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(54) **LEG SWING TRAJECTORIES**

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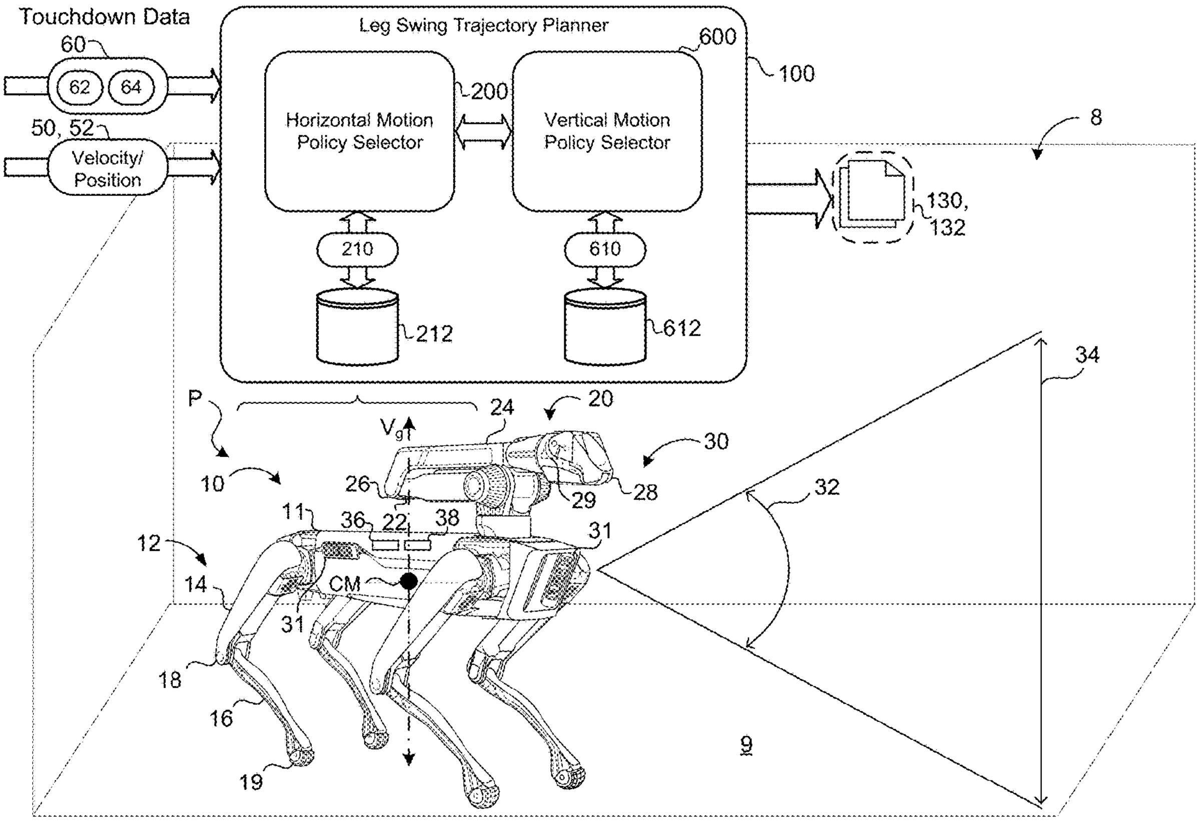
CPC ***B62D 57/032*** (2013.01)

(57) **ABSTRACT**

A method of planning a swing trajectory for a leg of a robot includes receiving an initial position of a leg of the robot, an initial velocity of the leg, a touchdown location, and a touchdown target time. The method also includes determining a difference between the initial position and the touchdown location and separating the difference between the initial position and the touchdown location into a horizontal motion component and a vertical motion component. The method also includes selecting a horizontal motion policy and a vertical motion policy to satisfy the motion components. Each policy produces a respective trajectory as a function of the initial position, the initial velocity, the touchdown location, and the touchdown target time. The method also includes executing the selected policies to swing the leg of the robot from the initial position to the touchdown location at the touchdown target time.



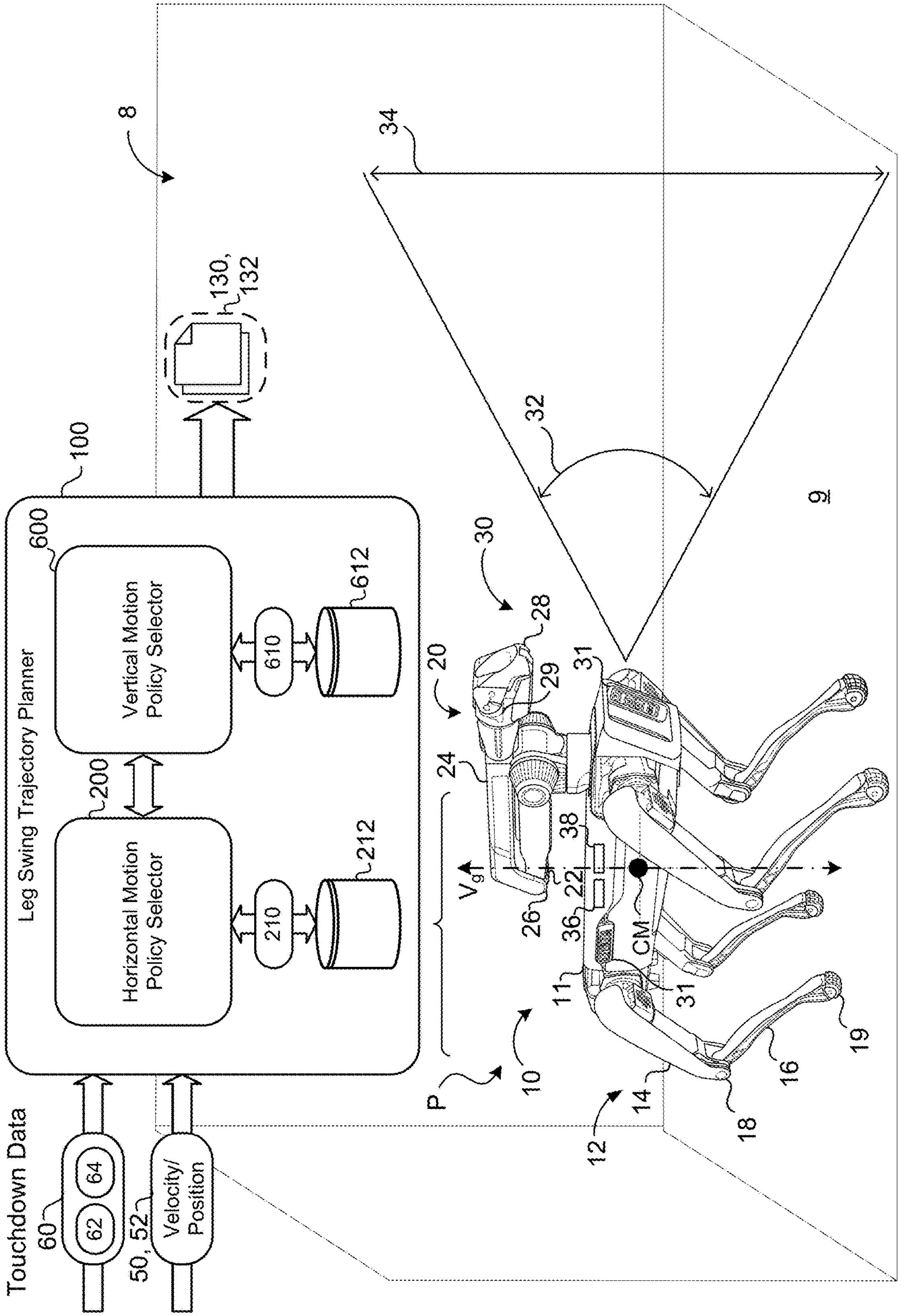

Touchdown Data
60
62
64
50, 52
Velocity/ Position
Leg Swing Trajectory Planner
100
Horizontal Motion Policy Selector
200
210
212
Vertical Motion Policy Selector
600
610
612
130, 132
8
34
32
9
30
28
20
29
31
24
38
22
26
36
V_g
CM
11
31
10
P
12
14
18
16
19

FIG. 1

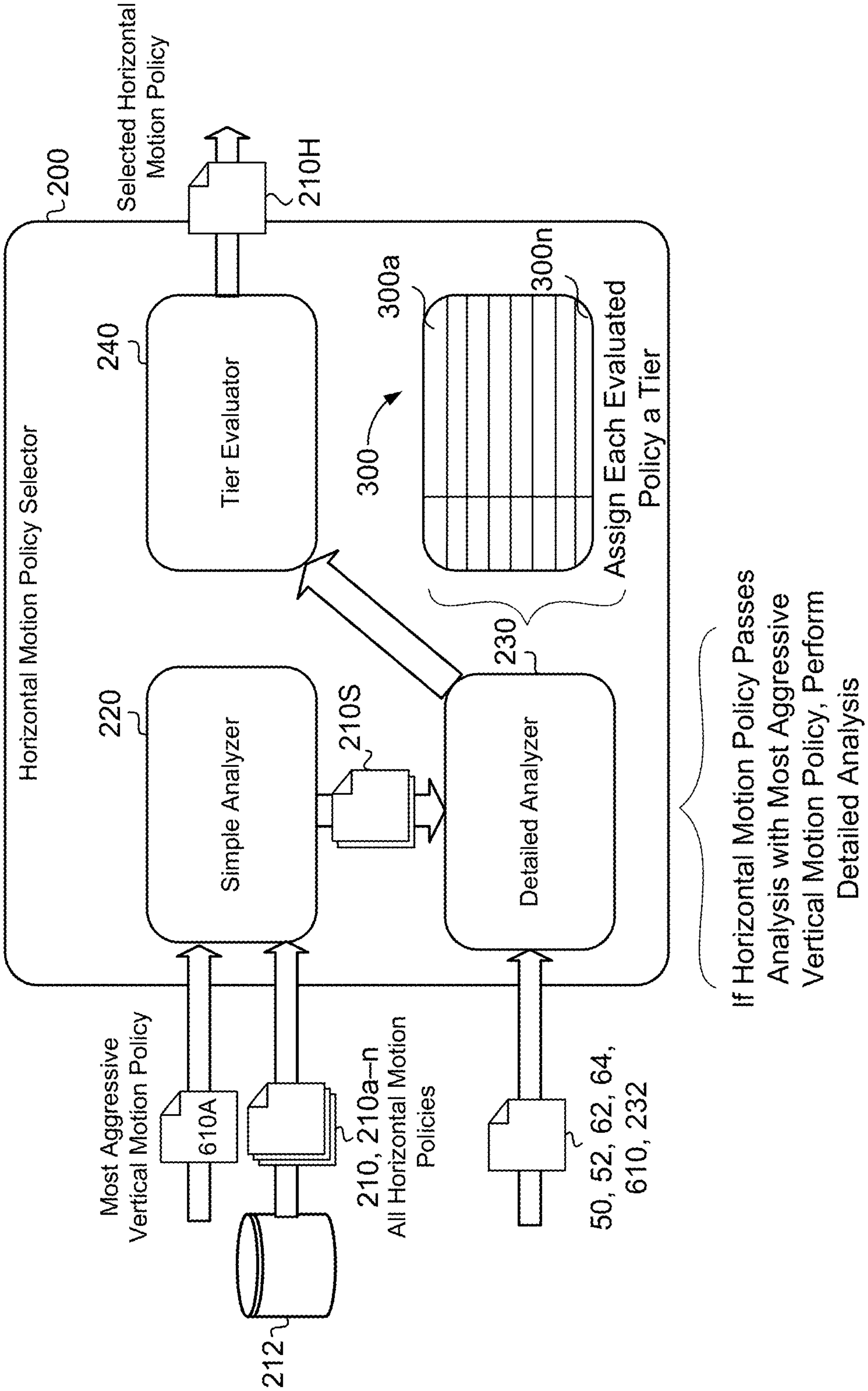

Horizontal Motion Policy Selector
200
Selected Horizontal Motion Policy
210H
240
Tier Evaluator
300a
300n
300
Assign Each Evaluated Policy a Tier
220
Simple Analyzer
210S
230
Detailed Analyzer
If Horizontal Motion Policy Passes Analysis with Most Aggressive Vertical Motion Policy, Perform Detailed Analysis
Most Aggressive Vertical Motion Policy
610A
210, 210a–n
All Horizontal Motion Policies
212
50, 52, 62, 64, 610, 232

FIG. 2

300, 300a-n

302, 302a-n

Tier	Tie Breaker
Success	Total Undesirability
XY-Success; Z-Impossible	Combination of: Collision Severity & Undesirability
Cliff Scraping	Horizontal Margin
Knee-Terrain Collision	Collision Severity; Undesirability if close
Knee Self-Collision	Collision Severity; Miss distance if close
Terrain Collision	Combination of: Collision Severity & Undesirability
XY Can't Reach Target	Miss Distance (with hysteresis)
Self Collision	Collision Severity; Miss distance if close
Default	N/A – Only one default
Violates Constraints	N/A – Never select

FIG. 3

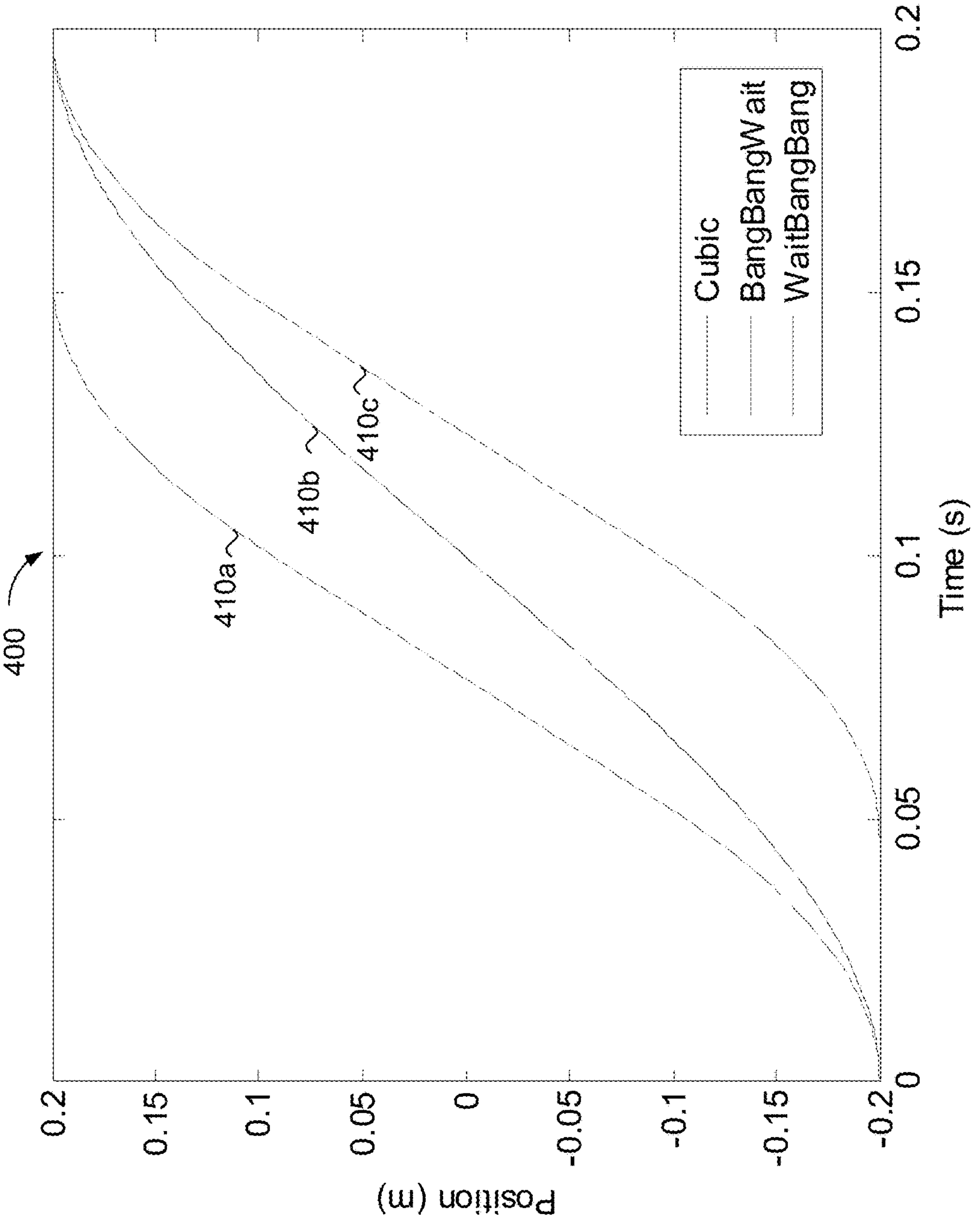

400
410a
410b
410c
Cubic
BangBangWait
WaitBangBang
Position (m)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Time (s)
0
0.05
0.1
0.15
0.2

