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Anderson, III

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(54) METHOD AND SYSTEM FOR DYNAMICALLY FILTERING THE MOTION OF ARTICULATED BODIES

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(51) **Int. Cl.**^{7} **G06T 15/70**

(52) **U.S. Cl.** **345/474**; 345/473

(58) **Field of Search** 345/473, 474, 345/646, 935; 348/578; 386/50, 73; 382/276, 109, 293

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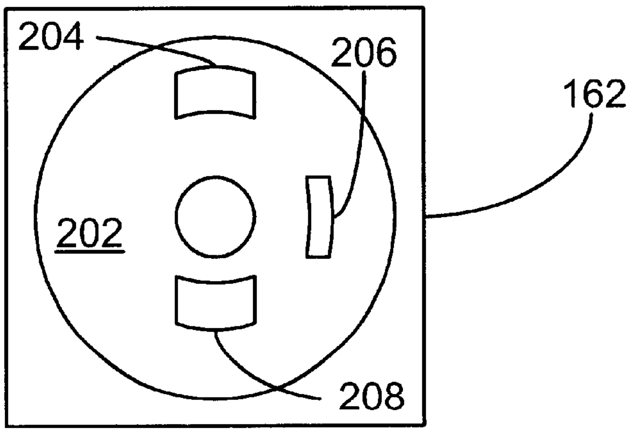
(57) **ABSTRACT**

In accordance with a set of embodiments of the present invention, a method can be used to filter the motion of a body or a system of articulated bodies so that the motion conforms to the laws of classical dynamics. Based on a specified set of kinematic inputs, on a dynamic model that represents the articulated bodies, and on a set of tunable filter parameters, an optimization-based inverse dynamics algorithm can be used to determine values of control variables and each time step during a forward simulation so that the model is driven toward the specified set of desired kinematics while at the same time potentially optimizing various other aspects of the motion. The embodiments may be useful in the areas of biomechanics, medicine, ergonomics, computer animation, or other areas where realistic motion generation is desired.

18 Claims, 10 Drawing Sheets



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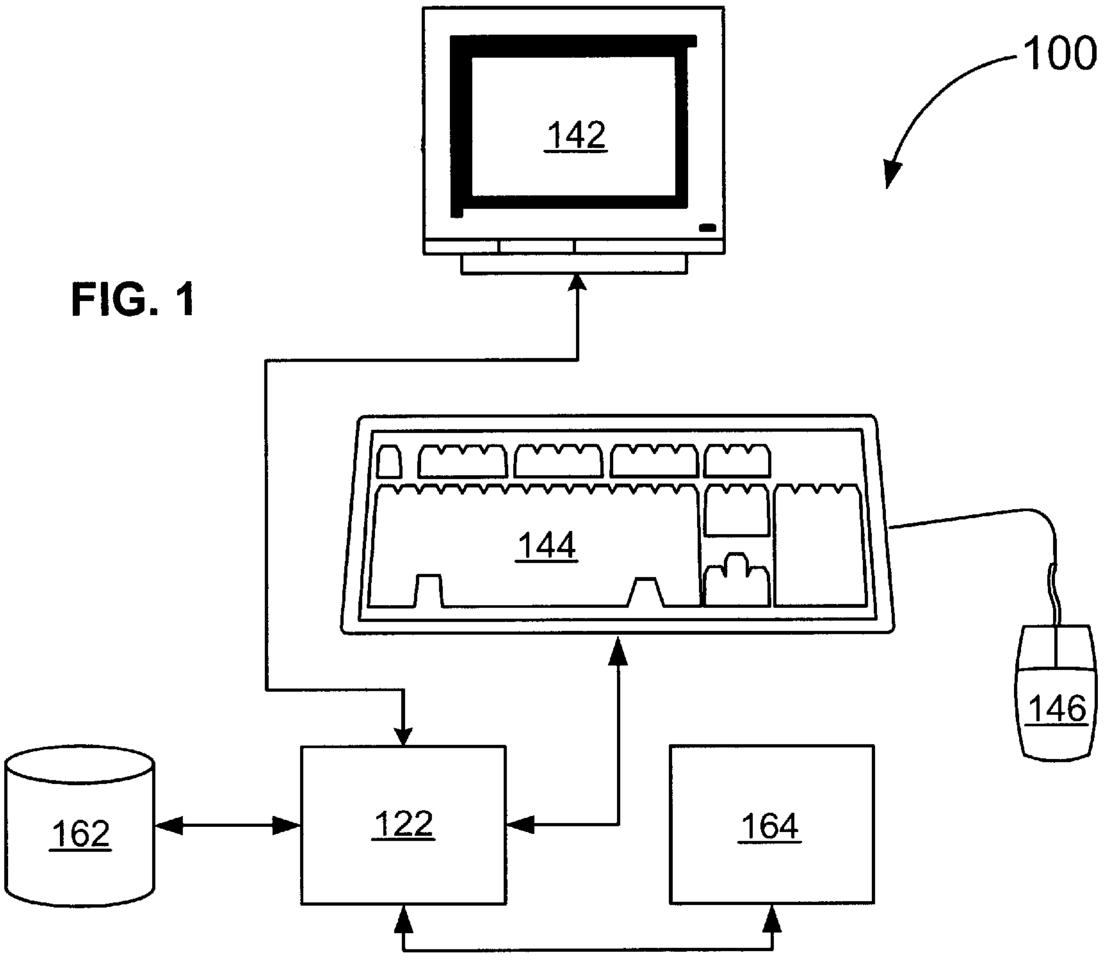


