robot as uncrossed contralateral leg impact, and moving the swing leg away from a sagittal plane of the robot.

[0010] In some configurations, classifying the condition for the leg of the robot corresponding to the respective impact includes determining that a knee of the swing leg is moving backwards during the swing phase, determining that the joint dynamics resulting in the unexpected torque corresponding to the respective impact comprise a flexion-extension torque about a hip joint of the swing leg that is greater than both a knee torque of the swing leg and an adduction-abduction torque about a hip joint of the swing leg, classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain behind a body of the robot, and shifting the knee of the swing leg forward relative to the body of the robot.

[0011] In some implementations, classifying the condition for the leg of the robot corresponding to the respective impact includes determining that a knee of the swing leg is adjacent to a perceived ground surface, the knee moving forward relative to a body of the robot, the perceived ground surface defined by sensor data about the robot. In this implementation, classifying the condition for the leg of the robot corresponding to the respective impact also includes determining that the knee of the swing leg is closer to the perceived ground surface than a distal end of the swing leg, determining that the unexpected torque corresponding to the respective impact occurs at a hip joint of the swing leg, classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain underneath the body of the robot, and continuing movement of the swing leg without response to the knee of the swing leg contacting terrain underneath the body of the robot.

[0012] In some examples, determining whether the unexpected torque on the swing leg of the robot corresponds to the impact on the swing leg includes determining whether the unexpected torque satisfies an impact detection threshold, the impact detection threshold including a magnitude of torque that corresponds to a known impact. In other examples, determining, by the data processing hardware, the unexpected torque on the swing leg is based on a difference between a measured torque measured by joint torque sensors about the robot, a first expected torque representing a respective torque caused by gravity, and a second expected torque representing a corresponding torque to accelerate the swing leg of the robot.

[0013] In some configurations, when a joint of the swing leg of the robot is adjacent to a limit on a range of motion for the joint, the method includes determining, by the data processing hardware, that the unexpected torque fails to indicate the impact on the swing leg during the swing phase. Determining whether the unexpected torque on the swing leg corresponds to the impact on the swing leg may include determining that the unexpected torque on the swing leg corresponds to an impact torque, the impact torque opposing motion of a joint of the swing leg.

[0014] In some implementations, the joint dynamics of the swing leg correspond to joint dynamics of a knee joint of the swing leg and joint dynamics of a hip joint of the swing leg. The joint dynamics of the hip joint may include an abduction-adduction torque abducting or adducting the swing leg and a flexion-extension torque flexing or extending the swing leg.

[0015] Another aspect of the disclosure provides a robot configured to perform footstep contact detection. The robot includes a body and two or more legs coupled to the body and configured to traverse an environment. The two or more legs include a swing leg. The robot also includes a control system in communication with the two or more legs where the control system includes data processing hardware and memory hardware in communication with the data processing hardware. The memory hardware stores instructions that when executed on the data processing hardware cause the data processing hardware to perform operations. The operations include receiving joint dynamics for the swing leg of the robot. The swing leg performs a swing phase of a gait of the robot. The operations also include receiving odometry defining an estimation of a pose of the robot relative to a world reference frame. The operations further include deter-

mining whether an unexpected torque on the swing leg corresponds to an impact on the swing leg. When the unexpected torque on the swing leg corresponds to the impact, the operations include determining whether the impact is indicative of a touchdown of the swing leg on a ground surface about the robot based on the odometry of the robot and the joint dynamics of the swing leg. When the impact is not indicative of the touchdown of the swing leg, the operations include classifying a cause of the impact based on the odometry of the robot and the joint dynamics of the swing leg.

[0016] Implementations of the disclosure may include one or more of the following optional features. In some implementations, the operations include generating a response for the swing leg of the robot based on the classified cause of the impact. When the impact is indicative of the touchdown of the swing leg, the operations may include changing a classification of the swing leg to a stance leg. The operations may include elevating the swing leg as a response to the respective impact when the cause of the impact is classified as a trip.

[0017] In some examples, classifying the cause of the impact includes determining that a percent completion of the swing phase for the swing leg of the robot satisfies a swing phase threshold based on the joint dynamics of the swing leg. Here, the swing phase threshold indicates that the swing leg is early in the swing phase. In this example, classifying the cause of the impact also includes classifying the cause of the impact on the swing leg as a liftoff scuffing. Here, the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the liftoff scuffing.

[0018] In some configurations, classifying the cause of the impact includes determining that a hip joint of the swing leg exceeds a pre-determined motion limit based on the joint dynamics of the swing leg. Here, the joint dynamics include an abduction-adduction component of the hip joint relative to the ground surface and a flexion-extension component of the hip joint relative to the ground surface and the abduction-adduction component includes the pre-determined motion limit as a function of the flexion-extension component. In this configuration, classifying the cause of the impact also includes classifying the cause of the impact on the swing leg as the swing leg contacts a body of the robot. Here, the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the swing leg contacts the body of the robot.

[0019] In some implementations, classifying the cause of the impact includes determining that a vector distance between a first closest point of the swing leg to a contralateral leg and a second closest point of the contralateral leg to the swing leg indicates the swing leg crossed the contralateral leg. Here, classifying the cause of the impact also includes determining that a distal end of the swing leg crossed a respective distal end of the contralateral leg, determining that a first knee joint of the swing leg crossed a second knee joint of the contralateral leg, classifying the condition causing the respective impact for the swing leg of the robot as the swing leg crossed the contralateral leg of the robot, and moving the swing leg to uncross with the contralateral leg of the robot.

[0020] In some examples, classifying the condition for the leg of the robot corresponding to the respective impact includes determining that the swing leg is positioned near a

contralateral leg of the robot, determining that the torque corresponding to the respective impact results from joint dynamics predominantly from a lateral component of a hip joint of the swing leg, classifying the condition causing the respective impact for the swing leg of the robot as uncrossed contralateral leg impact, and moving the swing leg away from a sagittal plane of the robot.

[0021] In some configurations, classifying the condition for the leg of the robot corresponding to the respective impact includes determining that a knee of the swing leg is moving backwards during the swing phase, determining that the joint dynamics resulting in the unexpected torque corresponding to the respective impact comprise a flexion-extension torque about a hip joint of the swing leg that is greater than both a knee torque of the swing leg and an adduction-abduction torque about a hip joint of the swing leg, classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain behind a body of the robot, and shifting the knee of the swing leg forward relative to the body of the robot.

[0022] In some implementations, classifying the condition for the leg of the robot corresponding to the respective impact includes determining that a knee of the swing leg is adjacent to a perceived ground surface, the knee moving forward relative to a body of the robot, the perceived ground surface defined by sensor data about the robot. In this implementation, classifying the condition for the leg of the robot corresponding to the respective impact also includes determining that the knee of the swing leg is closer to the perceived ground surface than a distal end of the swing leg, determining that the unexpected torque corresponding to the respective impact occurs at a hip joint of the swing leg, classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain underneath the body of the robot, and continuing movement of the swing leg without response to the knee of the swing leg contacting terrain underneath the body of the robot.

[0023] In some examples, determining whether the unexpected torque on the swing leg of the robot corresponds to the impact on the swing leg includes determining whether the unexpected torque satisfies an impact detection threshold where the impact detection threshold includes a magnitude of torque that corresponds to a known impact. In other examples, determining the unexpected torque on the swing leg is based on a difference between a measured torque measured by joint torque sensors about the robot, a first expected torque representing a respective torque caused by gravity, and a second expected torque representing a corresponding torque to accelerate the swing leg of the robot.

[0024] In some configurations, when a joint of the swing leg of the robot is adjacent to a limit on a range of motion for the joint, the operations include determining that the unexpected torque fails to indicate the impact on the swing leg during the swing phase. Determining whether the unexpected torque on the swing leg corresponds to the impact on the swing leg may include determining that the unexpected torque on the swing leg corresponds to an impact torque, the impact torque opposing motion of a joint of the swing leg.

[0025] In some implementations, the joint dynamics of the swing leg correspond to joint dynamics of a knee joint of the swing leg and joint dynamics of a hip joint of the swing leg. The joint dynamics of the hip joint may include an abduc-tion-adduction torque abducting or adducting the swing leg and a flexion-extension torque flexing or extending the swing leg.

[0026] The details of one or more implementations of the disclosure are set forth in the accompanying drawings and the description below. Other aspects, features, and advantages will be apparent from the description and drawings, and from the claims.

DESCRIPTION OF DRAWINGS

[0027] FIG. 1A is a schematic view of an example robot within an environment.

[0028] FIG. 1B is a schematic view of example systems for the robot of FIG. 1A.

[0029] FIG. 2A is a schematic view of an example impact detection system for the robot of FIG. 1A.

[0030] FIG. 2B-2E are schematic views of example swing legs during impact detection by the impact detection system for the robot of FIG. 1A.

[0031] FIGS. 2G-2L are perspective views of example impact conditions experienced by the robot of FIG. 1A.

[0032] FIG. 2F is a schematic view of an example impact detection system for the robot of FIG. 1A.

[0033] FIG. 3 is example arrangement of operations for a robot to detect impacts in environment about the robot.