FIG. 4

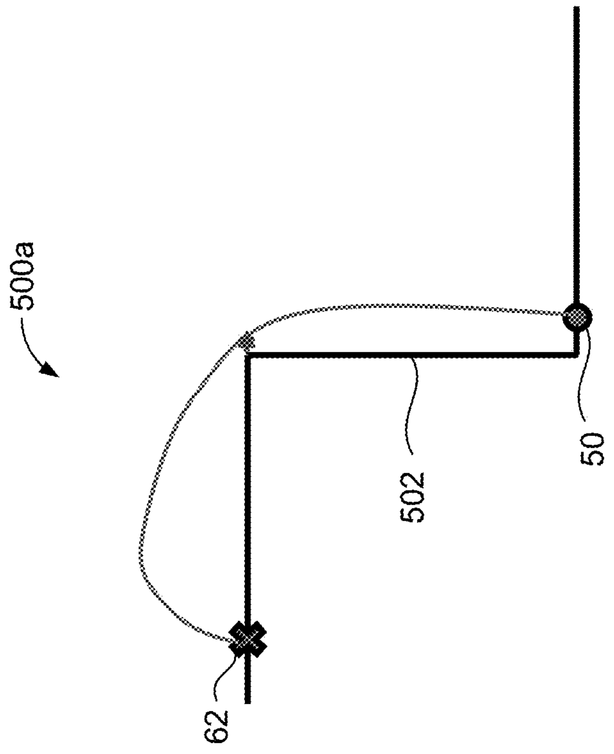


FIG. 5A

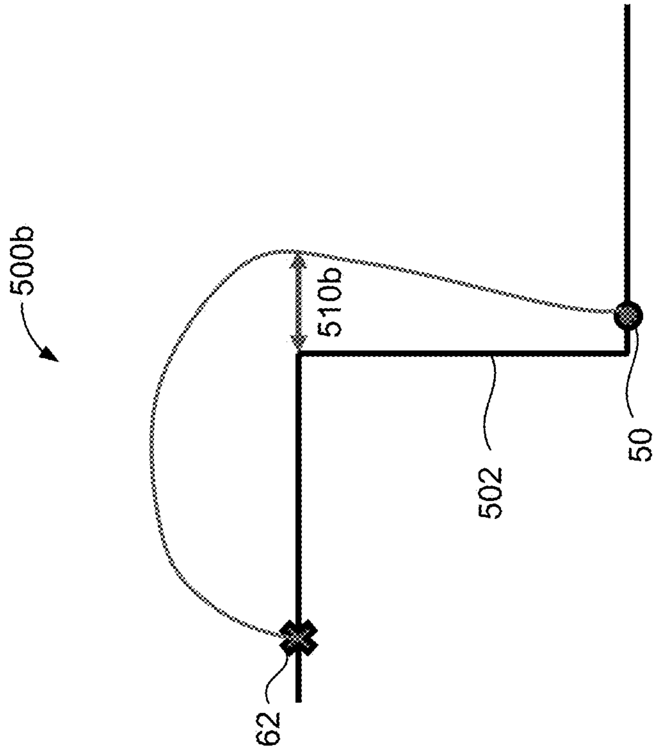


FIG. 5B

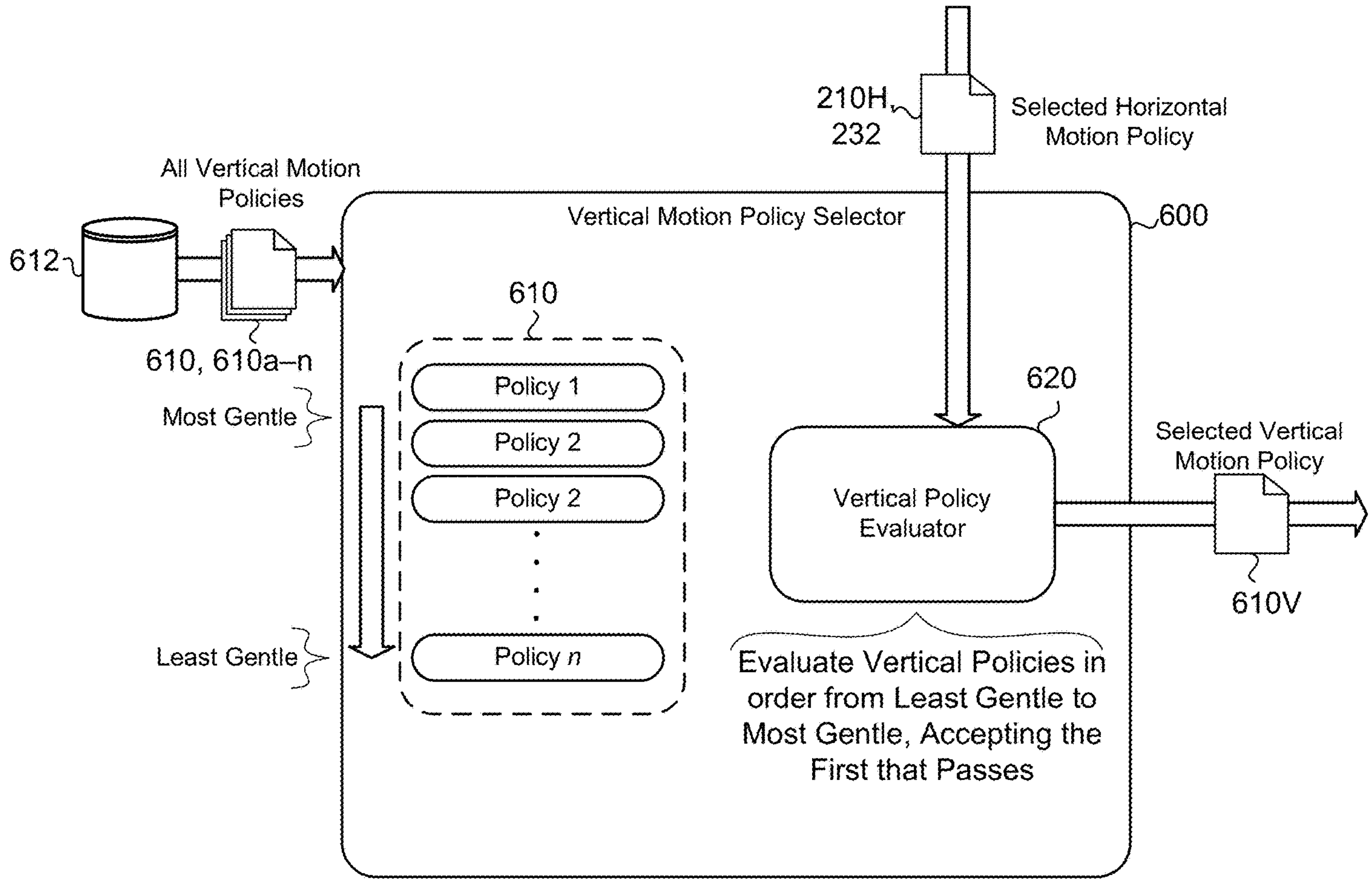

210H,
232
Selected Horizontal
Motion Policy
All Vertical Motion
Policies
Vertical Motion Policy Selector
600
612
610
610, 610a–n
Most Gentle
Least Gentle
Policy 1
Policy 2
Policy 2
Policy *n*
620
Vertical Policy
Evaluator
Selected Vertical
Motion Policy
610V
Evaluate Vertical Policies in order from Least Gentle to Most Gentle, Accepting the First that Passes

FIG. 6

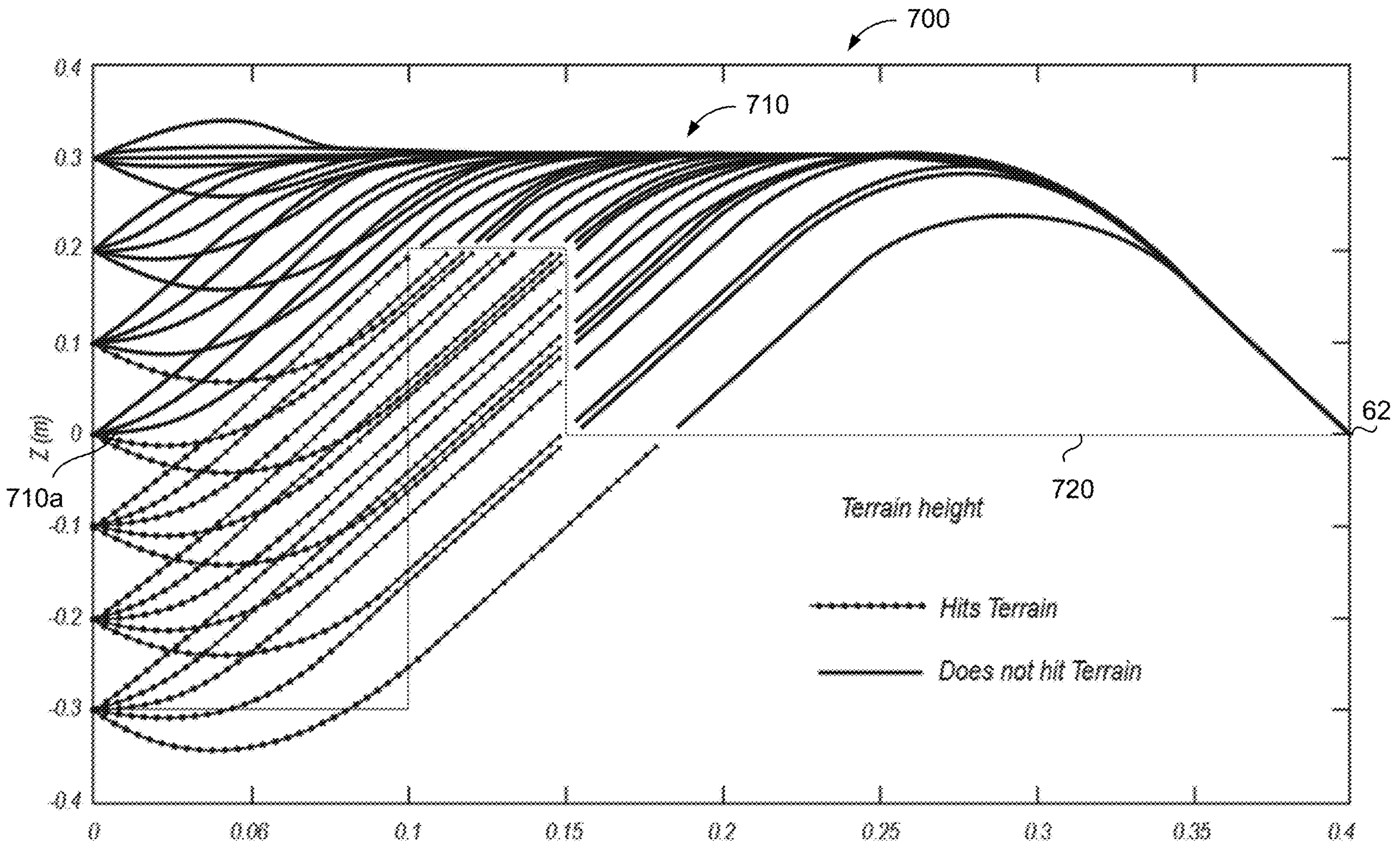

700
710
0.4
0.3
0.2
0.1
0
Z (m)
-0.1
-0.2
-0.3
-0.4
710a
62
720
Terrain height
Hits Terrain
Does not hit Terrain
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

FIG. 7

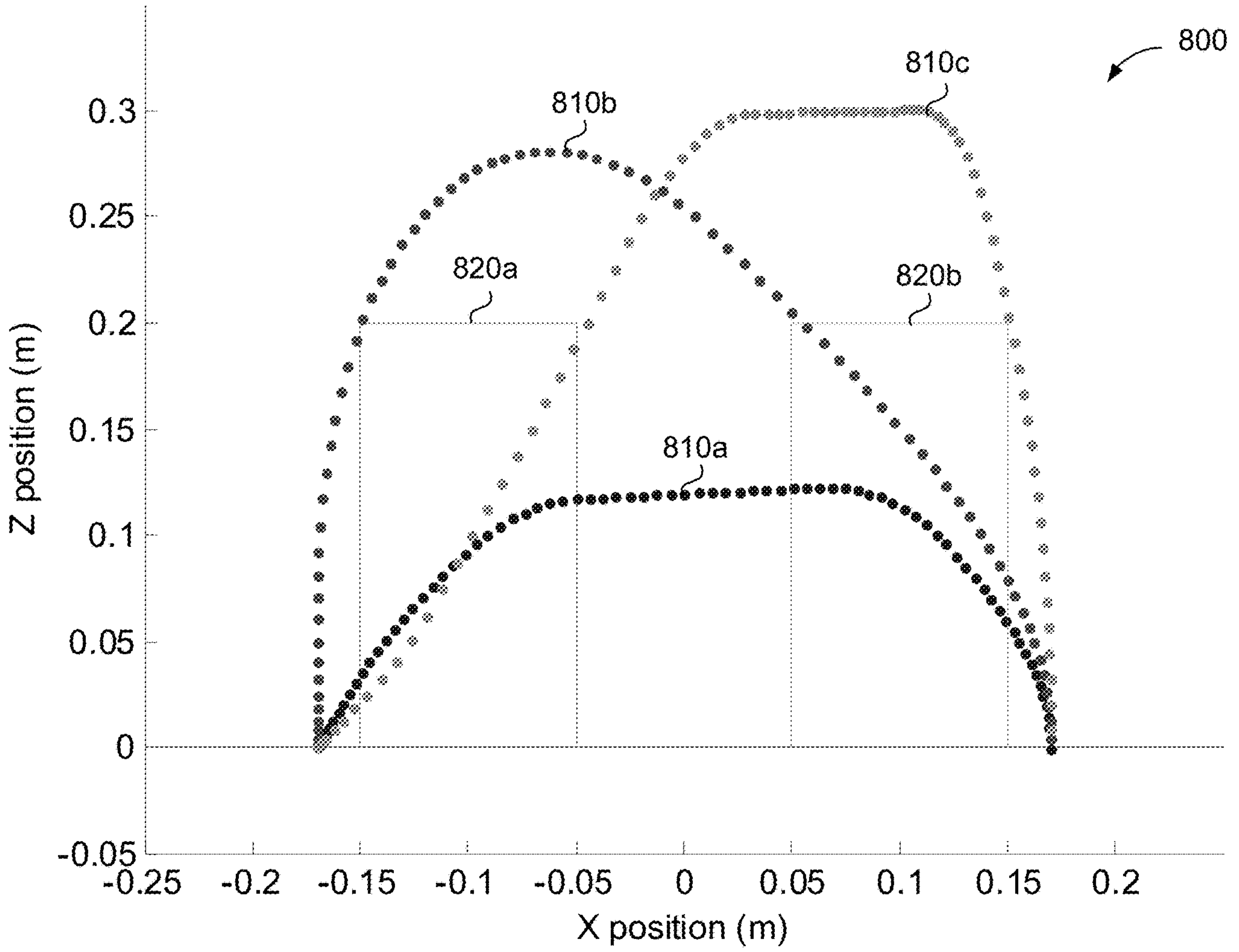

800
810c
810b
820a
820b
810a
Z position (m)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
X position (m)
-0.25
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2