FIG. 1

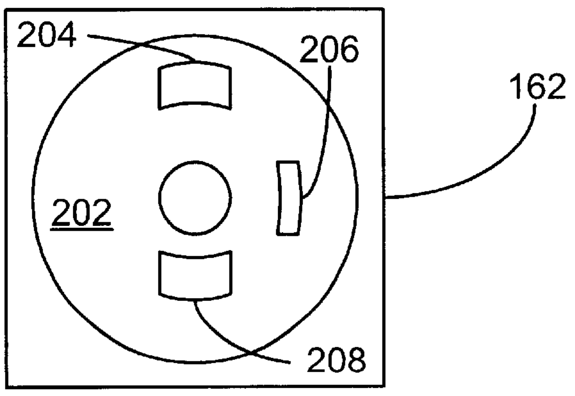


FIG. 2

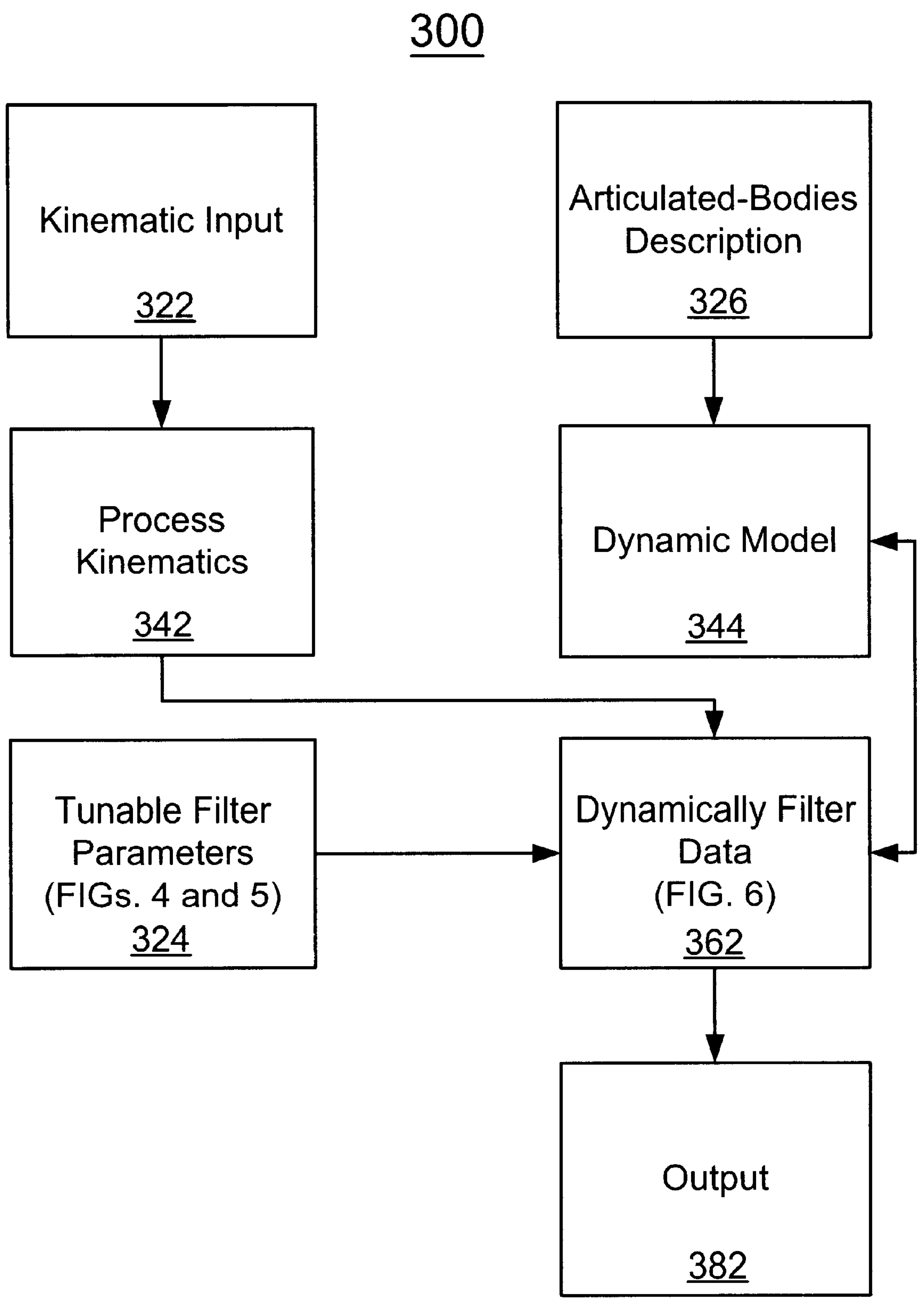

300
Kinematic Input
322
Articulated-Bodies Description
326
Process Kinematics
342
Dynamic Model
344
Tunable Filter Parameters (FIGs. 4 and 5)
324
Dynamically Filter Data (FIG. 6)
362