[0034] FIG. 4 is a schematic view of an example computing device that may be used to implement the systems and methods described herein.

[0035] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0036] As a robot maneuvers about an environment, various system of the robot communicate with the robot to indicate where to step (e.g., foot placement for a leg), how to move legs of the robot (e.g., swing trajectories), how to avoid obstacles, how to maintain balance, etc. One of the more critical aspects of robot movement is understanding the robot's relationship with its environment. For instance, one aspect is understanding how a structure of the robot interacts with itself or objects in the environment (e.g., a traction surface of the environment). During movement, these interactions depend not only on the environment, but also on characteristics of the robot (e.g., speed, gait, location, etc.). To understand these relationships for the robot, the robot uses various techniques for impact detection and/or impact reaction.

[0037] With a legged-robot, it may be important to accurately detect when a leg of the robot has contacted a traction surface (e.g., a ground surface). For instance, when a leg of the robot contacts the ground surface (i.e., touches down), but the robot does not detect the leg's touchdown, the robot will continue moving this leg downward, essentially attempting to push the leg through a ground surface. Here, when continuing to move the leg downward, the robot experiences a normal force from the ground surface acting on the leg. Problematically, this normal force may disrupt the balance of the robot and, in some situations, cause the robot to turn over (e.g., flip over). When the robot detects touchdown late, it affects lateral stability for the robot because the robot experiences a larger than expected impact. In other words, the robot does not anticipate ground impact

when it actually occurs. Therefore, the robot may not account for, or properly counterbalance, such an impact.

[0038] Besides accurately detecting touchdown, the robot also employs impact detection to detect trips. A trip generally refers to a disruption in a gait of the robot. In other words, the robot may have a planned movement trajectory (e.g., based on a gait controller), but trip due to contact with some object, element of the environment, or itself. For both trips and traction surface contact (e.g., touchdown of a leg), it may be advantageous to not only detect such conditions, but also to minimize a time it takes to detect and/or to respond to such a condition. Often with trips, the more quickly a robot detects a trip, the less force (or rotation) the robot will experience from the trip. Additionally, there may be a proportional relationship between how fast a trip is detected and a likelihood that a robot will overcome the trip condition (e.g., stabilize or continue with motion). In other words, quickly detecting a trip may allow systems of the robot to quickly react and/or respond to a trip. Therefore, trip detection aims to minimize disruptions to the robot during movement about the environment.

[0039] Referring to FIG. 1A, the robot 100 includes a body 110 with locomotion based structures such as legs 120a-d coupled to the body 110 that enable the robot 100 to move about the environment 10. In some examples, each leg 120 is an articulable structure such that one or more joints J permit members 122 of the leg 120 to move. For instance, each leg 120 includes a hip joint J_H coupling an upper member 122, 122_U of the leg 120 to the body 110 and a knee joint J_K coupling the upper member 122_U of the leg 120 to a lower member 122_L of the leg 120. For impact detection, the hip joint J_H may be further broken down into abduction-adduction rotation of the hip joint J_H designated as "J_{Hx}" for occurring in a frontal plane of the robot 100 (i.e., a X-Z plane extending in directions of a x-direction axis A_x and the z-direction axis A_Z) and a flexsion-extension rotation of the hip joint J_H designated as "J_{Hy}," for occurring in a sagittal plane of the robot 100 (i.e., a Y-Z plane extending in directions of a y-direction axis A_Y and the z-direction axis A_Z). Although FIG. 1A depicts a quadruped robot with four legs 120a-d, the robot 100 may include any number of legs or locomotive based structures (e.g., a biped or humanoid robot with two legs) that provide a means to traverse the terrain within the environment 10.

[0040] In order to traverse the terrain, each leg 120 has a distal end 124 that contacts a surface of the terrain (i.e., a traction surface). In other words, the distal end 124 of the leg 120 is the end of the leg 120 used by the robot 100 to pivot, plant, or generally provide traction during movement of the robot 100. For example, the distal end 124 of a leg 120 corresponds to a foot of the robot 100. In some examples, though not shown, the distal end 124 of the leg 120 includes an ankle joint J_A such that the distal end 124 is articulable with respect to the lower member 122_L of the leg 120.

[0041] The robot 100 has a vertical gravitational axis (e.g., shown as a Z-direction axis A_Z) along a direction of gravity, and a center of mass CM, which is a point where the weighted relative position of the distributed mass of the robot 100 sums to zero. The robot 100 further has a pose P based on the CM relative to the vertical gravitational axis A_Z (i.e., the fixed reference frame with respect to gravity) to define a particular attitude or stance assumed by the robot 100. The attitude of the robot 100 can be defined by an orientation or an angular position of the robot 100 in space.

Movement by the legs 120 relative to the body 110 alters the pose P of the robot 100 (i.e., the combination of the position of the CM of the robot and the attitude or orientation of the robot 100). Here, a height generally refers to a distance along the z-direction. The sagittal plane of the robot 100 corresponds to the Y-Z plane extending in directions of a y-direction axis A_Y and the z-direction axis A_Z. In other words, the sagittal plane bisects the robot 100 into a left and right side. Generally perpendicular to the sagittal plane, a ground plane (also referred to as a transverse plane) spans the X-Y plane by extending in directions of the x-direction axis A_X and the y-direction axis A_Y. The ground plane refers to a ground surface 12 where distal ends 124 of the legs 120 of the robot 100 may generate traction to help the robot 100 move about the environment 10. Another anatomical plane of the robot 100 is the frontal plane that extends across the body 110 of the robot 100 (e.g., from a left side of the robot 100 with a first leg 120a to a right side of the robot 100 with a second leg 120b). The frontal plane spans the X-Z plane by extending in directions of the x-direction axis A_X and the z-direction axis A_Z.

[0042] When a legged-robot moves about the environment 10, the legs 120 of the robot undergo a gait cycle. Generally, a gait cycle begins when a leg 120 touches down or contacts a ground surface 12 and ends when that same leg 120 once again contacts the ground surface 12. The gait cycle may predominantly be divided into two phases, a swing phase and a stance phase. During the swing phase, a leg 120 performs (i) lift-off from the ground surface 12 (also sometimes referred to as toe-off and the transition between the stance phase and swing phase), (ii) flexion at a knee joint J_K of the leg 120, (iii) extension of the knee joint J_K of the leg 120, and (iv) touchdown back to the ground surface 12. Here, a leg 120 in the swing phase is referred to as a swing leg 120_{SW}. As the swing leg 120_{SW} proceeds through the movement of the swing phase 120_{SW}, another leg 120 performs the stance phase. The stance phase refers to a period of time where a distal end 124 (e.g., a foot) of the leg 120 is on the ground surface 12. During the stance phase a leg 120 performs (i) initial ground surface contact which triggers a transition from the swing phase to the stance phase, (ii) loading response where the leg 120 dampens ground surface contact, (iii) mid-stance support for when the contralateral leg (i.e., the swing leg 120_{SW}) lifts-off and swings to a balanced position (about halfway through the swing phase), and (iv) terminal-stance support from when the robot's COM is over the leg 120 until the contralateral leg 120 touches down to the ground surface 12. Here, a leg 120 in the stance phase is referred to as a stance leg 120_{ST}.

[0043] In order to maneuver about the environment 10, the robot 100 includes a sensor system 130 with one or more sensors 132, 132a-n (e.g., shown as a first sensor 132, 132a and a second sensor 132, 132b). The sensors 132 may include vision/image sensors, inertial sensors (e.g., an inertial measurement unit (IMU)), force sensors, and/or kinematic sensors. Some examples of sensors 132 include a camera such as a stereo camera, a scanning light-detection and ranging (LIDAR) sensor, or a scanning laser-detection and ranging (LADAR) sensor. In some examples, the sensor 132 has a corresponding field(s) of view F_V defining a sensing range or region corresponding to the sensor 132. For instance, FIG. 1A depicts a field of a view F_V for the robot 100. Each sensor 132 may be pivotable and/or rotatable such that the sensor 132 may, for example, change the field of

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view F_V about one or more axis (e.g., an x-axis, a y-axis, or a z-axis in relation to a ground plane).

[0044] In some implementations, the sensor system **130** includes sensor(s) **132** coupled to a joint J. In some examples, these sensors **132** couple to a motor that operates a joint J of the robot **100** (e.g., sensors **132**, **132***a-b*). Here, these sensors **132** generate joint dynamics **134**, **134**$_{JD}$ in the form of joint-based sensor data **134**. Joint dynamics **134**$_{JD}$ collected as joint-based sensor data **134** may include joint angles (e.g., an upper member **122**$_U$ relative to a lower member **122**$_L$), joint speed (e.g., joint angular velocity or joint angular acceleration), and/or joint torques experienced at a joint J (also referred to as joint forces). Here, joint-based sensor data **134** generated by one or more sensors **132** may be raw sensor data, data that is further processed to form different types of joint dynamics **134**$_{JD}$, or some combination of both. For instance, a sensor **132** measures joint position (or a position of member(s) **122** coupled at a joint J) and systems of the robot **100** perform further processing to derive velocity and/or acceleration from the positional data. In other examples, a sensor **132** is configured to measure velocity and/or acceleration directly.