FIG. 8

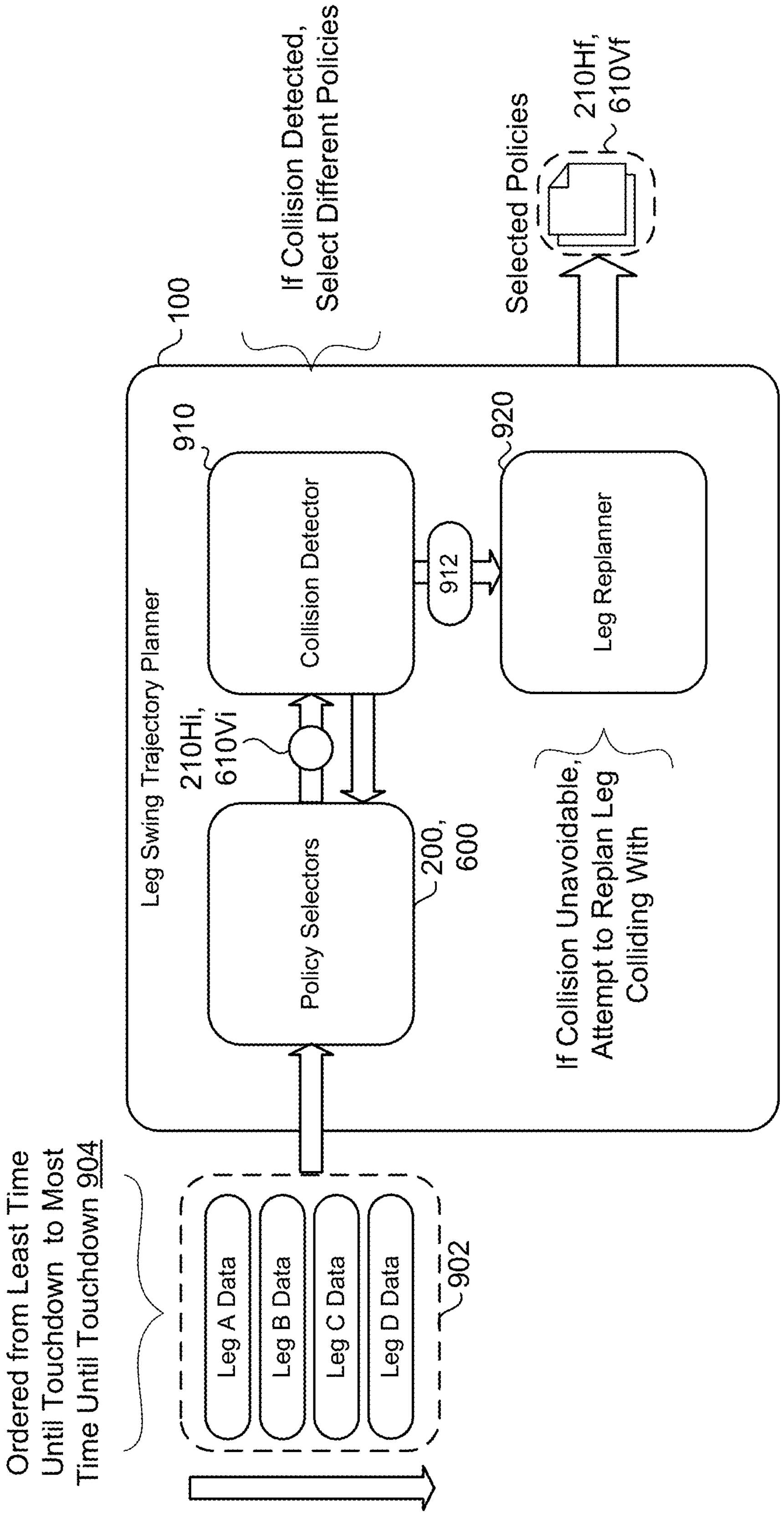

Ordered from Least Time Until Touchdown to Most Time Until Touchdown 904
Leg A Data
Leg B Data
Leg C Data
Leg D Data
902
100
Leg Swing Trajectory Planner
Policy Selectors
200, 600
210Hi, 610Vi
Collision Detector
910
912
Leg Replanner
920
If Collision Detected, Select Different Policies
If Collision Unavoidable, Attempt to Replan Leg Colliding With
Selected Policies
210Hf, 610Vf