Output
382

FIG. 3

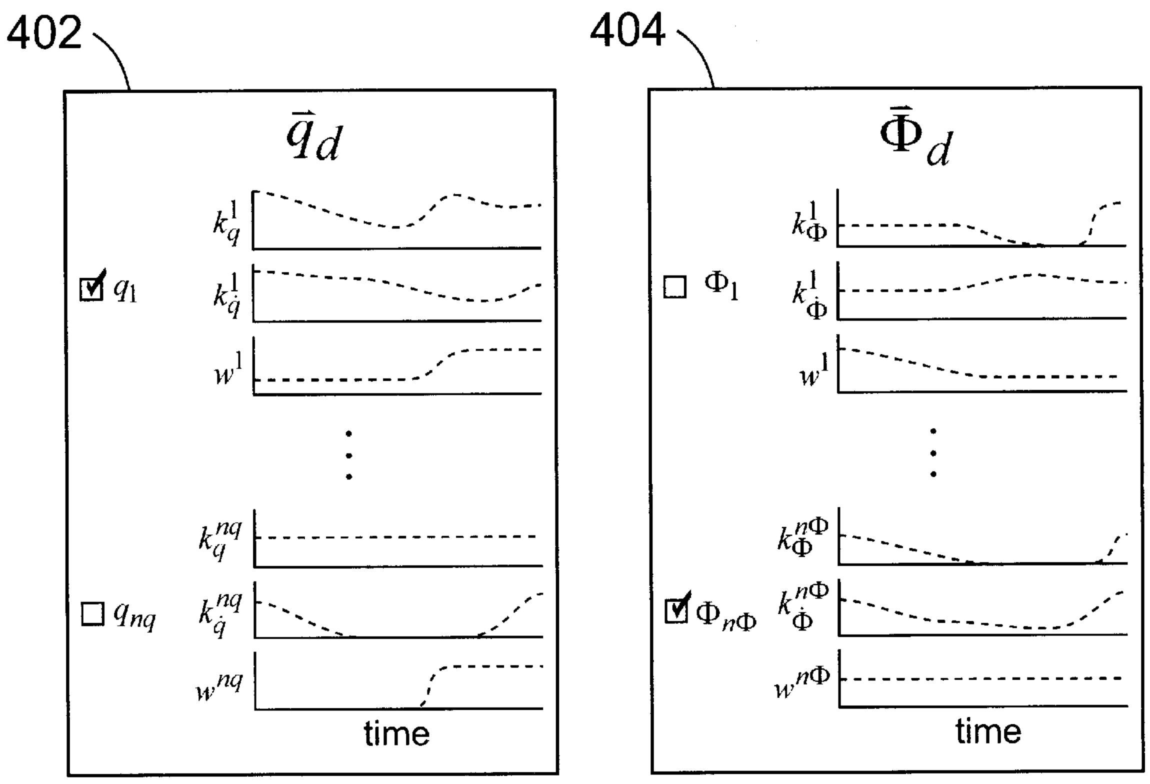

402
404
$\vec{q}_d$
$\vec{\Phi}_d$
k_q^1
$k_{\dot{q}}^1$
w^1
q_1
k_q^{nq}
$k_{\dot{q}}^{nq}$
w^{nq}
q_{nq}
k_Φ^1
$k_{\dot{\Phi}}^1$
w^1
Φ_1
$k_\Phi^{n\Phi}$
$k_{\dot{\Phi}}^{n\Phi}$
$w^{n\Phi}$
$\Phi_{n\Phi}$
time
time