[0045] When surveying a field of view F_V with a sensor **132**, the sensor system **130** generates sensor data **134** (also referred to as image data) corresponding to the field of view F_V. In some examples, the sensor data **134** is image data that corresponds to a three-dimensional volumetric point cloud generated by a three-dimensional volumetric image sensor **132**. Additionally or alternatively, when the robot **100** is maneuvering about the environment **10**, the sensor system **130** gathers pose data for the robot **100** that includes inertial measurement data (e.g., measured by an IMU). In some examples, the pose data includes kinematic data and/or orientation data about the robot **100**, for instance, kinematic data and/or orientation data about joints J or other portions of a leg **120** of the robot **100**. With the sensor data **134**, a perception system **200** of the robot **100** may generate maps **182** for the terrain about the environment **10**.

[0046] While the robot **100** maneuvers about the environment **10**, the sensor system **130** gathers sensor data **134** relating to the terrain of the environment **10** and/or structure of the robot **100** (e.g., joint dynamics and/or odometry of the robot **100**). For instance, FIG. 1A depicts the sensor system **130** gathering sensor data **134** about a room as the environment **10** of the robot **100**. As the sensor system **130** gathers sensor data **134**, a computing system **140** is configured to store, to process, and/or to communicate the sensor data **134** to various systems of the robot **100** (e.g., the control system **170**, the perception system **180**, the odometry system **190**, and/or the impact detector **200**). In order to perform computing tasks related to the sensor data **134**, the computing system **140** of the robot **100** includes data processing hardware **142** and memory hardware **144**. The data processing hardware **142** is configured to execute instructions stored in the memory hardware **144** to perform computing tasks related to activities (e.g., movement and/or movement based activities) for the robot **100**. Generally speaking, the computing system **140** refers to one or more locations of data processing hardware **142** and/or memory hardware **144**.

[0047] In some examples, the computing system **140** is a local system located on the robot **100**. When located on the robot **100**, the computing system **140** may be centralized (i.e., in a single location/area on the robot **100**, for example, the body **110** of the robot **100**), decentralized (i.e., located at various locations about the robot **100**), or a hybrid combination of both (e.g., where a majority of centralized hardware and a minority of decentralized hardware). To illustrate some differences, a decentralized computing system **140** may allow processing to occur at an activity location (e.g., at motor that moves a joint of a leg **120**) while a centralized computing system **140** may allow for a central processing hub that communicates to systems located at various positions on the robot **100** (e.g., communicate to the motor that moves the joint of the leg **120**).

[0048] Additionally or alternatively, the computing system **140** includes computing resources that are located remotely from the robot **100**. For instance, the computing system **140** communicates via a network **150** with a remote system **160** (e.g., a remote server or a cloud-based environment). Much like the computing system **140**, the remote system **160** includes remote computing resources such as remote data processing hardware **162** and remote memory hardware **164**. Here, sensor data **134** or other processed data (e.g., data processing locally by the computing system **140**) may be stored in the remote system **160** and may be accessible to the computing system **140**. In some examples, the computing system **140** is configured to utilize the remote resources **162**, **164** as extensions of the computing resources **142**, **144** such that resources of the computing system **140** may reside on resources of the remote system **160**.

[0049] In some implementations, as shown in FIGS. 1A and 1B, the robot **100** includes a control system **170** and a perception system **180**. The perception system **180** is configured to receive the sensor data **134** from the sensor system **130** and to process the sensor data **134** into maps **182**. With the maps **182** generated by the perception system **180**, the perception system **180** may communicate the maps **182** to the control system **170** in order perform controlled actions for the robot **100**, such as moving the robot **100** about the environment **10**. In some examples, by having the perception system **180** separate from, yet in communication with the control system **170**, processing for the control system **170** may focus on controlling the robot **100** while the processing for the perception system **180** focuses on interpreting the sensor data **134** gathered by the sensor system **130**. For instance, these systems **170**, **180** execute their processing in parallel to ensure accurate, fluid movement of the robot **100** in an environment **10**.

[0050] In some examples, the control system **170** includes at least one controller **172**, a path generator **174**, a step locator **176**, and a body planner **178**. The control system **170** may be configured to communicate with at least one sensor system **130** and any other system of the robot **100** (e.g., the perception system **180**, the odometry system **190**, and/or the impact detector **200**). The control system **170** performs operations and other functions using hardware **140**. The controller **172** is configured to control movement of the robot **100** to traverse about the environment **10** based on input or feedback from the systems of the robot **100** (e.g., the control system **170**, the perception system **180**, the odometry system **190**, and/or the impact detector **200**). This may include movement between poses and/or behaviors of the robot **100**. For example, the controller **172** controls different footstep patterns, leg patterns, body movement patterns, or vision system sensing patterns.

[0051] In some examples, the controller **172** includes a plurality of controllers **172** where each of the controllers **172** has a fixed cadence. A fixed cadence refers to a fixed timing

for a step or swing phase of a leg **120**. For example, the controller **172** instructs the robot **100** to move the legs **120** (e.g., take a step) at a particular frequency (e.g., step every 250 milliseconds, 350 milliseconds, etc.). With a plurality of controllers **172** where each controller **172** has a fixed cadence, the robot **100** can experience variable timing by switching between controllers **172**. In some implementations, the robot **100** continuously switches/selects fixed cadence controllers **172** (e.g., re-selects a controller **170** every 3 milliseconds) as the robot **100** traverses the environment **10**.

[0052] Referring to FIG. 1B, the path generator **174** is configured to determine horizontal motion for the robot **100**. For instance, the horizontal motion refers to translation (i.e., movement in the X-Y plane) and/or yaw (i.e., rotation about the Z-direction axis A_Z) of the robot **100**. The path generator **174** determines obstacles within the environment **10** about the robot **100** based on the sensor data **134**. The path generator **174** communicates the obstacles to the step locator **176** such that the step locator **176** may identify foot placements for legs **120** of the robot **100** (e.g., locations to place the distal ends **124** of the legs **120** of the robot **100**). The step locator **176** generates the foot placements (i.e., locations where the robot **100** should step) using inputs from the perceptions system **180** (e.g., map(s) **182**). The body planner **178**, much like the step locator **176**, receives inputs from the perceptions system **180** (e.g., map(s) **182**). Generally speaking, the body planner **178** is configured to adjust dynamics of the body **110** of the robot **100** (e.g., rotation, such as pitch or yaw and/or height of COM) to successfully move about the environment **10**.

[0053] The perception system **180** is a system of the robot **100** that helps the robot **100** to move more precisely in a terrain with various obstacles. As the sensors **132** collect sensor data **134** for the space about the robot **100** (i.e., the robot's environment **10**), the perception system **180** uses the sensor data **134** to form one or more maps **182** for the environment **10**. Once the perception system **180** generates a map **182**, the perception system **180** is also configured to add information to the map **182** (e.g., by projecting sensor data **134** on a preexisting map) and/or to remove information from the map **182**.

[0054] Referring further to FIG. 1B, the odometry system **190** is configured to measure where the robot **100** is located within a world reference frame (e.g., the environment **10**) and how fast the robot **100** is moving in that world reference frame. In other words, the odometry system **190** generates odometry information **192** as one or more estimations (e.g., measurements) for a characteristic of the robot **100** relative to a world reference frame. In some examples, the odometry system **190** receives sensor data **134** from a sensor **132** such as an IMU (e.g., accelerometer(s) and/or gyro(s)). With the sensor data **134**, the odometry system **190** may generate odometry information **192** based on an assumption that when a distal end **124** of a leg **120** is in contact with the ground surface **12** and not slipping, the distal end **124** is stationary. By combining this assumption with the sensor data **134**, the odometry system **190** generates odometry information **192** regarding robot motion relative to the world reference frame (e.g., the environment **10**). In other words, the odometry system **190** accounts for kinematics and inertial measurements to produce estimations about the robot **100** with respect to the world reference frame.

[0055] The impact detection system **200** of the robot **100** is configured to receive inputs from other systems of the robot **100** (e.g., the sensor system **130**, the computing system **140**, the remote system **160**, the control system **170**, the perception system **180**, and/or the odometry system **190**). By capitalizing on information from the other systems of the robot **100**, the impact detection system **200** attempts to make an informed decision to identify an impact **202**, classify the impact **202**, and, in some instances, generate a response **204** to the impact **202** (e.g., invoke a trip response). In some examples, the impact detection system **200** receives joint dynamics 134_{JD} as inputs. For example, the impact detection system **200** receives joint forces 134_{JD}, $134_{JD}a$ to enable the impact detection system **200** to detect when a distal end **124** (also referred to as a foot **124** of the robot **100**) contacts the ground surface **12**. In some examples, the impact detection system **200** receives joint angles 134_{JD}, $134_{JD}b$ to detect when the distal end **124** stops moving and/or a location of the distal end **124** relative to the ground surface **12** (e.g., as perceived by the robot **100**). In some implementations, the impact detection system **200** receives angular velocities 134_{JD}, $134_{JD}c$ to detect a velocity of the distal end **124** (e.g., to detect whether the foot has stopped moving relative to the ground). Although FIG. 2A depicts the impact detection system **200** receiving each of the joint forces, joint angles, and angular velocities $134_{JD}a$-c, some types of detection by the impact detection system **200** may use more or less inputs.