FIG. 9

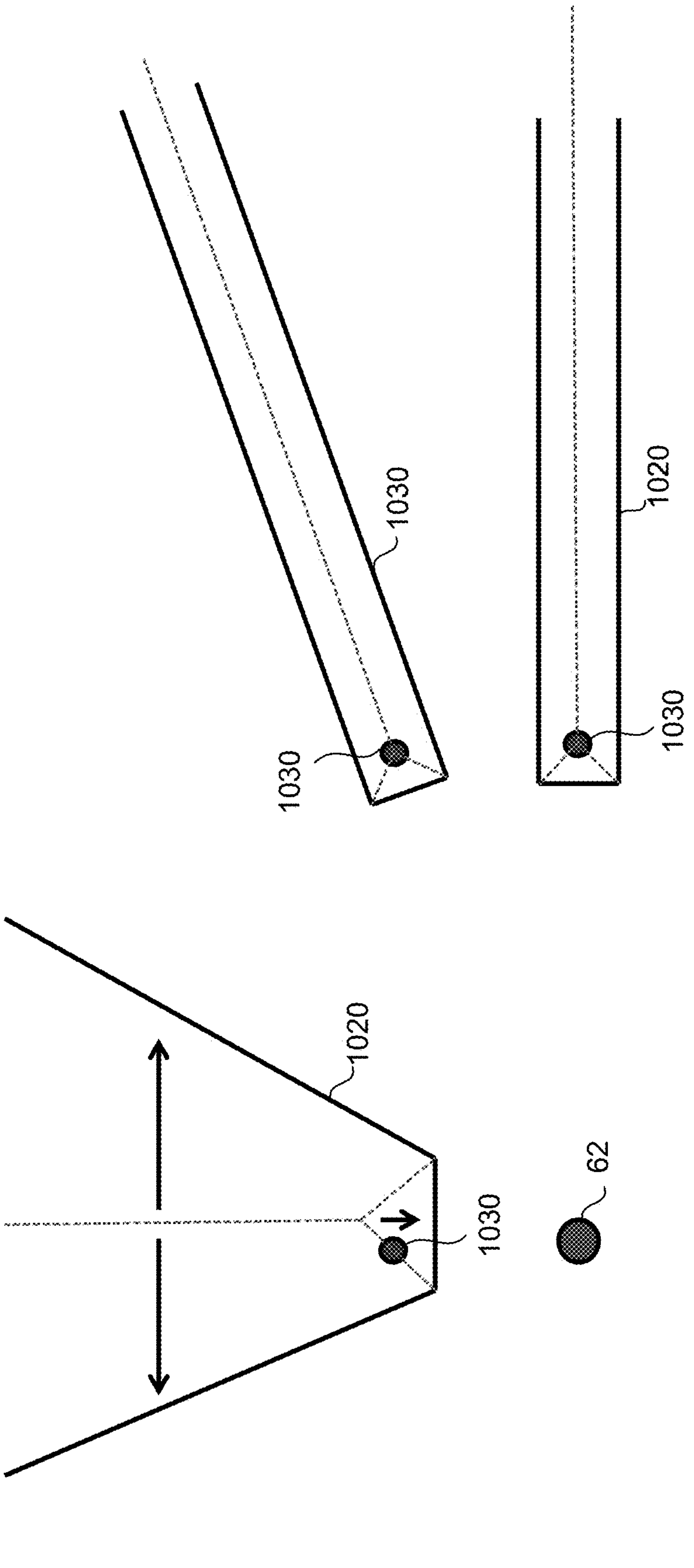


FIG. 10

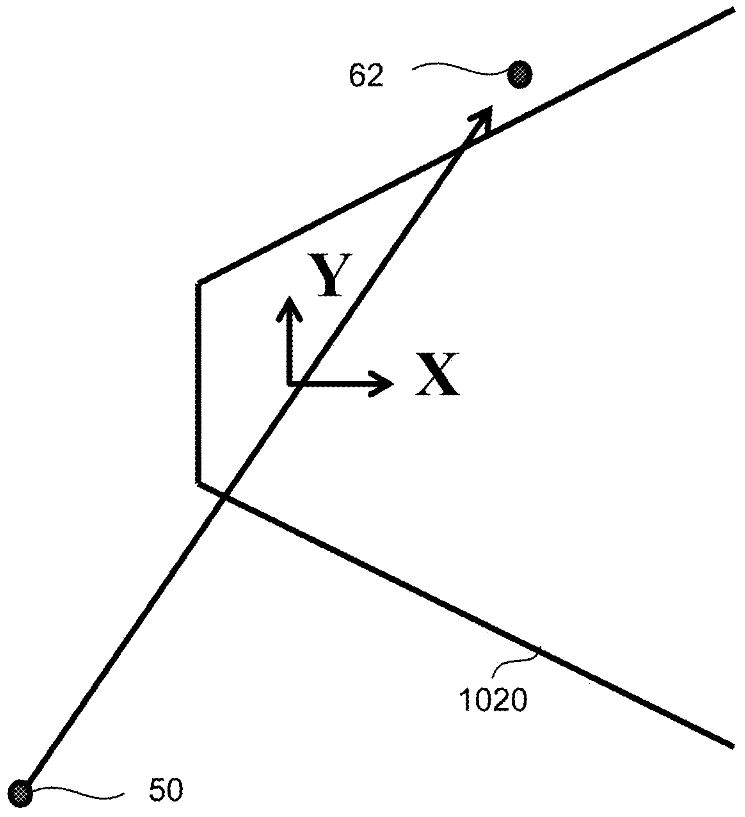


FIG. 11A

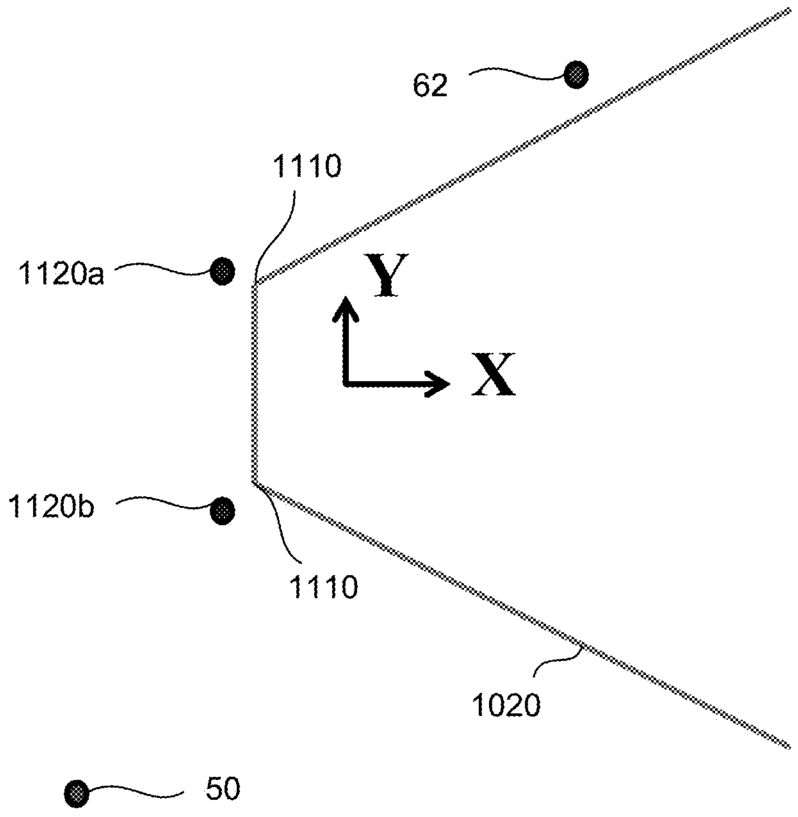


FIG. 11B

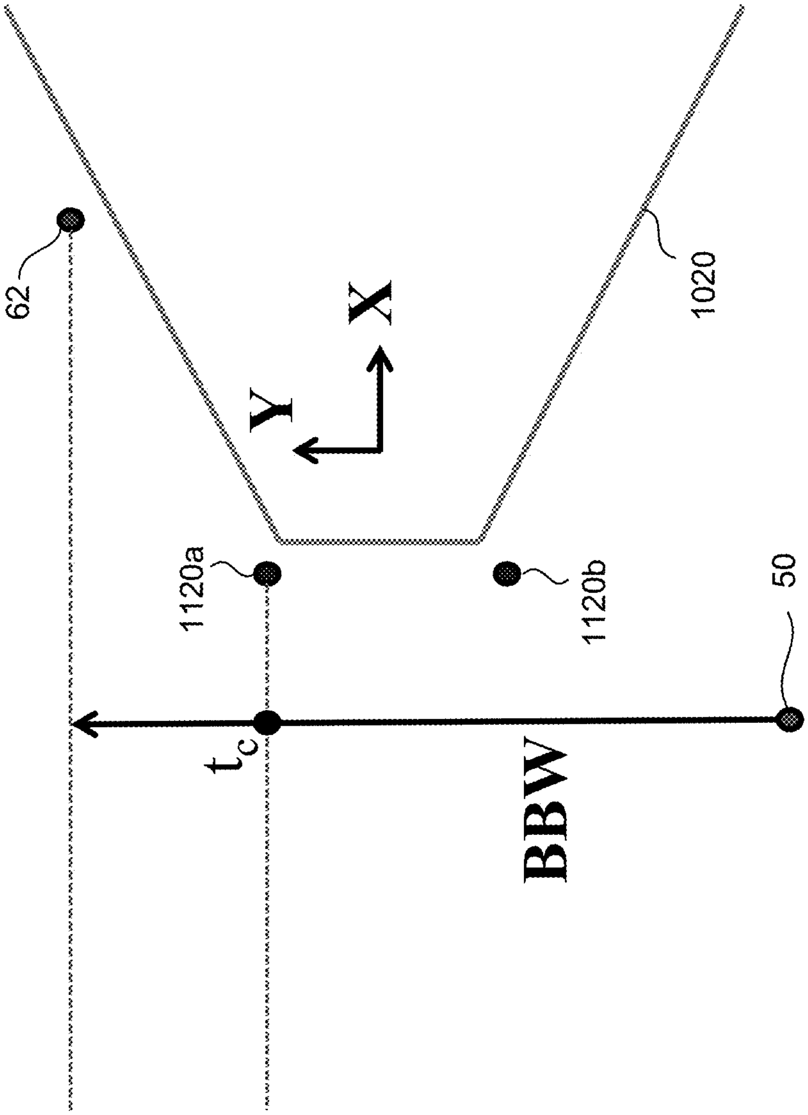


FIG. 11C

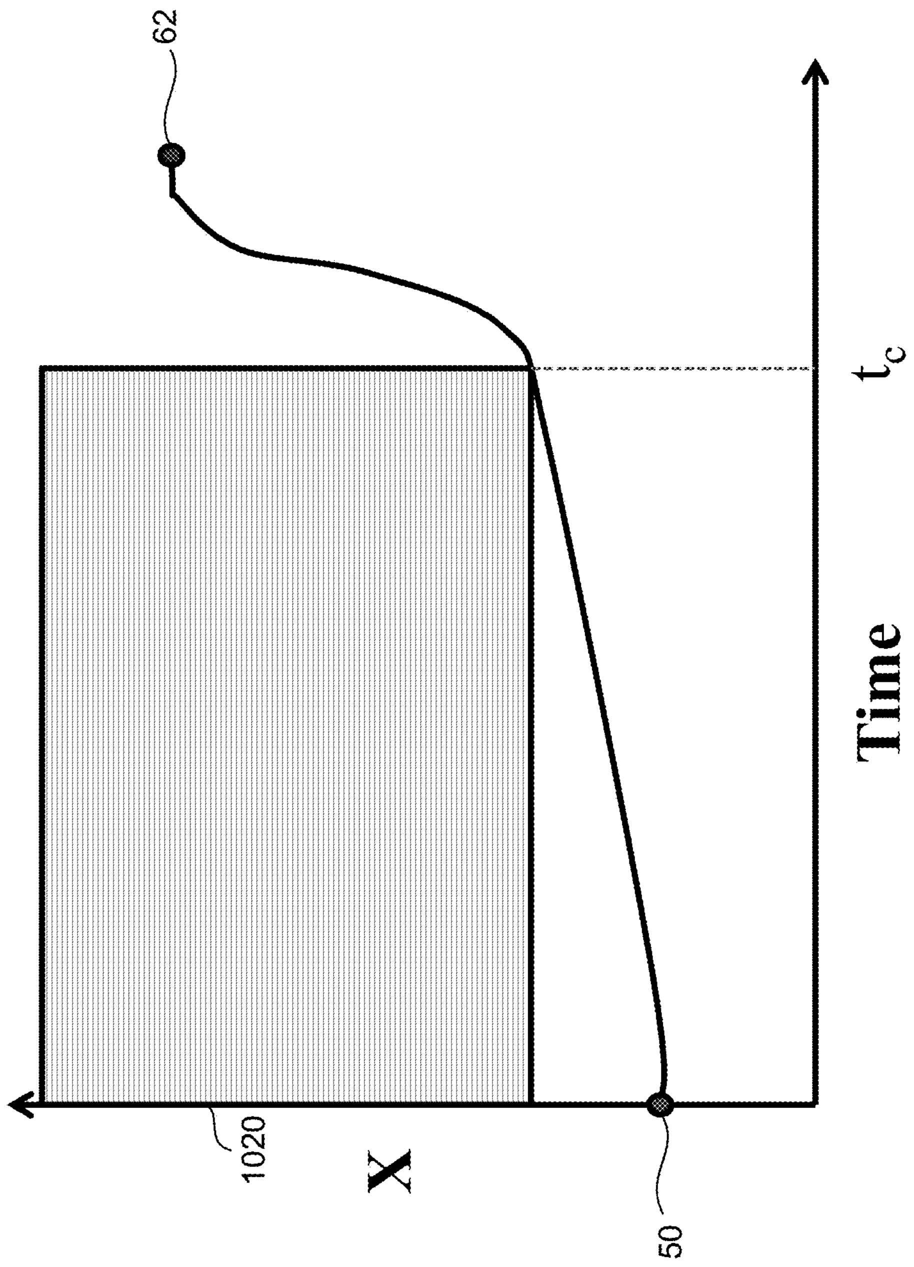


FIG. 12

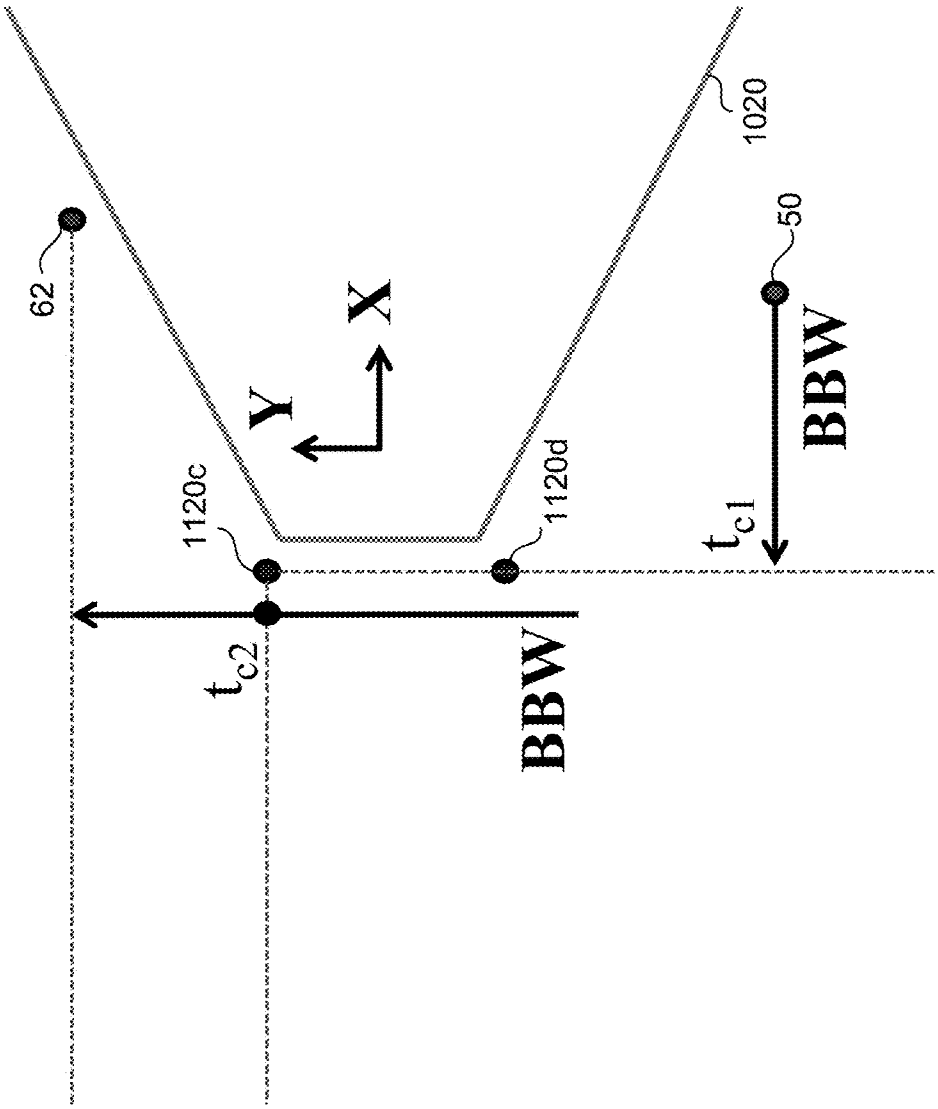


FIG. 13

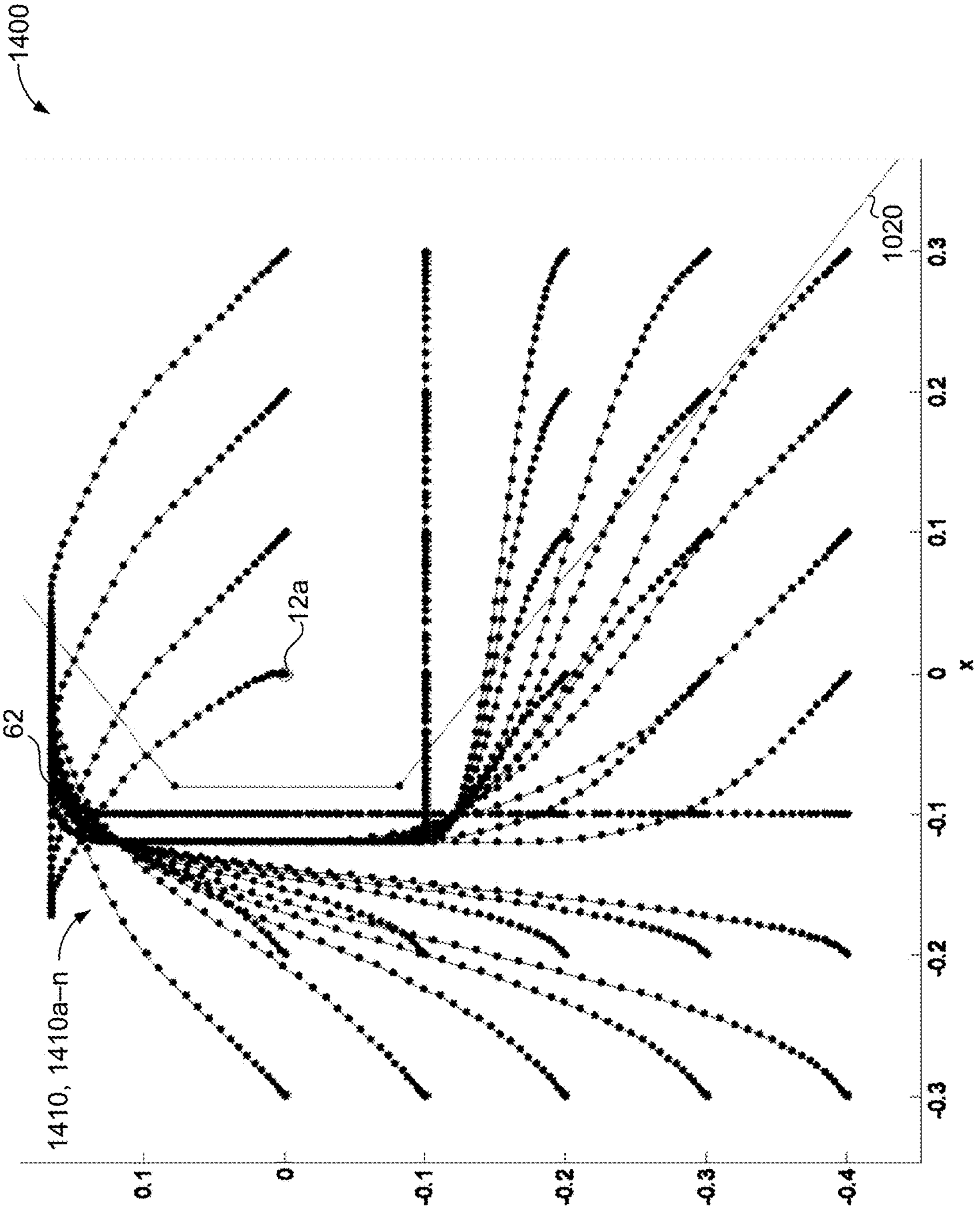


FIG. 14

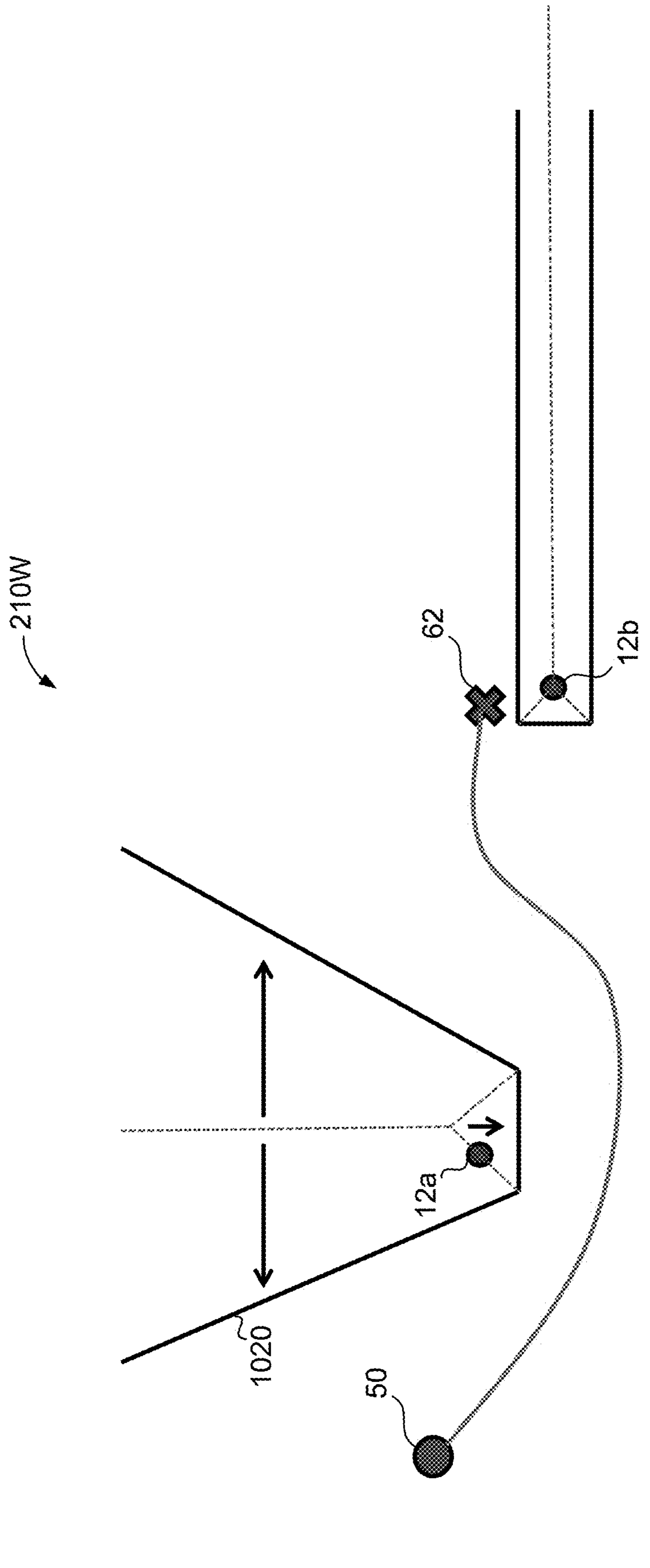


FIG. 15

1600

Trip Type	Response
Normal Trip	Stop forward motion; Elevate foot
Recent normal trip	Elevate foot
Knee trip	Special XY policy
Self-collision (crossed)	Special XY policy
Self-collision (uncrossed)	Special XY policy