FIG. 4

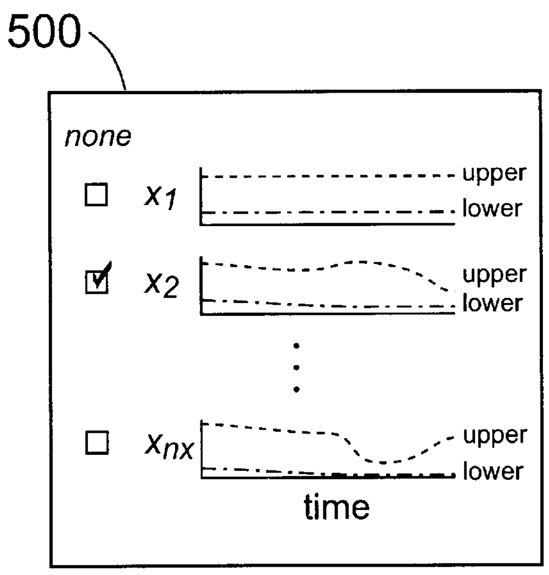

500
none
x_1
x_2
x_{nx}
upper
lower
upper
lower
upper
lower
time

FIG. 5

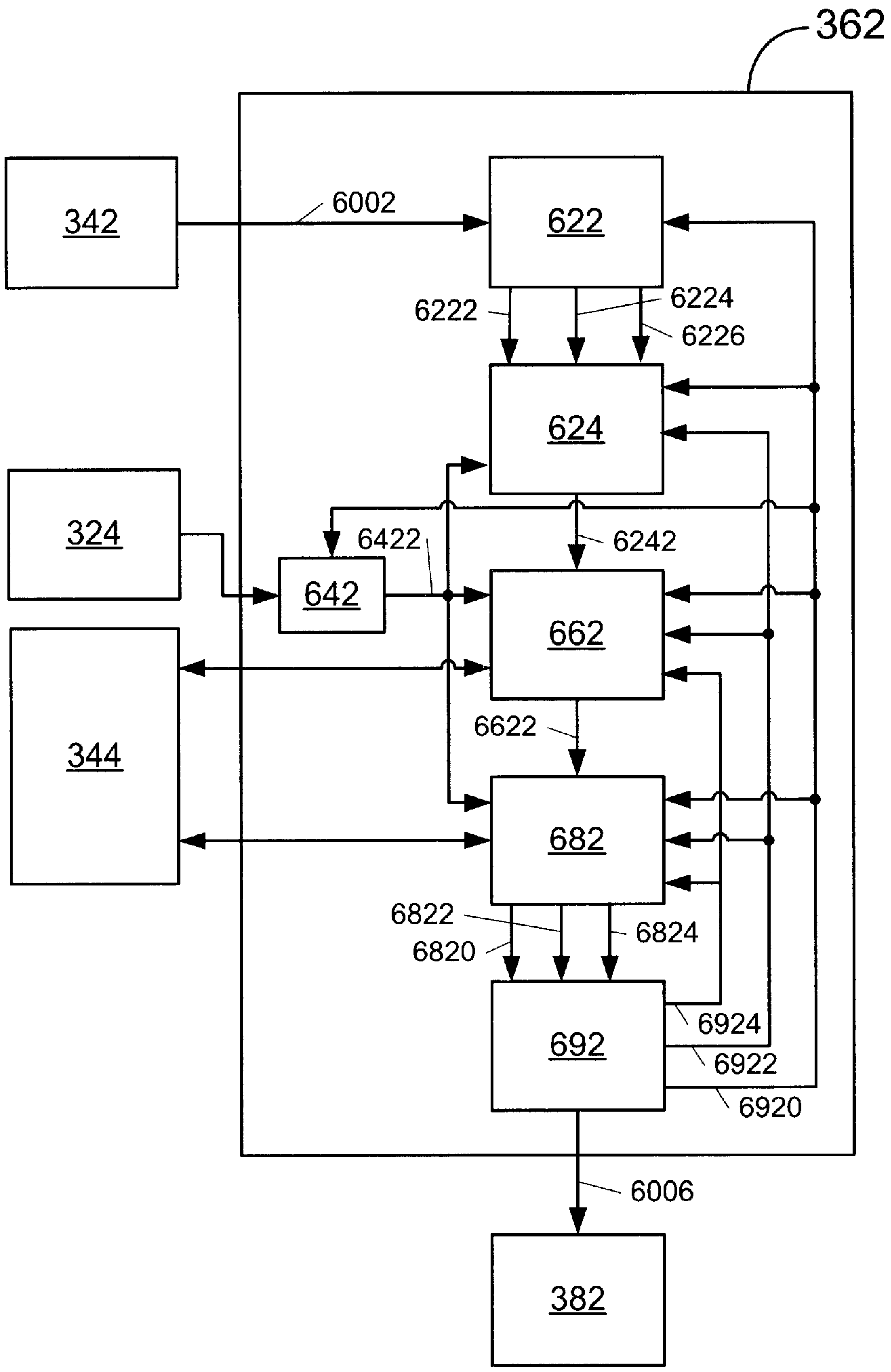

362
342
6002
622
6222
6224
6226
624
324
6422
642
6242
662
344
6622
682
6822
6820
6824
692
6924
6922
6920
6006
382