[0056] In some configurations, in addition to the joint dynamics 134_{JD}, the impact detection system **200** receives odometry **192** of the robot **100**. The odometry enables the impact detection system **200** to determine estimations for dynamics of the structure of the robot **100** by accounting for both kinematics of a world reference frame (e.g., the robot **100** with respect to the environment **10**) and kinematics of a relative reference frame (e.g., the body **110** or legs **120** of the robot **100** with respect to the robot **100** itself). For example, a velocity of a foot **124** of the robot **100** is equal to a velocity of the body **110** in the world reference frame (e.g., as determined by the odometry system **190**) plus a velocity of the foot **124** relative to the body **110** (e.g., as sensed by the sensor system **130**).

[0057] Additionally or alternatively, the impact detection system **200** receives a map **182** from the perception system **180** (e.g., in addition to joint dynamics 134_{JD} and/or odometry **192**). In some examples, the impact detection system **200** accounts for failures of the perception system **180** to understand trip conditions or traction surface contact. Yet in some implementations, maps **182** of the perception system **180** allow the impact detection system **200** to classify a type of trip. For example, it is more likely that the foot **124** touched down against the ground surface when a map **182** perceived the ground surface as near to the foot **124** than if the map **182** did not perceive the foot **124** in the vicinity of the ground surface **12**.

[0058] Referring to FIG. 2A, the impact detection system **200** includes a detector **210**. The detector **210** is configured to identify unexpected force(s) F (or torques T) on one or more legs **120** (e.g., feet) of the robot **100**. When the impact detection system **200** identifies an unexpected force F (or torque T), the impact detection system **200** determines whether the unexpected force F corresponds to an impact **202**. During movement, a swing leg 120_{SW} typically generates a minimal amount of torque T. This minimal amount of

torque T is generally predictable by inverse dynamics. In other words, based on inverse dynamics and gravity, there is an expected amount of torque T that acts on the swing leg 120_{SW}. This expected amount of torque T is equal to a torque contributed by gravity (i.e., gravitational torque T_g) in combination with a torque T that is expected in order to accelerate the leg **120** to achieve gait motion (i.e., torque from inverse dynamics T_{ID}). Because a majority of the torque T experienced by a swing leg 120_{SW} is known, the detector **210** is configured to determine an unexpected torque T (also referred to as a compensated torque T_{comp}). For example, Equation (1) below illustrates an equation that the detector **210** uses to determine the compensated torque T_{com}.

$$T_{comp} = T_{measured} - T_g - T_{ID} \tag{1}$$

Here, $T_{measured}$ is the torque measured from joint sensor(s) **132**. In other words, the detector **210** is configured to receive and/or to determine a measured amount of torque $T_{measured}$ acting on the swing leg 120_{SW} based on sensor data **134** (e.g., from sensors **132** at joints J of the robot **100**) from the sensor system **130**. With the measured amount of torque $T_{measured}$ and the expected torques T (i.e., the gravitational torque T_g and the torque from inverse dynamics T_{ID}), the detector **210** determines the compensated torque T_{comp}. Based on the compensated torque T_{comp}, the detector **210** is configured to identify when the swing leg 120_{SW} experiences an impact **202**.

[0059] In some implementations, the detector **210** determines whether the torque T on the swing leg 120_{SW} corresponds to an impact **202** on the swing leg 120_{SW} by determining whether the compensated torque T_{comp} satisfies an impact torque threshold T_{th} (e.g., the detector **210** determines that the compensated torque T_{comp} exceeds a value set as the impact torque threshold T_{th}). Here, the impact torque threshold T_{TH} is configured to represent how much noise the impact detection system **200** expects during impact detection. In other words, the detector **210** may be configured with an impact torque threshold T_{TH} to ensure that the detector **210** generally does not falsely detect an impact **202** based on sensor noise. When the compensated torque T_{comp} satisfies the impact torque threshold T_{th}, the detector **210** communicates that an impact **202** (or a potential impact **202**) has occurred on the swing leg 120_{SW}. Conversely, when the compensated torque T_{comp} fails to satisfy the impact torque threshold T_{th}, the detector **210** continues monitoring the torque T on the swing leg 120_{SW}.

[0060] In some examples, the detector **210** monitors the torque T on each joint J of the swing leg 120_{SW}. For instance, the detector **210** monitors the torque T at the knee joint J_K, the abduction-adduction component of the hip joint J_{Hx}, and the flexion-extension component of the hip joint J_{Hy}. In some implementations, for each joint J, the detector **210** generates evidence **212** corresponding to a potential impact. Here, as shown in FIG. **2A**, the evidence **212** refers to an area under a curve representing the compensated torque T_{COMP} that is greater than the impact torque threshold T_{TH}. For instance, the detector **210** generates the evidence **212** as the integral under the curve representing the compensated torque T_{COMP}, but above the impact torque threshold T_{TH}. As shown in FIG. **2A**, to determine the evidence **212**, the detector **210** integrates the absolute value of the compensated torque T_{COMP}.

[0061] When the detector **210** generates evidence **212**, the detector **210** may be further configured to remove evidence **212** when the value of the compensated torque T_{COMP} indicates an impact **202** has not occurred. In some examples, the curve representing the compensated torque T_{COMP} will exceed the impact torque threshold T_{TH}, but then drop to a value below the impact torque threshold T_{TH}. When this drop below the impact torque threshold T_{TH} occurs, the detector **210** removes the evidence **212** to reduce the likelihood that the impact detection system **200** identifies a false impact. Similarly, in some implementations, the value of the compensated torque T_{COMP} indicates an impact **202** has not occurred because the value of the compensated torque T_{COMP} changes signs (e.g., from positive to negative or vice versa). Here, the detector **210** clears any evidence **212** prior to the sign change because the impact detection system **200** is configured to identify an impact **202** as a having the same sign (e.g., based on the integral of the absolute value of the compensated torque T_{COMP}). Therefore, a change in sign indicates a potential false impact.

[0062] In some examples, the detector **210** determines that an impact **202** occurs on the swing leg 120_{SW} when a sum of the evidence **212** for all joints J of a leg **120** satisfy an evidence threshold 212_{TH}. Here, the evidence threshold 212_{TH} refers to a required amount of evidence that the swing leg 120_{SW} experiences overall across all joints J that indicates an impact **202**. Although FIG. **2A** depicts the detector **210** determining whether the sum of the evidence **212** for all joints J of a leg **120** satisfies an evidence threshold 212_{TH}, other configurations of the detector **210** may perform this determination for less than all joints J of a leg **120** (e.g., for the knee joint J_K and one component of the hip joint J_H or both components of the hip joint J_H without knee joint J_K).

[0063] In some configurations, the evidence threshold 212_{TH} depends on the swing phase. For instance, the impact detection system **200** is configured to have greater sensitivity when a touchdown of the swing leg 120_{SW} is expected than when a touchdown of the swing leg 120_{SW} is not expected. Based on this, the evidence threshold 212_{TH} may be scaled or modified based on a percent completion of the swing phase. Here, other systems of the robot **100** may communicate the percent completion of the swing phase to the impact detector system **200**. For example, the control system **170** communicates the percent completion of the swing phase to the impact detection system **200** because the percent completion may be derived based on a controller **172** performing the gait cycle for the swing leg 120_{SW} having a fixed cadence. In some examples, the impact detection system **200** is configured to determine the percent completion of the swing phase based on a current location of the swing leg 120_{SW} (e.g., as determined by sensor data **134**) and a controller **172** operating the swing leg 120_{SW}.

[0064] Referring to FIG. **2B**, in some implementations, the detector **210** is configured to perform further analysis on a potential impact or an impact **202**. In other words, there may be circumstances where although the required evidence 212_{TH} indicates an impact **202**, the actual circumstances of the detected impact **202** may be analyzed to confirm whether the detected impact **202** is an actual impact. In some examples, such as FIG. **2B**, the structure of a leg **120** of the robot **100** includes end stops **126** that restrict a range of motion of the leg **120**. For instance, the range of motion is limited by an end stop **126** to prevent damage to the structure of the leg **120** or based on limitations of one or more motors

that articulate the leg **120**. When an end stop restricts **126** a range of motion of the leg **120**, the joint sensors **132** of the leg **120** may experience a sudden measured torque caused by a force F exerted by the end stop **126**. Even though this force F from the end stop **126** generates a correct sign for the torque T, the detector **210** is configured to ignore an impact **202** that occurs subsequent to when the detector **210** identifies the swing leg **120**$_{SW}$ is near an end stop **126**.