FIG. 16

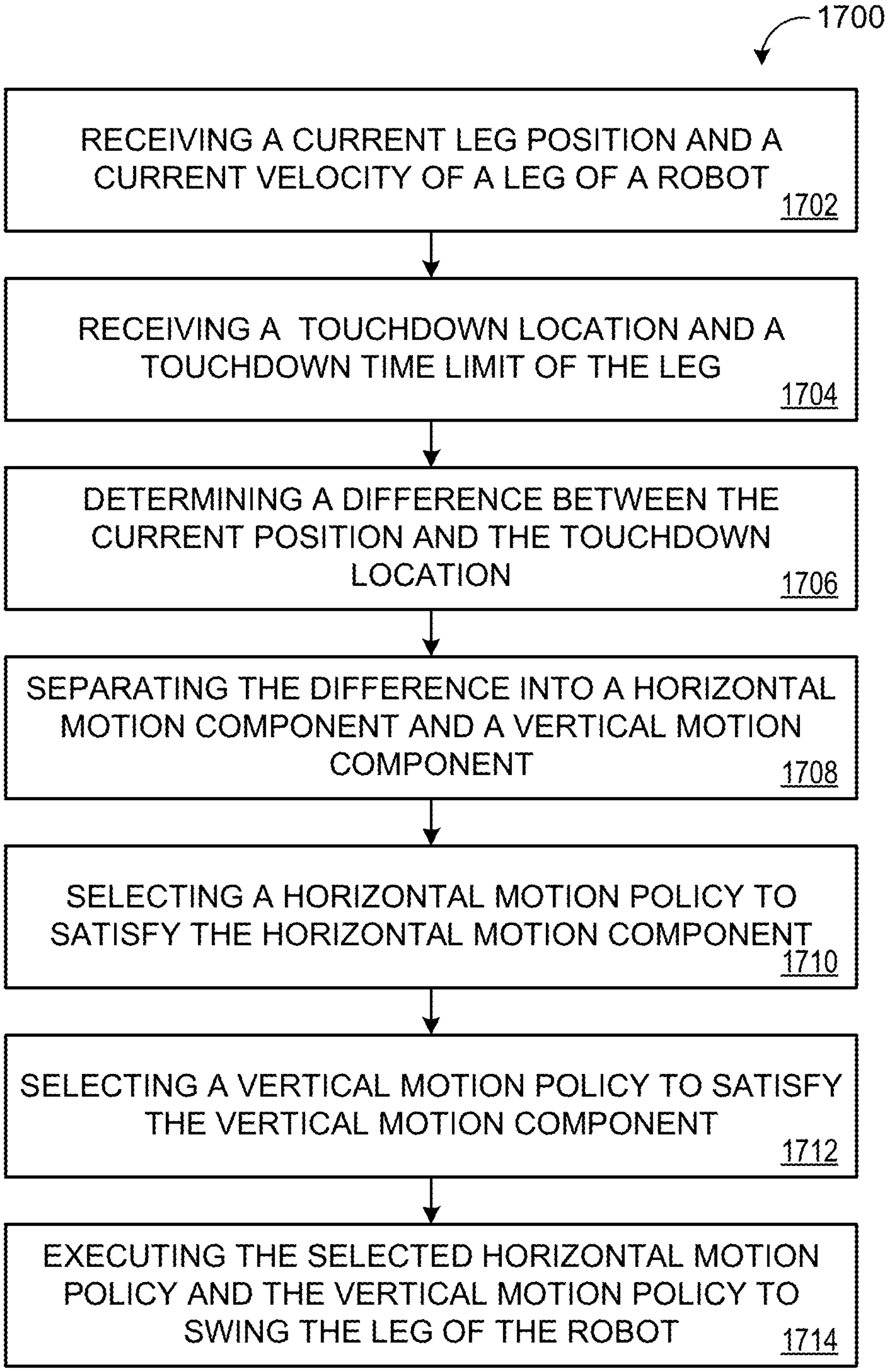

1700
RECEIVING A CURRENT LEG POSITION AND A CURRENT VELOCITY OF A LEG OF A ROBOT
1702
RECEIVING A TOUCHDOWN LOCATION AND A TOUCHDOWN TIME LIMIT OF THE LEG
1704
DETERMINING A DIFFERENCE BETWEEN THE CURRENT POSITION AND THE TOUCHDOWN LOCATION
1706
SEPARATING THE DIFFERENCE INTO A HORIZONTAL MOTION COMPONENT AND A VERTICAL MOTION COMPONENT
1708
SELECTING A HORIZONTAL MOTION POLICY TO SATISFY THE HORIZONTAL MOTION COMPONENT
1710
SELECTING A VERTICAL MOTION POLICY TO SATISFY THE VERTICAL MOTION COMPONENT
1712
EXECUTING THE SELECTED HORIZONTAL MOTION POLICY AND THE VERTICAL MOTION POLICY TO SWING THE LEG OF THE ROBOT
1714

FIG. 17

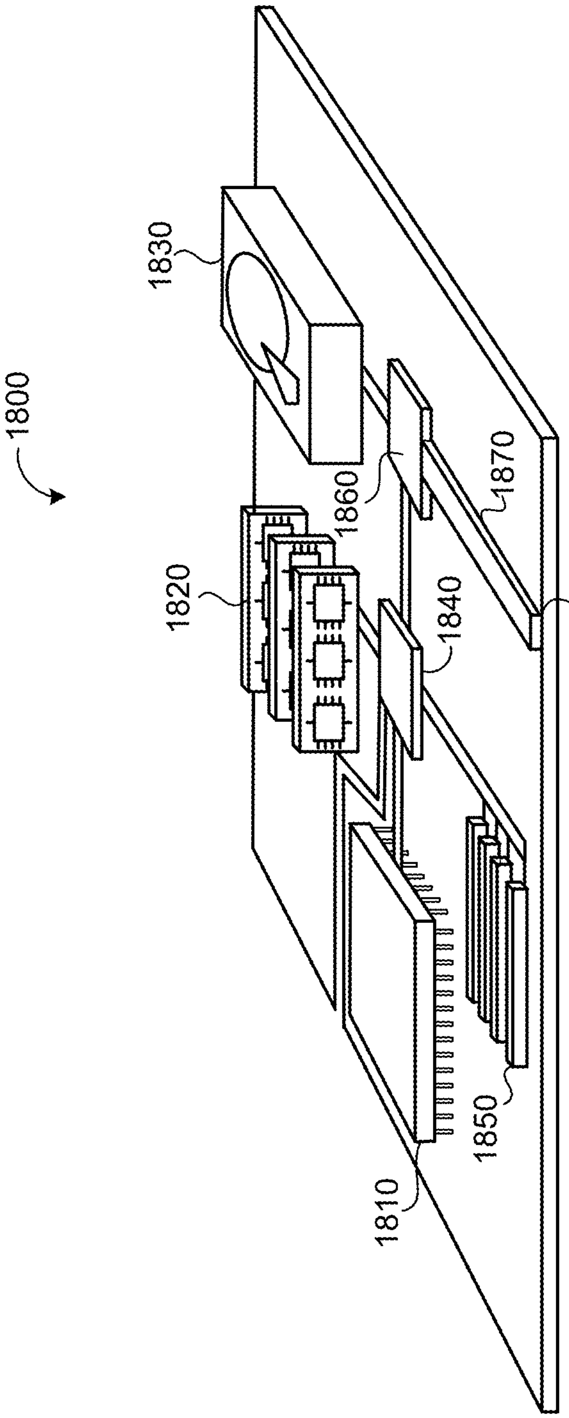


FIG. 18

LEG SWING TRAJECTORIES

CROSS REFERENCE TO RELATED APPLICATION

[0001] This U.S. patent application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application 62/883,502, filed on Aug. 6, 2019, which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] This disclosure relates to leg swing trajectories of a robot.

BACKGROUND

[0003] Robotic devices are increasingly being used in constrained or otherwise restricted environments to perform a variety of tasks or functions. These robotic devices often need to efficiently navigate through these constrained environments without stepping on or bumping into obstacles. As these robotic devices become more prevalent, there is a need for real-time navigation and step planning that avoids contact with obstacles while maintaining balance and speed.

SUMMARY

[0004] One aspect of the disclosure provides a method of planning a swing trajectory for a leg of a robot. The method includes receiving, at data processing hardware of a robot, an initial position of a leg of the robot and an initial velocity of the leg of the robot. The method also includes receiving, at the data processing hardware, a touchdown location for the leg and a touchdown target time for the leg. The touchdown target time represents an amount of time until the leg of the robot should touchdown at the touchdown location. The method also includes determining, by the data processing hardware, a difference between the initial position of the leg and the touchdown location and separating, by the data processing hardware, the difference between the initial position of the leg and the touchdown location into a horizontal motion component and a vertical motion component. The method also includes selecting, by the data processing hardware, a horizontal motion policy from a set of horizontal motion policies to satisfy the horizontal motion component. Each horizontal motion policy produces a horizontal trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg. The method also includes selecting, by the data processing hardware, a vertical motion policy from a set of vertical motion policies to satisfy the vertical motion component. Each vertical motion policy produces a vertical trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg. The method also includes executing, by the data processing hardware, the selected horizontal motion policy and the selected vertical motion policy to swing the leg of the robot from the initial position to the touchdown location at the touchdown target time.

[0005] Implementations of the disclosure may include one or more of the following optional features. In some implementations, the method includes determining, by the data processing hardware, a most aggressive vertical motion policy of the set of vertical motion policies. The most aggressive vertical policy maximizes vertical acceleration of the leg within a vertical acceleration limit of the leg and maximizes vertical velocity of the leg within a vertical velocity limit of the leg. Selecting the horizontal motion policy from the set of horizontal motion policies, in some examples, includes evaluating each horizontal motion policy of the set of horizontal motion policies with the most aggressive vertical motion policy. Optionally, selecting the horizontal motion policy from the set of horizontal motion policies includes assigning each horizontal motion policy of the set of horizontal motion policies a tier from a plurality of tiers. Each tier is associated with an amount of preference for selecting the respective tier and each tier includes a tiebreaking parameter. The tiebreaking parameter is associated with each horizontal motion policy of the set of horizontal motion policies. Selecting the horizontal motion policy from the set of horizontal motion policies may also include selecting the horizontal motion policy from the set of horizontal motion policies based on the assigned tiers and the tiebreaking parameters.

[0006] The tiebreaking parameter, in some implementations, includes a total undesirability based on a sum of a horizontal undesirability and a vertical undesirability. Selecting the vertical motion policy from the set of vertical motion policies may occur after selecting the horizontal motion policy from the set of horizontal motion policies. In some examples, selecting the vertical motion policy from the set of vertical motion policies includes selecting the vertical motion policy from the set of vertical motion policies associated with a minimum acceleration and a minimum velocity that satisfies the vertical motion component.

[0007] The method, optionally, includes receiving, at the data processing hardware, an indication of a trip by the robot. In response to receiving the indication of the trip by the robot, the method may include selecting, by the data processing hardware, one of a horizontal motion policy from a second set of horizontal motion policies or a vertical motion policy from a second set of vertical motion policies. The second set of horizontal motion policies are associated with tripping and the second set of vertical motion policies are also associated with tripping. Selecting the horizontal motion policy from the set of horizontal motion policies may include evaluating each horizontal motion policy of the set of horizontal motion policies with a simple analysis and evaluating a sub-set of the set of horizontal motion policies with a detailed analysis based on the simple analysis.

[0008] In some implementations, the method further includes receiving, at the data processing hardware, the touchdown target time for each of a plurality of legs of the robot, determining, at the data processing hardware, a touchdown order of the legs based on the touchdown target time for each of the plurality of legs of the robot, and selecting, by the data processing hardware, the horizontal motion policy and the vertical motion policy for each leg in a planning order based on the touchdown order. Optionally, each vertical motion policy of the set of vertical motion policies includes a maximum velocity, a maximum acceleration, and a swing height. At least one horizontal motion policy of the set of horizontal motion policies may include a lateral motion policy and a longitudinal motion policy.

[0009] Another aspect of the disclosure provides a robot that includes a body and legs coupled to the body and configured to maneuver the robot about an environment. The robot also includes data processing hardware in communication with the legs 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 an initial position of a leg of the robot and an initial velocity of the leg of the robot. The operations also include receiving, at the data processing hardware, a touchdown location for the leg and a touchdown target time for the leg. The touchdown target time represents an amount of time until the leg of the robot should touchdown at the touchdown location. The operations also include determining a difference between the initial position of the leg and the touchdown location and separating the difference between the initial position of the leg and the touchdown location into a horizontal motion component and a vertical motion component. The operations also include selecting a horizontal motion policy from a set of horizontal motion policies to satisfy the horizontal motion component. Each horizontal motion policy produces a horizontal trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg. The operations also include selecting a vertical motion policy from a set of vertical motion policies to satisfy the vertical motion component. Each vertical motion policy produces a vertical trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg. The operations also include executing the selected horizontal motion policy and the selected vertical motion policy to swing the leg of the robot from the initial position to the touchdown location at the touchdown target time.

[0010] Implementations of the disclosure may include one or more of the following optional features. In some implementations, the operations include determining a most aggressive vertical motion policy of the set of vertical motion policies. The most aggressive vertical policy maximizes vertical acceleration of the leg within a vertical acceleration limit of the leg and maximizes vertical velocity of the leg within a vertical velocity limit of the leg. Selecting the horizontal motion policy from the set of horizontal motion policies, in some examples, includes evaluating each horizontal motion policy of the set of horizontal motion policies with the most aggressive vertical motion policy. Optionally, selecting the horizontal motion policy from the set of horizontal motion policies includes assigning each horizontal motion policy of the set of horizontal motion policies a tier from a plurality of tiers. Each tier is associated with an amount of preference for selecting the respective tier and each tier includes a tiebreaking parameter. The tiebreaking parameter is associated with each horizontal motion policy of the set of horizontal motion policies. Selecting the horizontal motion policy from the set of horizontal motion policies may also include selecting the horizontal motion policy from the set of horizontal motion policies based on the assigned tiers and the tiebreaking parameters.

[0011] The tiebreaking parameter, in some implementations, includes a total undesirability based on a sum of a horizontal undesirability and a vertical undesirability. Selecting the vertical motion policy from the set of vertical motion policies may occur after selecting the horizontal motion policy from the set of horizontal motion policies. In some examples, selecting the vertical motion policy from the set of vertical motion policies includes selecting the vertical motion policy from the set of vertical motion policies associated with a minimum acceleration and a minimum velocity that satisfies the vertical motion component.

[0012] The operations, optionally, include receiving an indication of a trip by the robot. In response to receiving the indication of the trip by the robot, the operations may include selecting one of a horizontal motion policy from a second set of horizontal motion policies or a vertical motion policy from a second set of vertical motion policies. The second set of horizontal motion policies are associated with tripping and the second set of vertical motion policies are also associated with tripping. Selecting the horizontal motion policy from the set of horizontal motion policies may include evaluating each horizontal motion policy of the set of horizontal motion policies with a simple analysis and evaluating a sub-set of the set of horizontal motion policies with a detailed analysis based on the simple analysis.

[0013] In some implementations, the operations further include receiving the touchdown target time for each of a plurality of legs of the robot, determining a touchdown order of the legs based on the touchdown target time for each of the plurality of legs of the robot, and selecting the horizontal motion policy and the vertical motion policy for each leg in a planning order based on the touchdown order. Optionally, each vertical motion policy of the set of vertical motion policies includes a maximum velocity, a maximum acceleration, and a swing height. At least one horizontal motion policy of the set of horizontal motion policies may include a lateral motion policy and a longitudinal motion policy.

DESCRIPTION OF DRAWINGS

[0014] FIG. **1** is a schematic view of an example robot executing a swing trajectory planner for planning a swing trajectory of a leg of the robot.

[0015] FIG. **2** is a schematic view of an example horizontal motion policy selector of the robot of FIG. **1**.