FIG. 6

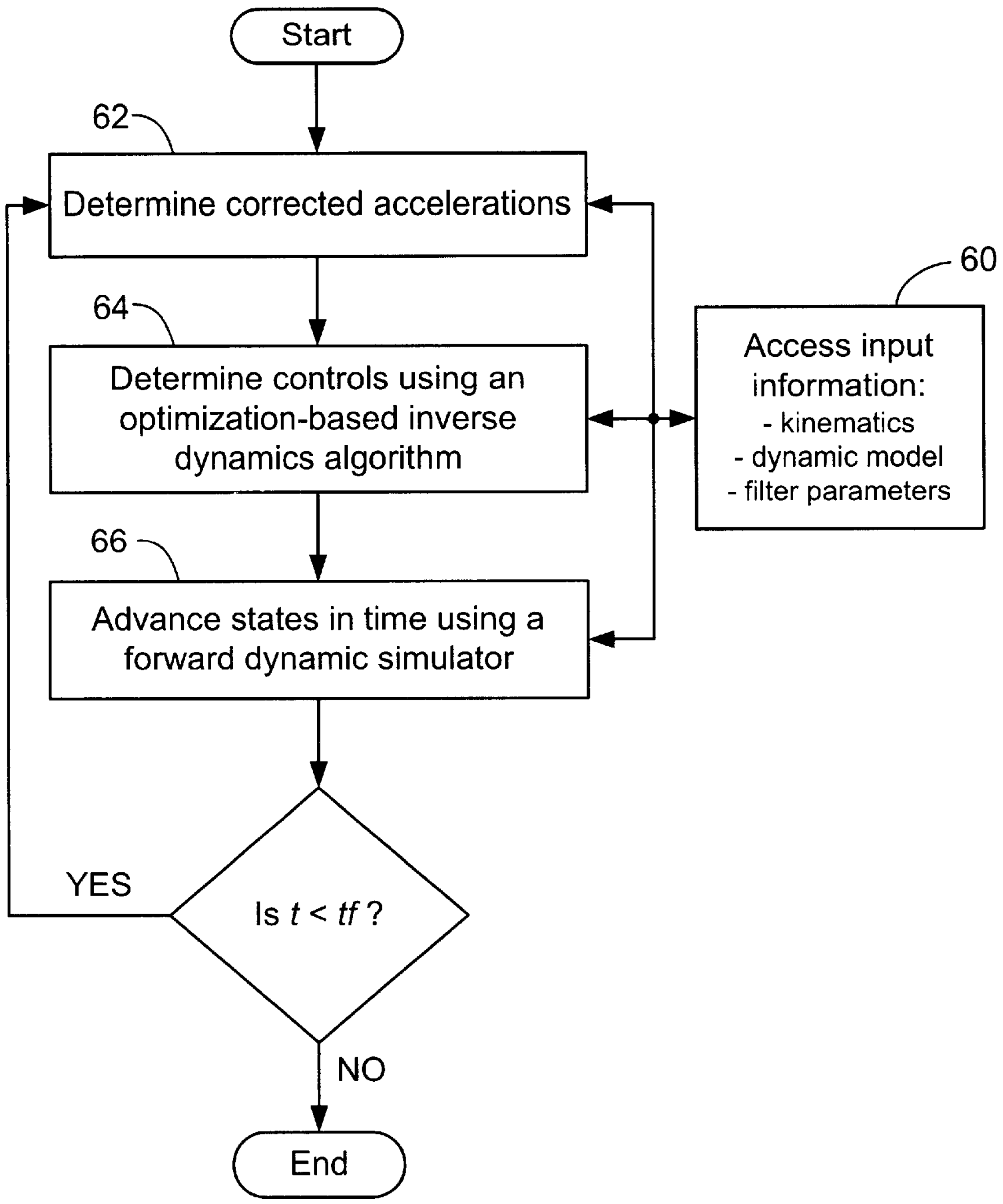

Start
62
Determine corrected accelerations
64
Determine controls using an optimization-based inverse dynamics algorithm
66
Advance states in time using a forward dynamic simulator
60
Access input information:
- kinematics
- dynamic model
- filter parameters
YES
Is $t < tf$?
NO
End