[0065] Referring to FIGS. 2C-2E, the detector **210** may be configured to ensure that a torque T causing a potential impact **202** always opposes motion of the leg **120** (e.g., motion of a foot **124** of the swing leg **120**$_{SW}$). In other words, the impact detection system **200** does not classify a condition as an impact **202** when the condition results in a measured torque that speeds up an associated joint J of the leg **120** (e.g., speeds up the leg **120** itself). FIGS. 2C-2E illustrate conditions where the detector **210** determines whether a torque T corresponding to an impact **202** opposes motion of the leg **120** (e.g., shown as motion of the foot **124** of the leg **120**). In each example, the foot **124** is moving in a direction of travel designated DT. Referring to FIG. 2C, the foot **124** is traveling to the left such that the detector **210** only considers a first torque T, T$_1$ at the knee joint J$_K$ and not a second torque T, T$_2$ at the knee joint J$_K$ because the second torque T$_2$ contributes to the motion of the foot **124**. In FIG. 2D, the direction of travel DT for the foot **124** is downward. Since a torque T in either direction may include opposing this downward motion, the detector **210** is configured to consider acting torque T in either direction (e.g., the first torque T$_1$ or the second torque T$_2$) when the potential torque contribution is unclear. In FIG. 2E, the direction of travel DT for the foot **124** is mostly downward, but with a directional component moving to the right. Here, the detector **210** may apply a weight to torques T in each direction such that the detector **210** requires a larger torque T in a direction that opposes the directional component of the foot **124** (e.g., the second torque T$_2$) to ensure that the torque T corresponds to an impact **202** (or vice versa).

[0066] In some examples, the detector **210** identifies the velocity of the foot **124** and then determines whether a potential impact torque T increases or decreases the velocity of the foot **124**. When the potential impact torque T contributes to an increase in the velocity of the foot **124**, the detector **210** ignores this impact **202** (or potential impact). On the other hand, when the potential impact torque T contributes to a decrease in the velocity of the foot **124**, the detector **210** may permit this impact **202** to be detected as an actual impact (e.g., subject to other criteria of the detector **210**).

[0067] Referring to FIGS. 2A and 2F, when the detector **210** detects an impact **202**, the detector **210** is configured to communicate that impact **202** to a classifier **220** of the impact detection system **200**. The classifier **220** is configured to determine a condition of the impact **202**. In other words, what type of impact **202** occurred or is occurring to the leg **120** of the robot **100** and, depending on the type of impact **202**, generate a response **204**. In some examples, the classifier **220** communicates the response **204** to the other systems of the robot **100** (e.g., the control system **170**). When the control system **170** receives the response **204**, a controller **172** of the control system **170** may generate an appropriate movement to overcome the impact **202** (e.g., stabilize the robot **100**). In some examples, the classifier **220** is configured in a hierarchy such that the classifier **220**

attempts to classify certain types of impacts **202** before other types of impacts **202** (e.g., touchdown contact before a trip condition).

[0068] In some examples, the classifier **220** utilizes characteristics of the distal end **124** (i.e., the foot **124**) of the leg **120** that experiences the impact **202** to classify the impact **202**. More particularly, the classifier **220** may use the position of the foot **124** in the world (e.g., derived from some combination of joint dynamics **134**$_{JD}$ and odometry information **192**), a velocity of the foot **124** in the world (e.g., derived from some combination of joint dynamics **134**$_{JD}$ and odometry information **192**), and forces on the foot **124** in the world frame. Here, the forces on the foot **124** in the world frame may be derived in two different ways. In a first approach, the classifier **220** may determine the forces in the world frame by deriving the forces from joint torques T of the joint dynamics **134**$_{JD}$ based on Jacobian transformation. In a second approach, classifier **220** uses inverse dynamics to generate the force on the foot **124** in the world frame. In some examples, the classifier **220** determines the force on the foot **124** based on both the first approach and the second approach, but uses whichever approach generates a force on the foot **124** in the world frame closer to zero to perform classification. In some implementations, when classifying a type of impact **202**, the classifier **220** associates an importance to the dynamics of the foot **124**. For instance, the force on the foot **124** is the most important characteristic, followed by the velocity of the foot **124**, and followed by the position of the foot **124** as the least important for classification purposes.

[0069] Referring to FIG. 2F, in some examples, the classifier **220** first determines whether the impact **202** corresponds to a touchdown of the swing leg **120**$_{SW}$. To classify the impact **202** as a touchdown, the classifier **220** generally determines whether a distal end **124** of the leg **120** experiences significant vertical forces (e.g., indicating a normal force from the ground surface **12**) and/or whether the velocity of the distal end **124** is no longer moving downward even though the control system **170** is instructing the distal end **124** to move downward. Here, the classifier **220** may be configured with a vertical force threshold that indicates a significant magnitude of a vertical force (e.g., that risks destabilization of the robot **100**). In other words, when the classifier **220** determines that a vertical force on the distal end **124** satisfies the vertical force threshold (e.g., exceeds a value set as the vertical force threshold), the classifier **220** classifies the impact **202** on the swing leg **120**$_{SW}$ as a touchdown. In some implementations, the classifier **220** modifies the vertical force threshold based on certain circumstances. For instance, the classifier **220** modifies the vertical force threshold when the robot **100** (e.g., via the control system **170**) is responding to a trip (e.g., the impact detection system **200** generated a response **204** to an impact **202**). In another examples, the classifier **220** modifies the vertical force threshold based on the swing phase (e.g., a percent completion of the swing phase). To illustrate, the classifier **220** may modify the vertical force threshold when the classifier **220** is aware the swing leg **120**$_{SW}$ is early in the swing phase (e.g., shortly after lift-off). Additionally or alternatively, when the classifier **220** identifies the impact **202** as a standard trip, but the robot **100** is unable to elevate the foot **124** as a response **204** to the standard trip, the classifier **220** classifies the impact **202** instead as a touchdown.

[0070] In some configurations, when the swing leg 120_{SW} is near an end of completion for the swing phase, the classifier 220 classifies any new impact 202 as a touchdown. For example, when a percent completion of the swing phase is greater than or equal to 95% complete, the classifier 220 classifies an impact 202 as a touchdown. Here, this condition protects the robot 100 from risking destabilization by a sudden undetected touchdown or other issues that may result from late detection of touchdown.

[0071] In some examples, the classifier 220 classifies the impact 202 as touchdown when the swing leg 120_{SW} is late in the swing phase and a planned trajectory for the swing leg 120_{SW} is moving downward toward the ground surface 12. For example, when a percent completion of the swing phase is about greater than or equal to 65% complete and the planned trajectory for the swing leg 120_{SW} is moving downward toward the ground surface 12, the classifier 220 classifies an impact 202 as a touchdown.

[0072] In these examples, where the swing leg 120_{SW} is late in the swing phase and the planned trajectory for the swing leg 120_{SW} is moving downward toward the ground surface 12, there may be additional criterial, but alternative criteria that the classifier 220 uses to classify an impact 202 as a touchdown. A first additional criteria may be that the force on the foot 124 is significantly large (e.g., satisfies the vertical force threshold or some version thereof). A second additional criterial may be that an impulse experienced by the foot 124 is quite large. For example, much like the vertical force threshold, the classifier 220 is configured with an impulse threshold that indicates an amount of force over time experienced by the foot 124 that indicates a touchdown (e.g., an impulse on the foot 124 exceeds the impulse threshold configured at the impact detection system 200). A third additional criteria may be that a measured velocity of the foot 124 is not as downward (in the z-direction towards the ground surface 12) as intended (e.g., by the control system 170). For example, the change in position of the foot 124 is greater than a threshold velocity of the foot 124 (e.g., greater than –0.5 m/s) such that although the control system 170 intended the foot 124 to be moving downwards in the z-direction towards the ground surface 12, the foot 124 is actually moving in decreasing speed towards the ground surface 12.

[0073] Referring further to FIG. 2F, when the impact 202 does not correspond to a touchdown of the swing leg 120_{SW}, the classifier 220 is configured to identify whether the impact 202 was caused by a special type of trip condition 222, 222_{SP}. Some examples of special trip conditions 222_{SP} include the following: when the thigh 122_U of the leg 120 is on the body 110; when the foot 124 experiences liftoff scuffing; when the swing leg 120_{SW} crosses a contralateral leg 120_{CL} (FIGS. 2G and 2H); when the swing leg 120_{SW} strikes the contralateral leg 120_{CL} (FIG. 2I); when the knee of the robot 100 is on terrain behind the robot 100 (FIG. 2J); and when the knee of the leg 120 is on terrain under the robot 100 (FIG. 2K). In some implementations, the classifier 220 identifies special trip condition 222_{SP} based on joint dynamics 134_{JD} and/or odometry information 192 of the robot 100. When the classifier 220 identifies a special type of trip condition 222_{SP}, depending on the type of trip, the classifier 220 (i) may generate a response 204 to overcome the trip and/or to reduce the effects of the trip. When the classifier 220 determines that the impact 202 was not caused by a special type of trip condition 222_{SP}, the classifier 220

classifies the impact 202 as caused by a standard trip condition 222, 222_{STD} (e.g., shown in FIG. 2L). For a standard trip condition 222_{STD}, the classifier 220 generates a response 204 to elevate the foot 124 that experienced the impact 202 (i.e., to increase the height of the foot 124 in the z-direction). FIG. 2L illustrates a standard trip condition 222_{STD} for the robot 100.