[0016] FIG. **3** is an example table of policy tiers and tiebreakers.

[0017] FIG. **4** is an example trajectory plot of multiple different horizontal motion policies.

[0018] FIGS. **5**A and **5**B are example plots of two trajectories categorized as Cliff Scraping.

[0019] FIG. **6** is a schematic view of an example vertical motion policy selector of the robot of FIG. **1**.

[0020] FIG. **7** is an example plot of multiple vertical trajectories with varying starting positions and velocities.

[0021] FIG. **8** is an example plot of multiple different policies and the interaction with obstacles.

[0022] FIG. **9** is a schematic view of example components of the robot of FIG. **1** that include a collision detector and a leg replanner.

[0023] FIG. **10** is a schematic view of example keep-out areas of other legs of the robot.

[0024] FIGS. **11A-11C** are schematic views of an example Swing Around policy for swinging around another leg of the robot.

[0025] FIG. **12** is a schematic view of an example horizontal trajectory of the Swing Around policy.

[0026] FIG. **13** is a schematic view of another example horizontal trajectory of the Swing Around policy.

[0027] FIG. **14** is an example plot of multiple Swing Around trajectories starting from various starting location.

[0028] FIG. **15** is a schematic view of an example Wiggle policy for maneuvering around multiple other legs of the robot.

[0029] FIG. **16** is an example table of types of trips and appropriate policy responses.

[0030] FIG. **17** is a flowchart of an example arrangement of operations for a method of planning a swing trajectory for a leg of a robot.

[0031] FIG. **18** is a schematic view of an example computing device that may be used to implement the systems and methods described herein.

[0032] Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0033] As legged robotic devices (also referred to as "robots") become more prevalent, there is an increasing need for the robots to navigate environments that are constrained in a number of ways. For example, a robot may need to traverse a cluttered room with large and small objects littered around on the floor. Or, as another example, a robot may need to negotiate a staircase. Typically, navigating these sort of environments has been a slow and arduous process that results in the legged robot frequently stopping, colliding with objects, and/or becoming unbalanced. Implementations herein are directed toward systems and methods for leg swing trajectory planning for generating leg swing trajectories in real-time, thus helping a legged robotic device to navigate a constrained environment quickly and efficiently while maintaining smoothness and balance.

[0034] Referring to FIG. **1**, a robot or robotic device **10** includes a body **11** and two or more legs **12**. The robot **10** is configured to execute a swing leg trajectory planner **100** for enabling the robot **10** to navigate a constrained environment **8**. Each leg **12** is coupled to the body **11** and may have an upper portion **14** and a lower portion **16** separated by a leg joint **18**. The lower portion **16** of each leg **12** ends in a foot **19**. The foot **19** of each leg is optional and the terminal end of the lower portion of one or more of the leg **12** may be coupled to a wheel or the distal end of each leg **12** may directly contact the a ground surface **9**. The robot **10** has a vertical gravitational axis Vg 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 **10** sums to zero. The robot **10** further has a pose P based on the CM relative to the vertical gravitational axis Vg (i.e., the fixed reference frame with respect to gravity) to define a particular attitude or stance assumed by the robot **10**. The attitude of the robot **10** can be defined by an orientation or an angular position of the robot **10** in space. Movement by the legs **12** relative to the body **11** alters the pose P of the robot **10** (i.e., the combination of the position of the CM of the robot and the attitude or orientation of the robot **10**).

[0035] In some implementations, the robot **10** further includes one or more appendages, such as an articulated arm **20** disposed on the body **11** and configured to move relative to the body **11**. The articulated arm **20** may have five-degrees or more of freedom. Moreover, the articulated arm **20** may be interchangeably referred to as a manipulator arm or simply an appendage. In the example shown, the articulated arm **20** includes two portions **22**, **24** rotatable relative to one another and also the body **11**; however, the articulated arm **20** may include more or less portions without departing from the scope of the present disclosure. The first portion **22** may be separated from second portion **24** by an articulated arm joint **26**. An end effector **28**, which may be interchangeably referred to as a manipulator head **28**, may be coupled to a distal end of the second portion **24** of the articulated arm **20** and may include one or more actuators **29** for gripping/grasping objects.

[0036] The robot **10** also includes a vision system **30** with at least one imaging sensor or camera **31**, each sensor or camera **31** capturing image data or sensor data **17** of the environment **8** surrounding the robot **10** with an angle of view **32** and within a field of view **34**. The vision system **30** may be configured to move the field of view **34** by adjusting the angle of view **32** or by panning and/or tilting (either independently or via the robot **10**) the camera **31** to move the field of view **34** in any direction. Alternatively, the vision system **30** may include multiple sensors or cameras **31** such that the vision system **30** captures a generally 360-degree field of view around the robot **10**. The camera(s) **31** of the vision system **30**, in some implementations, include one or more stereo cameras (e.g., one or more RGBD stereo cameras). In other examples, the vision system **30** includes one or more radar sensors such as a scanning light-detection and ranging (LIDAR) sensor, or a scanning laser-detection and ranging (LADAR) sensor, a light scanner, a time-of-flight sensor, or any other three-dimensional (3D) volumetric image sensor (or any such combination of sensors). The vision system **30** provides image data or sensor data **17** derived from image data captured by the cameras or sensors **31** to data processing hardware **36** of the robot **10**. The data processing hardware **36** is in digital communication with memory hardware **38** and, in some implementations, may be a remote system. The remote system may be a single computer, multiple computers, or a distributed system (e.g., a cloud environment) having scalable/elastic computing resources and/or storage resources.

[0037] The robot **10** executes the swing leg trajectory planner **100** on the data processing hardware **36**. The leg swing trajectory planner **100** receives an initial or current position or location **50** and an initial or current velocity **52** of a leg **12** of the robot **10** (e.g., from sensors monitoring the corresponding leg **12**). The swing leg trajectory planner **100** also receives touchdown data **60** for the leg **12**. The touchdown data **60** includes a touchdown location **62** and a touchdown target time **64**. The touchdown location **62** represents a location on the ground surface **9** that the leg should contact in order to complete a step. The touchdown target time **64** represents an amount of time until the leg **12** of the robot **10** should touchdown at the touchdown location **62**. That is, the touchdown target time **64** represents a point in time (or window of time) that the leg **12** should contact the ground surface **9** at the touchdown location **62** to maintain gait, balance, timing, etc.

[0038] The leg swing trajectory planner **100**, in some implementations, determines a difference between the initial or current position of the leg **12** and the touchdown location **62**. That is, the leg swing trajectory planner **100** determines how far the leg **12** must travel from its initial or current location **50** to arrive at the touchdown location **62**. In some implementations, the planner **100** only uses an initial location **50** (e.g., a takeoff location of the foot) and does not rely on real-time positional measurements of the leg during swinging. In other implementations, the planner **100** continually receives the current location **50** of the leg (e.g., via measurement). As used herein, initial location and current location are interchangeable. Similarly, initial velocity **52** and current velocity **52** are also interchangeable. The leg swing trajectory planner **100** decouples or separates the difference between the current position of the leg **12** and the touchdown location **62** into a horizontal motion component and a vertical motion component. Put another way, the leg swing trajectory planner **100** separates the determination of the leg swing trajectory into the horizontal movement (e.g., horizontal motion component) required by the leg **12** and the vertical movement (e.g., vertical motion component) required by the leg **12** in order to reach the touchdown location **62** by the touchdown target time **64**. Based at least in part on this difference, a horizontal motion policy selector **200** may select a horizontal motion policy **210** from a set of horizontal motion policies (e.g., from a horizontal motion policy datastore **212**) and a vertical motion policy selector **600** may select a vertical motion policy **610** from a set of vertical motion policies **610** (e.g., from a vertical motion policy datastore **612**). The selected horizontal motion policy **210** and the selected vertical motion policy **610** collectively provide a set of selected policies **130** to form a swing trajectory **132** that, when executed by the data processing hardware **36** of the robot **10**, cause the leg **12** of the robot **10** to swing from the current location **50** to the touchdown location **62** within the touchdown target time **64**. Each policy **210**, **610** selected by the respective selectors **200**, **600** of the planner **100** executes on the data processing hardware **36** of the robot **10** to produce a swing trajectory of the leg **12** as a function of the current position **50** and velocity **52** of the leg and the touchdown location **62** and touchdown target time **64**.

[0039] In some implementations, at least a portion of the swing leg trajectory planner **100** executes on a remote device in communication with the robot **10**. For instance, the horizontal motion policy selector **200** and/or the vertical motion policy selector **600** may execute on a remote device to select the respective policies **210**, **610** (e.g., selected set of policies **130**) and a control system executing on the robot **10** may receive and execute the set of policies **130** to swing the leg **12** of the robot **10** from the current position **50** to the touchdown location **62** at the touchdown target time **64**. Optionally, the entire swing trajectory planner **100** may execute on a remote device and the remote device may control/instruct the robot **10** to swing the legs **12** based on the selected set of policies **130**.

[0040] Referring now to FIG. **2**, in some implementations, the horizontal motion policy selector **200** includes a simple analyzer **220**, a detailed analyzer **230**, and a tier evaluator **240**. The simple analyzer **220** may receive a most aggressive vertical motion policy **610**A and each horizontal motion policy **210**, **210***a-n* of the set of horizontal motion policies stored in datastore **212**. In some examples, the simple analyzer **220** quickly analyzes the most aggressive vertical motion policy **610**A with each of the horizontal motion policies **210**. This is because generally if the most aggressive vertical motion policy **610**A fails, all vertical motion policies **610** will fail. The most aggressive vertical motion policy **610** uses the greatest acceleration and velocity within constraints, and therefore when the policy **610**A fails to make the touchdown target time **64** or avoid an obstacle, likely no other policy **610** will either. The most aggressive vertical motion policy **610**A is defined as a vertical motion policy **610** that instructs the robot **10** to keep the velocity, acceleration, and swing height of the leg **12** as high as possible within any applicable constraints **232**. For example, the most aggressive vertical motion policy **610**A may nominally accelerate the leg **12** upward (i.e., vertical acceleration) until an upward or vertical velocity limit is hit, then coast upwards at an upward or vertical constant velocity (i.e., at the upward velocity limit). The policy **610**A may then accelerate downward until the upward movement of the leg **12** is stopped at a desired swing height (i.e., the maximum swing height). The policy **610**A may remain at the desired swing height for as long as possible while still arriving at the touchdown location **62** on time. The most aggressive vertical motion policy **610**A may accelerate downward until a downward velocity limit is hit (which may be the same or different than the upward velocity limit), then coast downward at a constant downward velocity (i.e., the downward velocity limit) until the leg **12** achieves touchdown at the touchdown location **62**.

[0041] When analyzing each horizontal motion policy **210** with the most aggressive vertical motion policy **610**A, the simple analyzer **220** may quickly eliminate unsatisfactory horizontal motion policies **210** from the set of horizontal motion policies **210***a-n*. Specifically, eliminating unsatisfactory horizontal motion policies **210** refers to eliminating these policies **210** as candidates for selection by the horizontal motion policy selector **200**. For example, the simple analyzer **220** may evaluate each horizontal motion policy **210** under best case scenarios for the respective policy **210** and measure an amount of total undesirability. Total undesirability may be a sum of horizontal undesirability and vertical undesirability. Horizontal undesirability and vertical undesirability are a measure of undesirable effects from the selected policy. For example, the higher a peak acceleration (i.e., vertical peak acceleration and horizontal peak acceleration) of a policy **210**, **610**, the greater the undesirability of that policy. Undesirability may be measured based on other characteristics of the policies **610**, **210** as well (e.g., peak velocity, touchdown speed, touchdown time, swing height, margin, etc.). Optionally, some policies may have the associated undesirability modified. For example, a preferred policy (e.g., a Cubic policy, as discussed in more detail below) may be weighed by a modifier to reduce overall undesirability. Other, less desirable policies may have a modifier that increases undesirability.

[0042] After analyzing each horizontal motion policy **210** with the most aggressive vertical motion policy **610**A, the simple analyzer **220** sends a set (i.e., a sub-set of the original set of all horizontal motion policies **610**) of the horizontal motion policies **210**S that passed the simple analysis to the detailed analyzer **230**. For example, policies **210**S that have a total undesirability under a threshold amount may be sent to the detailed analyzer. Optionally, whether the simple analyzer **220** passes a respective policy **210** to the detailed analyzer (i.e., whether the policy **210** is included in set **210**S) is dependent upon other policies **210**. For example, when the simple analyzer **220** determines that a respective policy **210** cannot outperform an already analyzed policy **210**, the simple analyzer **220** may decline to pass the respective policy **210** to the detailed analyzer **230**. In some implementations, the simple analyzer **220** analyzes the policies **210** in an order designed to analyze the most likely to be best policies **210** first to optimize the evaluation policy by potentially reducing the number of policies **210** that are evaluated. The order may be static or dynamic based on terrain or other constraints.

[0043] With continued reference to FIG. **2**, the detailed analyzer **230** performs a more thorough analysis than the simple analyzer **220**. In some implementations, the detailed analyzer **230** assigns each policy **210** of the set of policies **210**S a tier **300**, **300***a-n* (FIG. **3**). Each tier **300**, in some examples, is associated with an amount of preference for selecting the respective tier. That is, each tier has an amount of selection desirability. To assign the tiers **300**, the detailed analyzer **230** performs a number of calculations using, for example, the touchdown location **62**, the touchdown target time **64**, the current position **50**, the current velocity **52**, and any applicable constraints **232** (e.g., maximum acceleration constraints, maximum velocity constraints, obstacle constraints, etc.). The detailed analyzer passes the set of policies **210**S and the assigned tiers **300** to the tier evaluator **240**. The tier evaluator **240** orders the tiers **300** (and subsequently the policies **210** assigned to the tiers **300**) from most desirable to least desirable (i.e., the amount of preference for selecting the tier) and then selects the policy **210**H that is assigned to the most desirable tier **300**. The tier evaluator **240** may determine the order of the tiers **300** statically based on predetermined instructions or dynamically based on the current environment or constraints **232**.

[0044] Referring now to FIG. **3**, each tier **300** may have an associated tiebreaker or tiebreaking parameter **302**, **302***a-n*. The tier evaluator **240** uses the tiebreaker when more than one policy **210** share the most desirable tier **300**. For example, the most desirable tier **300** may be "Success" with a tiebreaker **302** of total undesirability. That is, the most desirable tier **300** may be a tier for policies **210** that cause the foot **19** of the leg **12** of the robot **10** to arrive at the touchdown location **62** at the touchdown target time **64**. When multiple policies **210** are assigned the Success tier **300**, the tier evaluator **240** may select the policy **210** with the lowest total undesirability from among the policies **210** assigned the Success tier **300**. In some implementations, when a specific policy **210** (e.g., a Cubic policy **210** or other preferred policy **210**) is assigned the Success tier **300**, the specific policy **210** may be selected without evaluating any other policies **210**. In this situation, no other policy may be better than the select policy **210** and the overall computation required to select the policy **210** is greatly reduced. In another example, the second most desirable tier **300** may be XY-Success; Z-Impossible. The tier evaluator **240** may assign policies **210** to this tier **300** that successfully arrive at the touchdown location **62** at the touchdown target time **64** in the horizontal dimension (i.e., XY), but there is no vertical motion policy **610** that successfully arrives at the touchdown location **62** at the touchdown target time **64**. For example, the foot may be unable to make it to the desired touchdown height (i.e., the height component of the touchdown location **62**) given current position **50** and/or current velocity **52** and constraints **232**. For this tier **300**, the tiebreaker **302** may be a combination of a severity of any collisions and total undesirability. When, for example, no policies **210** are assigned to the success tier **300** and two or more policies **210** are assigned to the XY-Success; Z-Impossible tier **300**, the tier evaluator **240** may use the tiebreaker **302** to select the policy **210**.