FIG. 6A

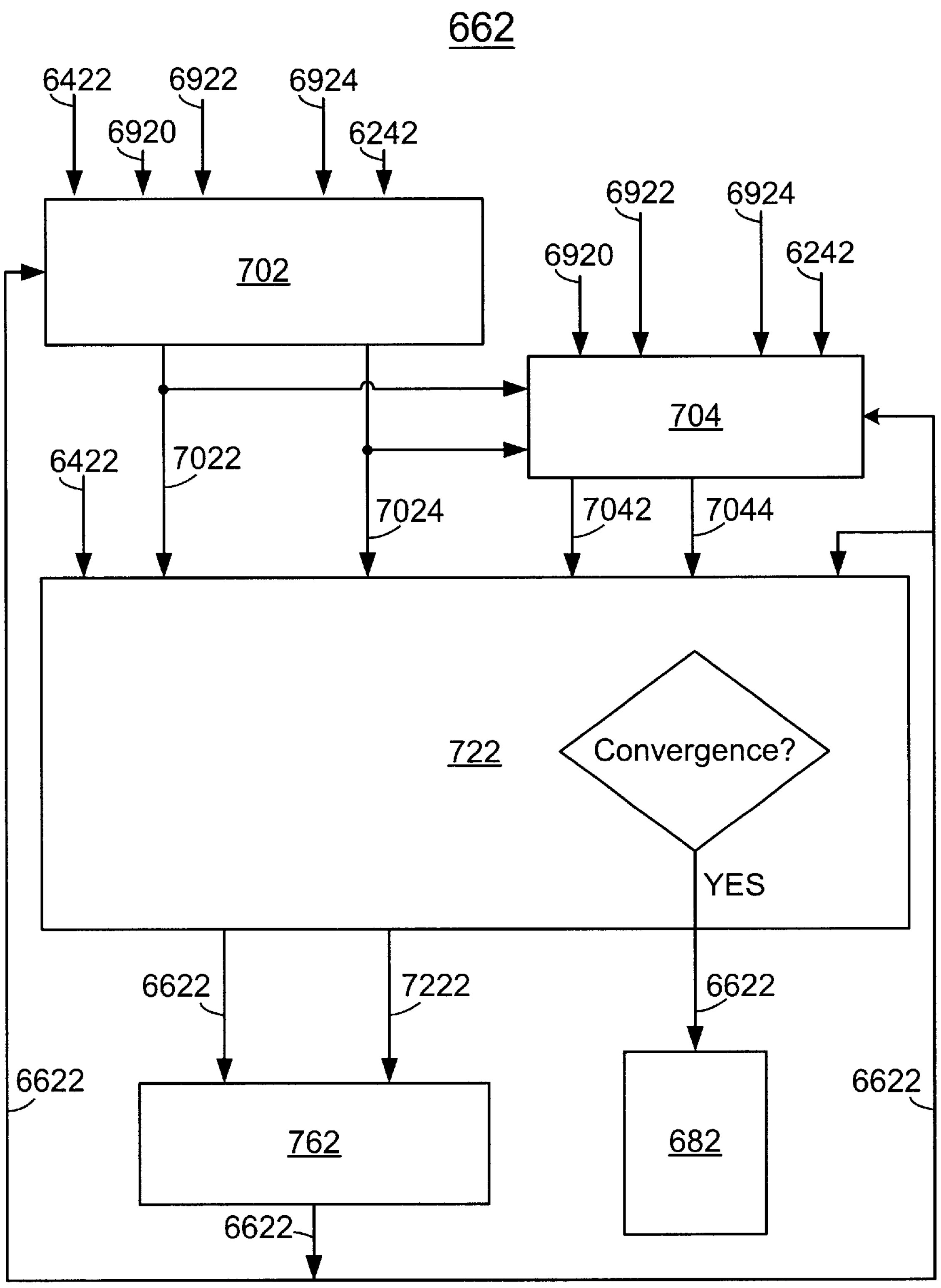

662
6422
6920
6922
6924
6242
702
6920
6922
6924
6242
704
6422
7022
7024
7042
7044
722
Convergence?
YES
6622
7222
6622
762
682
6622
6622
6622