[0074] In some configurations, when the classifier 220 determines that the impact 202 was not caused by a touchdown of the swing leg 120_{SW} and the swing leg 120_{SW} is early in the swing phase (e.g., less than 10% complete with the swing phase), the classifier 220 classifies the impact 202 as a liftoff scuffing. In some examples, the classifier 220 determines that a percent completion of the swing phase satisfies a swing phase threshold (e.g., is less than the swing phase threshold) that indicates that the swing leg 120_{SW} is early in the swing phase. Here, a liftoff scuffing refers to when the swing leg 120_{SW} contacts the ground surface as the swing leg 120_{SW} lifts-off the ground surface 12 (e.g., the robot 100 stubs its foot 124 as it takes off). In this special trip condition 222_{SP}, the swing leg 120_{SW} will continue lifting off the ground surface 12 and thus clear the ground surface 12 that caused the impact 202. Therefore, the classifier 220 does not generate a response 204 based on this liftoff scuffing because the swing leg 120_{SW} does not risk any resistance as a result of the impact 202.

[0075] In some configurations, the classifier 220 determines that a position of the thigh (i.e., upper member 122_L of the leg 120) on the body 110 of the robot 100 caused the detected impact 202. Here, this special trip condition 222_{SP} occurs when the joint dynamics 134_{JD} indicate that the abduction-adduction component of the hip joint J_{Hx} exceeds a predetermined limit. Generally speaking, each component of the hip joint $J_{Hx,z}$ may be configured with a predetermined limit. For instance, the control system 170 or another system of the robot 100 may set the predetermined limits based on the dimensions of the robot 100 and/or a payload of the robot 100. In some examples, the abduction-adduction component of the hip joint J_{Hx} has a predetermined limit that is a function of the flexion-extension component of the hip joint J_{Hy}. In other words, when the abduction/adduction exceeds the predetermined limit for the abduction-adduction component of the hip joint J_{Hx}, the upper member 122_U of the leg 120 risks collision with the body 110 of the robot 100. Much like the special trip condition 222_{SP} of liftoff scuffing, the classifier 220 does not generate a response 204 based on this type of impact 202 and the swing leg 120_{SW} continues performing the swing phase of the gait.

[0076] Referring to FIGS. 2G and 2H, in some examples, the classifier 220 determines that the swing leg 120_{SW} (e.g., shown as a first leg 120a) crossed the contralateral leg 120_{CL} (e.g., shown as a second leg 120b, 120_{ST}) to cause the impact 202. Here, a contralateral leg 120_{CL} refers to a relationship between two legs 120a-b such that the first leg 120a is opposite the sagittal plane (i.e., the Y-Z plane) from the second leg 120b. For instance, with a quadruped robot (as shown) the stance leg 120_{ST} is generally a contralateral leg 120_{CL} to the swing leg 120_{SW} (and vice versa) to maintain balance for the robot 100 during movement. In some examples, the classifier 220 determines this type of special trip condition 222_{SP} by determining whether the swing leg 120_{SW} is near a contralateral leg 120_{CL} based on kinematics of the robot 100. In these examples, determining whether the swing leg 120_{SW} is near a contralateral leg 120_{CL} may

include determining a vector distance between a first closest point of the swing leg 120_{SW} to the contralateral leg 120_{CL} and a second closest point of the contralateral leg 120_{CL} to the swing leg 120_{SW}. Here, when the vector distance indicates the swing leg 120_{SW} crossed the contralateral leg 120_{CL}, the classifier 220 may additionally determine whether the feet 124*a-b* of each leg 120_{SW}, 120_{CL} are crossed and/or whether the knee joints J_K, J_Ka-b of each leg 120_{SW}, 120_{CL} are crossed. In some configurations, the classifier 220 is configured to determine that one or more of these conditions are true (e.g., one is true, two are true, or all three are true). In other words, the classifier 220 determines whether (i) the vector distance indicates the legs 120_{SW}, 120_{CL} are crossed, (ii) the position of the knee joints J_K, J_Ka-b indicates that the legs 120_{SW}, 120_{CL} are crossed, or (iii) the position of the feet 124*a-b* indicates that the legs 120_{SW}, 120_{CL} are crossed. When the swing leg 120_{SW} crossing the contralateral leg 120_{CL} results in an impact 202, the classifier 220 may generate a response 204 to uncross the legs 120_{SW}, 120_C. For instance, the classifier 220 moves the knee joint J_K of the swing leg 120_{SW} towards a vertical axis in the z-direction of the hip joint J_H of the swing leg 120_{SW}.

[0077] Referring to FIG. 2I, in some implementations, the classifier 220 determines that the swing leg 120_{SW} is near a contralateral leg 120_{CL}, but not crossed over the contralateral leg 120_{CL} (e.g., based on kinematics of the robot 100). Here, the classifier 220 may determine the swing leg 120_{SW} contacted the contralateral leg 120_{CL} causing the impact 202, but did not cross over the contralateral leg 120_{CL} during, before, or shortly thereafter the impact 202. In some examples, the classifier 220 forms this determination by identifying (i) that the swing leg 120_{SW} is not too late in the swing phase (e.g., less than 65% complete) and (ii) that the evidence 212, which the detector 210 used to determine the impact 202, was predominantly from the abduction-adduction component of the hip joint J_{Hx}. In other words, the torque of lateral rotation of the hip joint J_{Hx} was a greater contributor to the evidence 212 identifying the impact 202 than torques of the flexion-extension component of the hip joint J_{Hy} and the knee joint J_K (e.g., each separately or combined together). When the swing leg 120_{SW} collides with the contralateral leg 120_{CL} causing the impact 202, the classifier 220 may generate a response 204 to separate the legs 120_{SW}, 120_{CL} (e.g., by moving one or more legs 120_{SW}, 120_{CL} away from each other in the frontal plane). In other words, swing leg 120_{SW} may continue its originally planned motion within the sagittal plane while overriding the originally planned motion in the frontal plane (e.g., along the x-axis A_X) to separate from the stance leg 120_{ST}.

[0078] Referring to FIGS. 2K-2L, in some configurations, the classifier 220 determines that a collision between the leg 120 (e.g., the swing leg 120_{SW}) and terrain either behind (e.g., shown in FIG. 2J) or beneath (e.g., shown in FIG. 2K) the body 110 of the robot 100 causes the impact 202. In the case of a special trip condition 222_{SP} where the impact 202 occurs based on contact between a knee joint J_K of the swing leg 120_{SW} and the terrain behind the robot 100, the classifier 220 determines (i) that the knee joint J_K of the swing leg 120_{SW} is moving backwards away from the body 110 (e.g., in the y-direction) and (ii) that the evidence 212 indicates that the flexion-extension component of the hip joint J_{Hy} for the swing leg 120_{SW} is the largest contributor of joint torque. In some examples, the flexion-extension component of the hip joint J_{Hy} for the swing leg 120_{SW} is larger than the joint

torque T contribution of both the knee joint J_K and the abduction-adduction component of the hip joint J_{Hx} (e.g., separately or in combination). In some implementations, the classifier 220 uses the kinematics of the swing leg 120_{SW} to determine that the knee joint J_K of the swing leg 120_{SW} is moving backwards away from the body 110. When the classifier 220 classifies the impact 202 as a collision between the leg 120 and the terrain behind the robot 100, the classifier 220 generates a response 204 to move bring the knee joint J_K forward (e.g., towards the CM of the robot 100 along the y-direction).

[0079] Referring to FIG. 2L, here, the classifier 220 determines that a collision between the leg 120 and the terrain beneath the body 110 of the robot 100 caused the impact 202. To determine this special trip condition 222_{SP}, the classifier 220 determines that the knee joint J_K is moving forward (e.g., forward in the y-direction with respect to the hip joint J_H of the swing leg 120_{SW}) and that the evidence 212 producing the impact 202 occurred in joints J other than the knee joint J_K. Additionally or alternatively, the classifier 220 may use one or more maps 182 of the perception system 180 to determine that the knee joint J_K of the swing leg 120_{SW} is closer to the ground surface 12 than the foot 124 of the swing leg 120_{SW}. The map 182 may also indicate that the knee joint J_K of the swing leg 120_{SW} was recently perceived near the ground surface 12. In this special trip condition 222_{SP}, the classifier 220 is configured to not generate a response 204 because the forward motion of the swing leg 120_{SW} by continuing the swing phase of the gait will carry the knee joint J_K past the object causing the impact 202.

[0080] In some examples, the impact detection system 200 may be advantageous when the perception system 180 is either off or not functioning well (e.g., issues with sensor(s) 132). When this occurs, the impact detection system 200 may be used as a primary system for detection within the environment 10. Conversely, when the perception system 180 is working properly, the impact detection system 200 may offer a robust auxiliary system for detection, especially in instances when the perception system 180 makes a mistake or encounters a temporary issue.