[0045] Referring now to FIG. **4**, horizontal trajectories **410***a-c* are illustrated on a plot **400** with a y-axis representing position (e.g., in meters) and an x-axis representing time (e.g., in seconds). A horizontal trajectory is the distance the leg must travel from the current location to the touchdown location **62** in the horizontal plane (i.e., laterally and/or forward and backward). For example, trajectory **410***a* may represent a Cubic horizontal motion policy **210**, the trajectory **410***b* may represent a BangBangWait (BBW) horizontal motion policy **210**, and the trajectory **410***c* may represent a WaitBangBang (WBB) horizontal motion policy **210**. The Cubic horizontal motion policy **210** follows the path of a cubic polynomial. The BBW horizontal motion policy **210** accelerates as fast as possible (within constraints **232**) to reach the maximum velocity as fast as possible, and then coasts until deceleration is required. The WBB horizontal motion policy **210** is the opposite of the BBW horizontal motion policy **210**, in that the WBB horizontal motion policy coasts at the current velocity **52** for as long as possible and then accelerates as fast as possible to the maximum velocity when required in order to still make the touchdown location **62** by the touchdown target time **64**.

[0046] The detailed analyzer **230** may assign policies **210** to any number of tiers **300**. In some examples, the tiers **300** include Cliff Scraping with a tiebreaker of horizontal margin. For example, the tiers **300** may include Knee-Terrain Collision and Knee Self-Collision with tiebreakers **302** of collision severity, undesirability, and/or miss distance (e.g., how close the leg of the robot is to missing the other leg/obstacle). Optionally, the planner **100**, based on predicted hip positions and planned foot positions, may compute and predict current and future knee positions of the robot **10**. Based on the computed knee position, the system **100** may compare the trajectory of the selected policy and compare it against the terrain near the robot **10**.

[0047] Other tiers **300** may include Terrain Collision with collision severity and/or undesirability as tiebreakers and XY Can't Reach Target (i.e., the leg **12** cannot make it to the touchdown location **62**) with miss distance as the tiebreaker **302**. The miss distance may include hysteresis. Optionally, the detailed analyzer **230** includes a Self-Collision tier **300** with collision severity and/or miss distance as tiebreakers **302**. In some implementations, the detailed analyzer **230** includes a Default tier **300** and a Violates Constraints tier **300**. The Violates Constraints may be a tier **300** for policies that will not be selected. For example, when a policy **210** would violate an acceleration constraint (i.e., a maximum acceleration), the detailed analyzer **230** may assign the policy **210** the Violates Constraints tier **300**. No tiebreaker is needed, as these policies will not be selected. The Default tier **300** may include a single default policy **210** that the tier evaluator **240** selects if all other policies **210** are assigned the Violates Constraints tier. Optionally, the default policy is the BBW horizontal motion policy.

[0048] Referring now to FIG. **5**A, in another example, a trajectory **500***a* may be categorized as Cliff Scraping when the trajectory **500***a* is very near or actually scrapes an obstacle **502** as the trajectory **500***a* of the leg moves from the current position **50** to the touchdown location **62**. A trajectory may be categorized as Cliff Scraping when the obstacle **502** is actually scraped or when a horizontal margin **510** between the leg **12** and the obstacle **502** is less than a threshold distance (even if there is no scraping or collision with the obstacle). For example, the trajectory **500***b* of FIG. **5**B may also be categorized as Cliff Scraping when the horizontal margin **510** is less than the threshold distance. In this scenario, trajectory **500***b* would be selected over trajectory **500***a*, as the tiebreaker (i.e., horizontal margin **510**) is greater for the trajectory **500***b*.

[0049] Referring now to FIG. **6**, in some implementations, after the horizontal motion policy **210**H is selected (FIGS. **2** and **3**), the vertical motion policy selector **600** receives the selected horizontal motion policy **210**H and each vertical motion policy **610**, **610***a-n* from the vertical motion policy datastore **612**. The vertical motion policy selector **600** may organize or categorize the vertical motion policies **610** based on a gentleness of the policy **610** (or, alternatively, an aggressiveness of the policy). For example, the vertical motion policy selector **600** may categorize a vertical motion policy **610** that has a lower peak acceleration as gentler than a policy **610** with a higher peak acceleration. The vertical motion policy selector **600** may include a vertical policy evaluator **620** that evaluates or analyzes the vertical motion policies **610** along with the selected horizontal motion policy **210**H. In some examples, the vertical policy evaluator **620** determines the gentlest vertical motion policy **610** that successfully navigates the foot **19** of the robot **10** to the touchdown location **62** at the touchdown target time **64** with sufficient margin (i.e., the distance between the trajectory and the ground). That is, the vertical policy evaluator **620** may select the vertical motion policy **610**V that is associated with a minimum acceleration and a minimum velocity that satisfies the vertical motion component of the leg swing trajectory. Satisfying the vertical motion component may be defined as arriving at the touchdown location **62** at the touchdown target time **64** with a threshold amount of margin from a collision with obstacles. In some examples, the vertical policy evaluator **620** evaluates the most gentle policy **610** not yet evaluated until a policy **610** is evaluated that satisfies the vertical motion component. Policies **610** after this point need not be evaluated. Alternatively, the vertical policy evaluator evaluates the least gentle policy **610** not yet evaluated until a policy **610** fails to satisfy the vertical motion component. Again, policies **610** after this point need not be evaluated.

[0050] In some examples, the vertical motion policy selector **600** selects special policies based upon unusual circumstances. For example, during a late touchdown (i.e., the robot **10** expected the leg to have achieved touchdown, but the leg has not yet done so), the selector **600** may select a special late touchdown policy that accelerates or decelerates to descend at a fixed velocity until touchdown is achieved. The policy selector **600** may select other special policies (and bypassing the standard selection sequence) when other unusual circumstances occur.

[0051] Thus, by decoupling the horizontal and vertical motion components of the swing leg trajectory and by performing the simple analysis with the most aggressive vertical motion policy **610**A, the system **100** greatly reduces the number of policy combinations that are evaluated. For example, given M horizontal motion policies **210** and N vertical motion policies **610**, a less sophisticated system may perform M×N evaluations, which is computationally expensive. In contrast, implementations herein may evaluate a maximum M+N policies (and generally far fewer) before selecting the ideal horizontal motion policy **210** and vertical motion policy **610**.

[0052] FIG. **7** illustrates a plot **700** of several vertical component swing trajectories **710** from seven different starting positions, each starting position showing five different starting velocities. The y-axis of the plot represents the height (in meters (m)) of the foot **19** of the robot **10**, while the x-axis represents time (in seconds (s)). An obstacle **720** with varying height is also illustrated. Each trajectory **710**, in this example, is set to the maximum height allowed by the constraints **232**. As is apparent from FIG. **7**, some starting locations (e.g., −0.3, −0.2, −0.1 in FIG. **7**) in some terrain situations result in a collision regardless of which vertical motion policy **610** is selected. However, in the given example, if there is sufficient margin between the trajectory **710** and the obstacle **720**, the vertical motion policy selector **600** may select a policy **610** that provides a gentler acceleration and still successfully arrive at the touchdown location **62** (i.e., not collide with the obstacle **720**).

[0053] Referring now to FIG. **8**, a plot **800** of three vertical trajectories **810***a-c* for three different vertical motion policies **610** is illustrated. The y-axis represents height (in meters (m)) of the foot **19** of the robot **10** and the x-axis denotes horizontal position (in meters (m)) of the foot **19** of the robot **10**. Trajectory **810***a* represents a trajectory that follows at least partially a Cubic vertical motion policy **610**, trajectory **810***b* represents a trajectory that at least partially follows a WBB vertical motion policy **610** (i.e., the policy waits for the foot to rise before moving forward), and trajectory **810***c* represents a trajectory that follows at least partially a BBW vertical policy **610** (i.e., the policy starts accelerating the foot forward before attaining significant height). Also illustrated are two different obstacles **820***a*, **820***b*. In this example, the Cubic vertical motion policy trajectory **810***a* fails to pass either obstacle **820***a*, **820***b*. In contrast, the WBB vertical motion policy trajectory **810***b* successfully passes the obstacle **820***a* but collides with the obstacle **820***b*, while the BBW vertical motion policy trajectory **810***c* collides with the obstacle **820***a*, but successfully passes the obstacle **820***b*. Thus, when presented with just the obstacle **820***a*, the vertical motion policy selector **600** may select the WBB vertical motion policy **610**, while when presented with just the obstacle **820***b*, the vertical motion policy selector **600** may select the BBW vertical motion policy **610**. When both obstacles **820***a*, **820***b* are present, the vertical motion policy selector **600** may select none of the vertical motion policies **610** associated with the trajectories **810***a*, **810***b*, **810***c*. The vertical motion policy selector **600** may be constrained by a variable amount of margin (i.e., how close the leg may pass to ab obstacle). Here, the required margin was zero and the trajectories **810***b*, **810***c* brush the corner of the respective obstacle **820***a*, **820***b*.

[0054] Referring now to FIG. **9**, in some implementations, the leg swing trajectory planner **100** plans the leg swing trajectory of the leg **12** of the robot **10** that has the least time remaining until touchdown. That is, the planner **100** plans the leg **12** of the robot **10** that is next to hit the ground, and then plans the second leg that is next to hit the ground after the first leg **12**, and so on. This is advantageous, as the leg **12** with the least amount of time until touchdown has the least amount of freedom to adjust trajectory. That is, legs with more time until touchdown have more freedom to adjust trajectories to avoid collisions with other legs. In some examples, the leg swing trajectory planner **100** determines a touchdown order **904** based on leg data **902** from each leg **12** (e.g., the current position **50**, the current velocity **52**, the touchdown location **62**, the touchdown target time **64**, etc.). Based on the touchdown order, the system **100** may select the policies **210**, **610** for each leg in a planning order based on the touchdown order.

[0055] The leg swing trajectory planner **100** may include a collision detector **910**. The collision detector **910** receives initial selected policies **210**Hi, **610**Vi from the policy selectors **200**, **600** and checks for collisions with previously planned legs. For example, the leg swing trajectory planner may plan leg 'A' first (as it is the next to make touchdown). Afterward, while planning leg 'B' (as, in this example, it is the next to make touchdown after leg 'A'), the collision detector **910** may determine if the selected policies **210**H, **610**V for leg 'B' will cause leg 'B' to collide with leg 'A'. When a collision is detected, the leg swing trajectory planner **100** may attempt to select new policies for the colliding leg (in this example, leg 'B'), as the colliding leg has more time until touchdown, and hence more flexibility regarding policies **210**, **610**. In the event that a collision is unavoidable (i.e., selecting new policies does not alleviate the collision), the collision detector **910**, in some examples, sends a replan signal **912** to leg replanner **920** in order to replan the previously planned leg (i.e., leg 'A') in an attempt to avoid the collision. The leg replanner **920** outputs the final selected policies **210**Hf, **610**Hf which may be the same as the initial selected policies **210**Hi, **610**Vi or different (e.g., due to replanning).

[0056] The leg swing trajectory planner **100**, in some implementations, projects "keep-out" areas around each leg to aid in avoiding self-collisions. Referring now to FIG. **10**, the leg swing trajectory planner may select policies **210**, **610**, that arrive at the touchdown location **62** while avoiding touchdown locations of other legs **1030** and corresponding keep-out areas **1020**.

[0057] Referring now to FIGS. **11**A-C, in some implementations, the horizontal motion policies **210** are further separated into an x-coordinate policy (e.g., a forward/backward or longitudinal motion policy) and a y-coordinate policy (e.g., a lateral motion policy). As illustrated in FIG. **11**A, in some situations, the horizontal motion policy selector **200** may need to plan a leg trajectory that crosses over another leg **12** of the robot **10** (e.g., during a turn or recovering from a trip). That is, the horizontal motion policy selector **200** may need to plan from a current position **50** to a touchdown location **62** that crosses the keep-out area **1020** of another leg **12** of the robot **10** (FIG. **11**A). In such a situation, planning a trajectory directly from the current position **50** to the touchdown location **62** will cross through the keep-out area **1020** and potentially cause a collision with the other leg **12**. Instead, the horizontal motion policy selector **200** may execute a Swing Around policy **210** to maneuver the leg **12** around the keep-out area **1020**. The horizontal motion policy selector **200**, in some examples, determines locations of corners **1110** of a polygon that represents the keep-out area **1020**. The planner **100** may place waypoints **1120***a*, **1120***b* a threshold distance (i.e., a margin) from the corners **1110** (FIG. **11**B).

[0058] As illustrated in FIG. **11**C, the horizontal motion policy selector **200** may separate the x and y movement required to reach the touchdown location **62**. For example, the selector **200** may plan a BBW horizontal motion policy **210** to maneuver the leg **12** from the current location **50** to a point beyond waypoint **1120***a*. The horizontal motion policy selector **200** may determine an amount of time t_c until the leg **12** reaches the waypoint **1120***a* in they axis. The horizontal motion policy selector **200** may ensure that there is no movement in the x direction toward the waypoints **1120***a*, **1120***b* until at least t_c time has passed. In some examples, the planner **100** may swing the leg over a keep-out area **1020** when possible. For example, if the contralateral leg is slanted, there may be an opportunity to swing over a portion of the keep-out area **1020** without colliding with the contralateral leg. In this scenario, the planner **100** may flag the possibility for future evaluation when selecting the vertical motion policy **610**.

[0059] FIG. **12** illustrates a plot of x position versus time in a Swing Around policy **210**. As illustrated, the horizontal motion policy selector **200** may select a policy **210** that accelerates until either a velocity limit is reached, further acceleration will overshoot the touchdown location **62**, or maintaining the current velocity will enter the keep-out area **1020**. In the illustrated example, the policy **210** accelerates the leg briefly until coasting (i.e., maintaining the current velocity) clips or touches the corner of the keep-out area **1020**. From this point, the leg **12** coasts until time t_c (i.e., the leg is past the corner of the keep-out area **1020**) and then accelerates in the direction of the touchdown location **62** (e.g., with a BBW policy **210**).

[0060] In some situations, the horizontal motion policy selector **200** may to further separate the motion components of the required trajectory. As illustrated in FIG. **13**, in some situations, the current location **50** lies on the other side of the keep-out area **1020** from the touchdown location **62**. In this situation, the horizontal motion policy selector **200** may perform a BBW policy (to the left in FIG. **13**) to pass waypoint **1120***d*. The horizontal motion policy selector **200** may determine the time until the waypoint **1120***d* is passed (t_{c1}) and then perform another BBW policy **210** (upward in FIG. **13**), then perform the remaining operations similarly as described with regards to FIGS. **11**A-C.

[0061] Referring now to FIG. **14**, several Swing Around trajectories **1410**, **1410***a-n* are shown on a plot **1400** from various starting locations, each attempting to reach the touchdown location **62**. The x-axis of the plot **1400** represents position of the leg **12** in the x-dimension while the y-axis of the plot **1400** represents the position of the leg **12** in the y-dimension. The Swing Around policy **210** attempts to avoid the keep-out area **1020** (and the leg **12***a* that is the source of the keep-out area **1020**).