[0081] FIG. 3 is an arrangement of operations to perform a method 300 of footstep contact detection. At operation 302, the method 300 receives joint dynamics 134_{JD} for a swing leg 120_{SW} of a robot 100. Here, the swing leg 120_{SW} performs a swing phase of a gait of the robot 100. At operation 304, the method 300 receives odometry 192 that defines an estimation of characteristics (e.g., a pose) of the robot 100 relative to a world reference frame. At operation 306, the method 300 determines whether a torque T on the swing leg 120_{SW} corresponds to an impact 202 on the swing leg 120_{SW}. When the torque T on the swing leg 120_{SW} corresponds to the impact 202, at operation 308, 308*a*, the method 300 determines whether the impact 202 is indicative of a touchdown of the swing leg 120_{SW} on a ground surface 12 about the robot 100 based on the odometry 192 of the robot 100 and the joint dynamics 134_{JD} of the swing leg 120_{SW}. At operation 308, 308*b*, when the impact 202 is not indicative of the touchdown of the swing leg 120_{SW}, the method 300 classifies a cause of the impact 202 based on the odometry 192 of the robot 100 and the joint dynamics 134_{JD} of the swing leg 120_{SW}.

[0082] FIG. 4 is schematic view of an example computing device 400 that may be used to implement the systems (e.g., the sensor system 130, the computing system 140, the

remote system **160**, the control system **170**, the perception system **180**, the odometry system **190**, and/or the impact detection system **200**) and methods (e.g., method **300**) described in this document. The computing device **400** is intended to represent various forms of digital computers, such as laptops, desktops, workstations, personal digital assistants, servers, blade servers, mainframes, and other appropriate computers. The components shown here, their connections and relationships, and their functions, are meant to be exemplary only, and are not meant to limit implementations of the inventions described and/or claimed in this document.

[0083] The computing device **400** includes a processor **410** (e.g., data processing hardware), memory **420** (e.g., memory hardware), a storage device **430**, a high-speed interface/controller **440** connecting to the memory **420** and high-speed expansion ports **450**, and a low speed interface/controller **460** connecting to a low speed bus **470** and a storage device **430**. Each of the components **410**, **420**, **430**, **440**, **450**, and **460**, are interconnected using various busses, and may be mounted on a common motherboard or in other manners as appropriate. The processor **410** can process instructions for execution within the computing device **400**, including instructions stored in the memory **420** or on the storage device **430** to display graphical information for a graphical user interface (GUI) on an external input/output device, such as display **480** coupled to high speed interface **440**. In other implementations, multiple processors and/or multiple buses may be used, as appropriate, along with multiple memories and types of memory. Also, multiple computing devices **400** may be connected, with each device providing portions of the necessary operations (e.g., as a server bank, a group of blade servers, or a multi-processor system).

[0084] The memory **420** stores information non-transitorily within the computing device **400**. The memory **420** may be a computer-readable medium, a volatile memory unit(s), or non-volatile memory unit(s). The non-transitory memory **420** may be physical devices used to store programs (e.g., sequences of instructions) or data (e.g., program state information) on a temporary or permanent basis for use by the computing device **400**. Examples of non-volatile memory include, but are not limited to, flash memory and read-only memory (ROM)/programmable read-only memory (PROM)/erasable programmable read-only memory (EPROM)/electronically erasable programmable read-only memory (EEPROM) (e.g., typically used for firmware, such as boot programs). Examples of volatile memory include, but are not limited to, random access memory (RAM), dynamic random access memory (DRAM), static random access memory (SRAM), phase change memory (PCM) as well as disks or tapes.

[0085] The storage device **430** is capable of providing mass storage for the computing device **400**. In some implementations, the storage device **430** is a computer-readable medium. In various different implementations, the storage device **430** may be a floppy disk device, a hard disk device, an optical disk device, or a tape device, a flash memory or other similar solid state memory device, or an array of devices, including devices in a storage area network or other configurations. In additional implementations, a computer program product is tangibly embodied in an information carrier. The computer program product contains instructions that, when executed, perform one or more methods, such as

those described above. The information carrier is a computer- or machine-readable medium, such as the memory **420**, the storage device **430**, or memory on processor **410**.

[0086] The high speed controller **440** manages bandwidth-intensive operations for the computing device **400**, while the low speed controller **460** manages lower bandwidth-intensive operations. Such allocation of duties is exemplary only. In some implementations, the high-speed controller **440** is coupled to the memory **420**, the display **480** (e.g., through a graphics processor or accelerator), and to the high-speed expansion ports **450**, which may accept various expansion cards (not shown). In some implementations, the low-speed controller **460** is coupled to the storage device **430** and a low-speed expansion port **490**. The low-speed expansion port **490**, which may include various communication ports (e.g., USB, Bluetooth, Ethernet, wireless Ethernet), may be coupled to one or more input/output devices, such as a keyboard, a pointing device, a scanner, or a networking device such as a switch or router, e.g., through a network adapter.

[0087] The computing device **400** may be implemented in a number of different forms, as shown in the figure. For example, it may be implemented as a standard server **400***a* or multiple times in a group of such servers **400***a*, as a laptop computer **400***b*, or as part of a rack server system **400***c*.

[0088] Various implementations of the systems and techniques described herein can be realized in digital electronic and/or optical circuitry, integrated circuitry, specially designed ASICs (application specific integrated circuits), computer hardware, firmware, software, and/or combinations thereof. These various implementations can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which may be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, and at least one output device.

[0089] These computer programs (also known as programs, software, software applications or code) include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming language, and/or in assembly/machine language. As used herein, the terms "machine-readable medium" and "computer-readable medium" refer to any computer program product, non-transitory computer readable medium, apparatus and/or device (e.g., magnetic discs, optical disks, memory, Programmable Logic Devices (PLDs)) used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term "machine-readable signal" refers to any signal used to provide machine instructions and/or data to a programmable processor.

[0090] The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed by special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application specific integrated circuit). Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors,

and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read only memory or a random access memory or both. The essential elements of a computer are a processor for performing instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto optical disks, or optical disks. However, a computer need not have such devices. Computer readable media suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto optical disks; and CD ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

[0091] To provide for interaction with a user, one or more aspects of the disclosure can be implemented on a computer having a display device, e.g., a CRT (cathode ray tube), LCD (liquid crystal display) monitor, or touch screen for displaying information to the user and optionally a keyboard and a pointing device, e.g., a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, e.g., visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input. In addition, a computer can interact with a user by sending documents to and receiving documents from a device that is used by the user; for example, by sending web pages to a web browser on a user's client device in response to requests received from the web browser.

[0092] A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the disclosure. Accordingly, other implementations are within the scope of the following claims.

What is claimed is:

1. A method comprising:

receiving, at data processing hardware of a robot, joint dynamics for a swing leg of the robot, the swing leg performing a swing phase of a gait of the robot;

receiving, at the data processing hardware, odometry defining an estimation of a pose of the robot relative to a world reference frame;

determining, by the data processing hardware, whether an unexpected torque on the swing leg corresponds to an impact on the swing leg; and

when the unexpected torque on the swing leg corresponds to the impact:

determining, by the data processing hardware, whether the impact is indicative of a touchdown of the swing leg on a ground surface about the robot based on the odometry of the robot and the joint dynamics of the swing leg; and

when the impact is not indicative of the touchdown of the swing leg, classifying, by the data processing

hardware, a cause of the impact based on the odometry of the robot and the joint dynamics of the swing leg.

2. The method of claim 1, further comprising generating, by the data processing hardware, a response for the swing leg of the robot based on the classified cause of the impact.

3. The method of claim 1, further comprising, when the impact is indicative of the touchdown of the swing leg, changing, by the data processing hardware, a classification of the swing leg to a stance leg.

4. The method of claim 1, further comprising, elevating the swing leg as a response to the respective impact when the cause of the impact is classified as a trip.

5. The method of claim 1, wherein classifying the cause of the impact comprises:

determining that a percent completion of the swing phase for the swing leg of the robot satisfies a swing phase threshold based on the joint dynamics of the swing leg, the swing phase threshold indicating that the swing leg is early in the swing phase; and

classifying the cause of the impact on the swing leg as a liftoff scuffing,

wherein the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the liftoff scuffing.

6. The method of claim 1, wherein classifying the cause of the impact comprises:

determining that a hip joint of the swing leg exceeds a pre-determined motion limit based on the joint dynamics of the swing leg, the joint dynamics comprising an abduction-adduction component of the hip joint relative to the ground surface and a flexion-extension component of the hip joint relative to the ground surface, the abduction-adduction component comprising the pre-determined motion limit as a function of the flexion-extension component; and

classifying the cause of the impact on the swing leg as the swing leg contacting a body of the robot,

wherein the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the swing leg contacts the body of the robot.

7. The method of claim 1, wherein classifying the cause of the impact comprises:

determining that a vector distance between a first closest point of the swing leg to a contralateral leg and a second closest point of the contralateral leg to the swing leg indicates the swing leg crossed the contralateral leg;

determining that a distal end of the swing leg crossed a respective distal end of the contralateral leg;

determining that a first knee joint of the swing leg crossed a second knee joint of the contralateral leg;

classifying the condition causing the respective impact for the swing leg of the robot as the swing leg crossed the contralateral leg of the robot; and

moving the swing leg to uncross with the contralateral leg of the robot.

8. The method of claim 1, wherein classifying the condition for the leg of the robot corresponding to the respective impact further comprises:

determining that the swing leg is positioned near a contralateral leg of the robot;

determining that the torque corresponding to the respective impact results from joint dynamics predominantly from a lateral component of a hip joint of the swing leg;

classifying the condition causing the respective impact for the swing leg of the robot as uncrossed contralateral leg impact; and

moving the swing leg away from a sagittal plane of the robot.

9. The method of claim 1, wherein classifying the condition for the leg of the robot corresponding to the respective impact further comprises:

determining that a knee of the swing leg is moving backwards during the swing phase;

determining that the joint dynamics resulting in the unexpected torque corresponding to the respective impact comprise a flexion-extension torque about a hip joint of the swing leg that is greater than both a knee torque of the swing leg and an adduction-abduction torque about a hip joint of the swing leg;

classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain behind a body of the robot; and

shifting the knee of the swing leg forward relative to the body of the robot.

10. The method of claim 1, wherein classifying the condition for the leg of the robot corresponding to the respective impact further comprises:

determining that a knee of the swing leg is adjacent to a perceived ground surface, the knee moving forward relative to a body of the robot, the perceived ground surface defined by sensor data about the robot;

determining that the knee of the swing leg is closer to the perceived ground surface than a distal end of the swing leg;

determining that the unexpected torque corresponding to the respective impact occurs at a hip joint of the swing leg;

classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain underneath the body of the robot; and

continuing movement of the swing leg without response to the knee of the swing leg contacting terrain underneath the body of the robot.

11. The method of claim 1, wherein determining whether the unexpected torque on the swing leg of the robot corresponds to the impact on the swing leg comprises determining whether the unexpected torque satisfies an impact detection threshold, the impact detection threshold comprising a magnitude of torque that corresponds to a known impact.

12. The method of claim 1, further comprising determining, by the data processing hardware, the unexpected torque on the swing leg based on a difference between:

a measured torque measured by joint torque sensors about the robot;

a first expected torque representing a respective torque caused by gravity; and

a second expected torque representing a corresponding torque to accelerate the swing leg of the robot.

13. The method of claim 1, further comprising, when a joint of the swing leg of the robot is adjacent to a limit on a range of motion for the joint, determining, by the data processing hardware, that the unexpected torque fails to indicate the impact on the swing leg during the swing phase.

14. The method of claim 1, wherein determining whether the unexpected torque on the swing leg corresponds to the impact on the swing leg comprises determining that the unexpected torque on the swing leg corresponds to an impact torque, the impact torque opposing motion of a joint of the swing leg.

15. The method of claim 1, wherein the joint dynamics of the swing leg correspond to joint dynamics of a knee joint of the swing leg and joint dynamics of a hip joint of the swing leg.

16. The method of claim 15, wherein the joint dynamics of the hip joint comprise an abduction-adduction torque abducting or adducting the swing leg and a flexion-extension torque flexing or extending the swing leg.

17. A robot comprising:

a body;

two or more legs coupled to the body and configured to traverse an environment, the two or more legs comprising a swing leg; and

a control system in communication with the two or more legs, the control system comprising data processing hardware and memory hardware in communication with the data processing hardware, the memory hardware storing instructions that when executed on the data processing hardware cause the data processing hardware to perform operations comprising:

receiving joint dynamics for the swing leg of the robot, the swing leg performing a swing phase of a gait of the robot;

receiving odometry defining an estimation of a pose of the robot relative to a world reference frame;

determining whether an unexpected torque on the swing leg corresponds to an impact on the swing leg; and

when the unexpected torque on the swing leg corresponds to the impact:

determining whether the impact is indicative of a touchdown of the swing leg on a ground surface about the robot based on the odometry of the robot and the joint dynamics of the swing leg; and

when the impact is not indicative of the touchdown of the swing leg, classifying a cause of the impact based on the odometry of the robot and the joint dynamics of the swing leg.

18. The robot of claim 17, wherein the operations further comprise generating a response for the swing leg of the robot based on the classified cause of the impact.

19. The robot of claim 17, wherein the operations further comprise, when the impact is indicative of the touchdown of the swing leg, changing a classification of the swing leg to a stance leg.

20. The robot of claim 17, wherein the operations further comprise elevating the swing leg as a response to the respective impact when the cause of the impact is classified as a trip.

21. The robot of claim 17, wherein classifying the cause of the impact comprises:

determining that a percent completion of the swing phase for the swing leg of the robot satisfies a swing phase threshold based on the joint dynamics of the swing leg, the swing phase threshold indicating that the swing leg is early in the swing phase; and

classifying the cause of the impact on the swing leg as a liftoff scuffing,

wherein the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the liftoff scuffing.

22. The robot of claim **17**, wherein classifying the cause of the impact comprises:

determining that a hip joint of the swing leg exceeds a pre-determined motion limit based on the joint dynamics of the swing leg, the joint dynamics comprising an abduction-adduction component of the hip joint relative to the ground surface and a flexion-extension component of the hip joint relative to the ground surface, the abduction-adduction component comprising the pre-determined motion limit as a function of the flexion-extension component; and

classifying the cause of the impact on the swing leg as the swing leg contacting a body of the robot,

wherein the swing leg continues performing the swing phase of the gait responsive to classifying the cause of the impact on the swing leg as the swing leg contacting the body of the robot.

23. The robot of claim **17**, wherein classifying the cause of the impact comprises:

determining that a vector distance between a first closest point of the swing leg to a contralateral leg and a second closest point of the contralateral leg to the swing leg indicates the swing leg crossed the contralateral leg;

determining that a distal end of the swing leg crossed a respective distal end of the contralateral leg;

determining that a first knee joint of the swing leg crossed a second knee joint of the contralateral leg;

classifying the condition causing the respective impact for the swing leg of the robot as the swing leg crossed the contralateral leg of the robot; and

moving the swing leg to uncross with the contralateral leg of the robot.

24. The robot of claim **17**, wherein classifying the condition for the leg of the robot corresponding to the respective impact further comprises:

determining that the swing leg is positioned near a contralateral leg of the robot;

determining that the torque corresponding to the respective impact results from joint dynamics predominantly from a lateral component of a hip joint of the swing leg;

classifying the condition causing the respective impact for the swing leg of the robot as uncrossed contralateral leg impact; and

moving the swing leg away from a sagittal plane of the robot.

25. The robot of claim **17**, wherein classifying the condition for the leg of the robot corresponding to the respective impact further comprises:

determining that a knee of the swing leg is moving backwards during the swing phase;

determining that the joint dynamics resulting in the unexpected torque corresponding to the respective impact comprise a flexion-extension torque about a hip joint of the swing leg that is greater than both a knee torque of the swing leg and an adduction-abduction torque about a hip joint of the swing leg;

classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain behind a body of the robot; and

shifting the knee of the swing leg forward relative to the body of the robot.

26. The robot of claim **17**, wherein classifying the condition for the leg of the robot corresponding to the respective impact further comprises:

determining that a knee of the swing leg is adjacent to a perceived ground surface, the knee moving forward relative to a body of the robot, the perceived ground surface defined by sensor data about the robot;

determining that the knee of the swing leg is closer to the perceived ground surface than a distal end of the swing leg;

determining that the unexpected torque corresponding to the respective impact occurs at a hip joint of the swing leg;

classifying the condition causing the respective impact for the swing leg of the robot as the knee of the swing leg contacting terrain underneath the body of the robot; and

continuing movement of the swing leg without response to the knee of the swing leg contacts terrain underneath the body of the robot.

27. The robot of claim **17**, wherein determining whether the unexpected torque on the swing leg of the robot corresponds to the impact on the swing leg comprises determining whether the unexpected torque satisfies an impact detection threshold, the impact detection threshold comprising a magnitude of torque that corresponds to a known impact.

28. The robot of claim **17**, wherein the operations further comprise determining the unexpected torque on the swing leg based on a difference between:

a measured torque measured by joint torque sensors about the robot;

a first expected torque representing a respective torque caused by gravity; and

a second expected torque representing a corresponding torque to accelerate the swing leg of the robot.

29. The robot of claim **17**, wherein the operations further comprise, when a joint of the swing leg of the robot is adjacent to a limit on a range of motion for the joint, determining that the unexpected torque fails to indicate the impact on the swing leg during the swing phase.

30. The robot of claim **17**, wherein determining whether the unexpected torque on the swing leg corresponds to the impact on the swing leg comprises determining that the unexpected torque on the swing leg corresponds to an impact torque, the impact torque opposing motion of a joint of the swing leg.

31. The robot of claim **17**, wherein the joint dynamics of the swing leg correspond to joint dynamics of a knee joint of the swing leg and joint dynamics of a hip joint of the swing leg.

32. The robot of claim **31**, wherein the joint dynamics of the hip joint comprise an abduction-adduction torque abducting or adducting the swing leg and a flexion-extension torque flexing or extending the swing leg.

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