[0062] While the illustrated examples of the Swing Around policy combine multiples of the same policy (e.g., BBW) to reach the touchdown location **62**, the policy selector **200**, in some implementations, combines different horizontal motion policies **210** as well. The horizontal motion policy selector **200** may combine different policies **210** by axis. For example, the selector **200** may select a BBW horizontal motion policy **210** in the x-dimension and a Cubic horizontal policy **210** in the y-dimension. The horizontal motion policy selector **200** may also combine policies **210** by time. For example, the horizontal motion policy selector **200** may select a BBW horizontal motion policy **210** for the first ten percent (or select number of seconds) of the swing and then switch to a Cubic horizontal policy **210** for the remainder of the swing. Combined policies, in other examples, are predefined (e.g., by a human operator) and the horizontal motion policy selector **200** may select the predefined combined policies.

[0063] Referring now to FIG. **15**, a single horizontal motion policy **210** (e.g., a Wiggle policy **210**W) may include any combination of individual horizontal motion policies (cubic, BBW, WBB, etc.) to reach the touchdown location **62**. As illustrated in FIG. **15**, in some scenarios, the horizontal motion policy selector **200** may need select policies **210** to maneuver the leg **12** around multiple other legs **12***a*, **12***b* and the associated keep-out areas **1020** of the robot **10**.

[0064] Referring now to FIG. **16**, in some implementations, the leg swing trajectory planner **100** selects specific policies **210**, **610** in response to the environment around the robot **10** or in response to determined or detected behavior. For example, when the planner **100** determines that the robot is maneuvering through level and unobstructed terrain, the planner **100** may default to a select policies **210**, **610** without requiring any detailed analysis by the detailed analyzer **230**. In another example, the planner **100** may receive an indication of a trip by the robot **10** and react with the default policies **210**, **610** associated with tripping. The trip policies may include horizontal motion policies **210** and vertical motion policies **610** or, alternatively, only horizontal motion policies **210**. As illustrated in FIG. **16**, the planner **100** may react to a normal trip, a recent normal trip, a knee trip, a self-collision where the legs are crossed, and a self-collision where the legs are not crossed. For example, in response to a knee trip, the planner **100** may move the knee slowly forward to recover. During a normal trip, the planner **100** may cease forward longitudinal movement of the swing leg **12** and elevate the foot **19**. During a crossed self-collision, the planner **100** may attempt to disentangle the swing leg, while during an uncrossed self-collision, the planner **100** may attempt to move away from the stance leg laterally and continue moving towards the touchdown location **62**.

[0065] Thus, the swing leg trajectory planner **100** decouples the swing trajectory of the leg **12** of the robot **10** into horizontal and vertical components. By first decoupling the horizontal and vertical components, the planner **100** reduces overall complexity and processing requirements. This allows the planner **100** to plan and replan the swing leg trajectories at a high frequency. For example, the planner **100** may plan a swing leg trajectory in 100 microseconds or less to allow the robot **10** to rapidly react to changes in the environment or to collisions with the robot **10**. Because a leg swing typically ranges from 200 milliseconds to over 600 milliseconds in duration, the planner **100** may replan the leg many times prior to touchdown. In some examples, the planner **100** plans each leg every three milliseconds. The planner **100** attempts to ensure that all constraints **232** are met while avoiding collisions with obstacles and self-collisions. When all constraints cannot be met and/or the touchdown location **62** or touchdown time **64** cannot be met, the planner **100** may provide graceful degradation by prioritizing (e.g., via the tier evaluator **240**) which constraints/requirements are met. The planner may also improve aesthetics and balance by, for example, minimizing lifting of the leg during the swing and keeping the swing trajectory smooth.

[0066] FIG. **17** is a flowchart of an exemplary arrangement of operations for a method **1700** for planning swing leg trajectories of a robot **10**. At operation **1602**, the method **1700** includes receiving, at data processing hardware **36**, an initial position **50** of a leg **12** of the robot **10** and an initial velocity **52** of the leg **12** of the robot **10**. Here, the data processing hardware **36** executes the leg swing trajectory planner **100** and may reside on the robot **10**, a remote system/device in communication with the robot **10**, or a combination thereof. At operation **1704**, the method **1700** includes receiving, at the data processing hardware **36**, a touchdown location **62** for the leg **12** and a touchdown target time **64** for the leg **12**. The touchdown target time **64** represents an amount of time until the leg **12** of the robot **10** should touchdown at the touchdown location **62**.

[0067] At operation **1706**, the method **1700** includes determining, by the data processing hardware **36**, a difference between the initial position **50** of the leg and the touchdown location **62** and, at operation **1708**, the method **1700** includes separating, by the data processing hardware **36**, the difference between the initial position **50** of the leg **12** and the touchdown location **62** into a horizontal motion component and a vertical motion component.

[0068] At operation **1710**, the method **1700** includes selecting, by the data processing hardware **36**, a horizontal motion policy **210** from a set of horizontal motion policies to satisfy the horizontal motion component. Each horizontal motion policy produces a horizontal trajectory as a function of the initial position **50** of the leg **12**, the initial velocity **52** of the leg **12**, the touchdown location **62** of the leg **12**, and the touchdown target time **64** of the leg **12**. The method **1700** also includes, at operation **1712**, selecting, by the data processing hardware **36**, a vertical motion policy **610** from a set of vertical motion policies to satisfy the vertical motion component. Each vertical motion policy **610** produces a vertical trajectory as a function of the initial position **50** of the leg **12**, the initial velocity **52** of the leg **12**, the touchdown location **62** of the leg **12**, and the touchdown target time **64** of the leg **12**. At operation **1714**, the method **1700** includes executing, by the data processing hardware **36**, the selected horizontal motion policy **210** and the selected vertical motion policy **610** to swing the leg **12** of the robot **10** from the initial position **50** to the touchdown location **62** at the touchdown target time **64**.

[0069] FIG. **18** is schematic view of an example computing device **1800** that may be used to implement the systems and methods described in this document (e.g., data processing hardware **36** and memory hardware **20**). 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.

[0070] The computing device **1800** includes a processor **1810** (e.g., data processing hardware **36**), memory **1820** (e.g., memory hardware **38**), a storage device **1830**, a high-speed interface/controller **1840** connecting to the memory **1820** and high-speed expansion ports **1850**, and a low speed interface/controller **1860** connecting to a low speed bus **1870** and a storage device **1830**. Each of the components **1810**, **1820**, **1830**, **1840**, **1850**, and **1860**, are interconnected using various busses, and may be mounted on a common motherboard or in other manners as appropriate. The processor **1810** can process instructions for execution within the computing device **1800**, including instructions stored in the memory **1820** or on the storage device **1830** to display graphical information for a graphical user interface (GUI) on an external input/output device, such as display **1880** coupled to high speed interface **1840**. 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 **1800** 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).

[0071] The memory **1820** stores information non-transitorily within the computing device **1800**. The memory **1820** may be a computer-readable medium, a volatile memory unit(s), or non-volatile memory unit(s). The non-transitory memory **1820** 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 **1800**. 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.

[0072] The storage device **1830** is capable of providing mass storage for the computing device **1800**. In some implementations, the storage device **1830** is a computer-readable medium. In various different implementations, the storage device **1830** 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 **1820**, the storage device **1830**, or memory on processor **1810**.

[0073] The high speed controller **1840** manages bandwidth-intensive operations for the computing device **1800**, while the low speed controller **1860** manages lower bandwidth-intensive operations. Such allocation of duties is exemplary only. In some implementations, the high-speed controller **1840** is coupled to the memory **1820** and to the high-speed expansion ports **1850**, which may accept various expansion cards (not shown). In some implementations, the low-speed controller **1860** is coupled to the storage device **1830** and a low-speed expansion port **1890**. The low-speed expansion port **1890**, 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.

[0074] 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.

[0075] 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.

[0076] The processes and logic flows described in this specification can be performed by one or more programmable processors, also referred to as data processing hardware, 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.

[0077] 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, an initial position of a leg of the robot and an initial velocity of the leg of the robot;

receiving, at the data processing hardware, a touchdown location for the leg and a touchdown target time for the leg, the touchdown target time representing an amount of time until the leg of the robot should touchdown at the touchdown location;

determining, by the data processing hardware, a difference between the initial position of the leg and the touchdown location;

separating, by the data processing hardware, the difference between the initial position of the leg and the touchdown location into a horizontal motion component and a vertical motion component;

selecting, by the data processing hardware, a horizontal motion policy from a set of horizontal motion policies to satisfy the horizontal motion component, each horizontal motion policy producing a horizontal trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg;

selecting, by the data processing hardware, a vertical motion policy from a set of vertical motion policies to satisfy the vertical motion component, each vertical motion policy producing a vertical trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg; and

executing, by the data processing hardware, the selected horizontal motion policy and the selected vertical motion policy to swing the leg of the robot from the initial position to the touchdown location at the touchdown target time.

2. The method of claim **1**, further comprising:

determining, by the data processing hardware, a most aggressive vertical motion policy of the set of vertical motion policies, the most aggressive vertical motion policy maximizing vertical acceleration of the leg within a vertical acceleration limit of the leg and maximizing vertical velocity of the leg within a vertical velocity limit of the leg,

wherein selecting the horizontal motion policy from the set of horizontal motion policies comprises evaluating each horizontal motion policy of the set of horizontal motion policies with the most aggressive vertical motion policy.

3. The method of claim **1**, wherein selecting the horizontal motion policy from the set of horizontal motion policies comprises:

assigning each horizontal motion policy of the set of horizontal motion policies a tier from a plurality of tiers, each tier associated with an amount of preference for selecting the respective tier, and each tier comprising a tiebreaking parameter, the tiebreaking parameter associated with each horizontal motion policy of the set of horizontal motion policies; and

selecting the horizontal motion policy from the set of horizontal motion policies based on the assigned tiers and the tiebreaking parameters.

4. The method of claim **3**, wherein the tiebreaking parameter comprises a total undesirability based on a sum of a horizontal undesirability and a vertical undesirability.

5. The method of claim **1**, wherein selecting the vertical motion policy from the set of vertical motion policies occurs after selecting the horizontal motion policy from the set of horizontal motion policies.

6. The method of claim **5**, wherein selecting the vertical motion policy from the set of vertical motion policies comprises selecting the vertical motion policy from the set of vertical motion policies associated with a minimum acceleration and a minimum velocity that satisfies the vertical motion component.

7. The method of claim **1**, further comprising:

receiving, at the data processing hardware, an indication of a trip by the robot; and

in response to receiving the indication of the trip by the robot, selecting, by the data processing hardware, one of:

a horizontal motion policy from a second set of horizontal motion policies, the second set of horizontal motion policies associated with tripping; or

a vertical motion policy from a second set of vertical motion policies, the second set of vertical motion policies associated with tripping.

8. The method of claim **1**, wherein selecting the horizontal motion policy from the set of horizontal motion policies comprises:

evaluating each horizontal motion policy of the set of horizontal motion policies with a simple analysis; and

evaluating a sub-set of the set of horizontal motion policies with a detailed analysis based on the simple analysis.

9. The method of claim **1**, further comprising:

receiving, at the data processing hardware, the touchdown target time for each of a plurality of legs of the robot;

determining, at the data processing hardware, a touchdown order of the legs based on the touchdown target time for each of the plurality of legs of the robot; and

selecting, by the data processing hardware, the horizontal motion policy and the vertical motion policy for each leg in a planning order based on the touchdown order.

10. The method of claim **1**, wherein each vertical motion policy of the set of vertical motion policies comprises a maximum velocity, a maximum acceleration, and a swing height.

11. The method of claim **1**, wherein at least one horizontal motion policy of the set of horizontal motion policies comprises a lateral motion policy and a longitudinal motion policy.

12. A robot comprising:

a body;

legs coupled to the body and configured to maneuver the robot about an environment;

data processing hardware in communication with the legs; 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 an initial position of a leg of the robot and an initial velocity of the leg of the robot;

receiving a touchdown location for the leg and a touchdown target time for the leg, the touchdown target time representing an amount of time until the leg of the robot should touchdown at the touchdown location;

determining a difference between the initial position of the leg and the touchdown location;

separating the difference between the initial position of the leg and the touchdown location into a horizontal motion component and a vertical motion component;

selecting a horizontal motion policy from a set of horizontal motion policies to satisfy the horizontal motion component, each horizontal motion policy producing a horizontal trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg;

selecting a vertical motion policy from a set of vertical motion policies to satisfy the vertical motion component, each vertical motion policy producing a vertical trajectory as a function of the initial position of the leg, the initial velocity of the leg, the touchdown location of the leg, and the touchdown target time of the leg; and

executing the selected horizontal motion policy and the selected vertical motion policy to swing the leg of the robot from the initial position to the touchdown location at the touchdown target time.

13. The robot of claim **12**, wherein the operations further comprise:

determining a most aggressive vertical motion policy of the set of vertical motion policies, the most aggressive vertical policy maximizing vertical acceleration of the leg within a vertical acceleration limit of the leg and maximizing vertical velocity of the leg within a vertical velocity limit of the leg,

wherein selecting the horizontal motion policy from the set of horizontal motion policies comprises evaluating each horizontal motion policy of the set of horizontal motion policies with the most aggressive vertical motion policy.

14. The robot of claim **12**, wherein selecting the horizontal motion policy from the set of horizontal motion policies comprises:

assigning each horizontal motion policy of the set of horizontal motion policies a tier from a plurality of tiers, each tier associated with an amount of preference for selecting the respective tier, and each tier comprising a tiebreaking parameter, the tiebreaking parameter associated with each horizontal motion policy of the set of horizontal motion policies; and

selecting the horizontal motion policy from the set of horizontal motion policies based on the assigned tiers and the tiebreaking parameters.

15. The robot of claim **14**, wherein the tiebreaking parameter comprises a total undesirability based on a sum of a horizontal undesirability and a vertical undesirability.

16. The robot of claim **12**, wherein selecting the vertical motion policy from the set of vertical motion policies occurs after selecting the horizontal motion policy from the set of horizontal motion policies.

17. The robot of claim **16**, wherein selecting the vertical motion policy from the set of vertical motion policies comprises selecting the vertical motion policy from the set of vertical motion policies associated with a minimum acceleration and a minimum velocity that satisfies the vertical motion component.

18. The robot of claim **12**, wherein the operations further comprise:

receiving an indication of a trip by the robot; and

in response to receiving the indication of the trip by the robot, selecting one of:

a horizontal motion policy from a second set of horizontal motion policies, the second set of horizontal motion policies associated with tripping; or

a vertical motion policy from a second set of vertical motion policies, the second set of vertical motion policies associated with tripping.

19. The robot of claim **12**, wherein selecting the horizontal motion policy from the set of horizontal motion policies comprises:

evaluating each horizontal motion policy of the set of horizontal motion policies with a simple analysis; and

evaluating a sub-set of the set of horizontal motion policies with a detailed analysis based on the simple analysis.

20. The robot of claim **12**, wherein the operations further comprise:

receiving the touchdown target time for each of a plurality of legs of the robot;

determining, at the data processing hardware, a touchdown order of the legs based on the touchdown target time for each of the plurality of legs of the robot; and

selecting the horizontal motion policy and the vertical motion policy for each leg in a planning order based on the touchdown order.

21. The robot of claim **12**, wherein each vertical motion policy of the set of vertical motion policies comprises a maximum velocity, a maximum acceleration, and a swing height.

22. The robot of claim **12**, wherein at least one horizontal motion policy of the set of horizontal motion policies comprises a lateral motion policy and a longitudinal motion policy.

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