FIG. 7

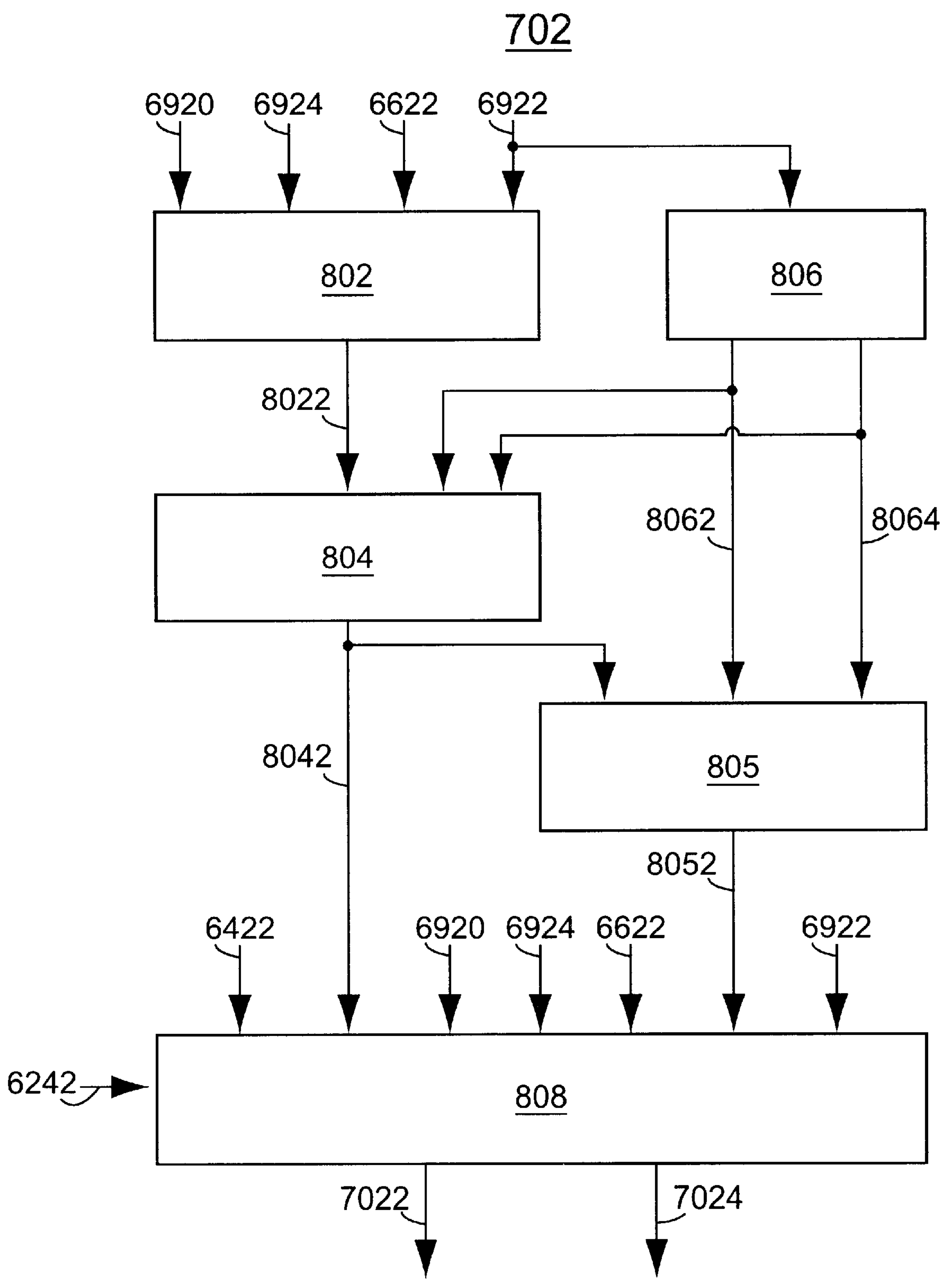
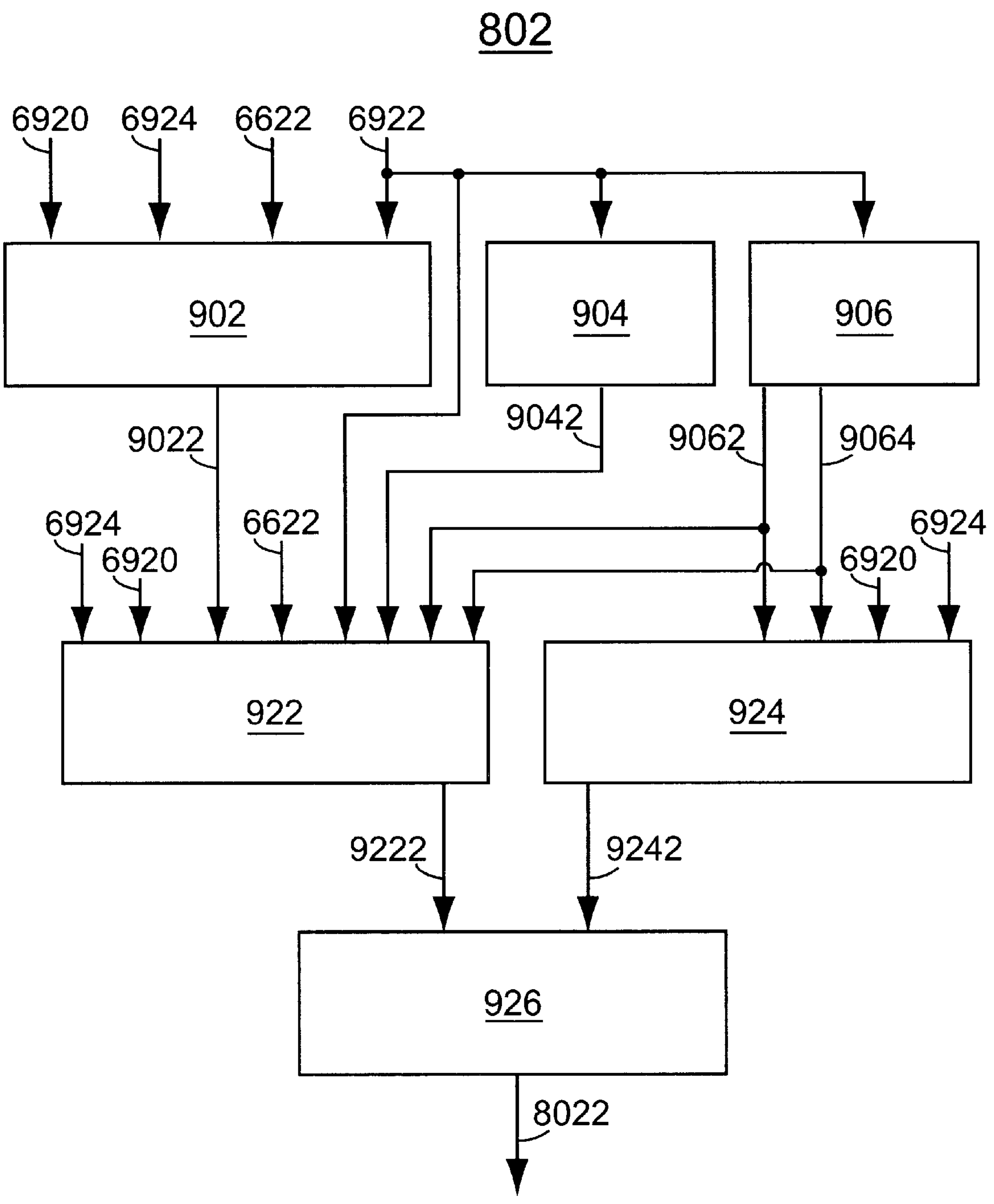

702
6920
6924
6622
6922
802
806
8022
804
8062
8064
805
8042
8052
6422
6920
6924
6622
6922
6242
808
7022
7024

FIG. 8


802
6920
6924
6622
6922
902
904
906
9022
9042
9062
9064
6924
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6622
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9242
926
8022

FIG. 9

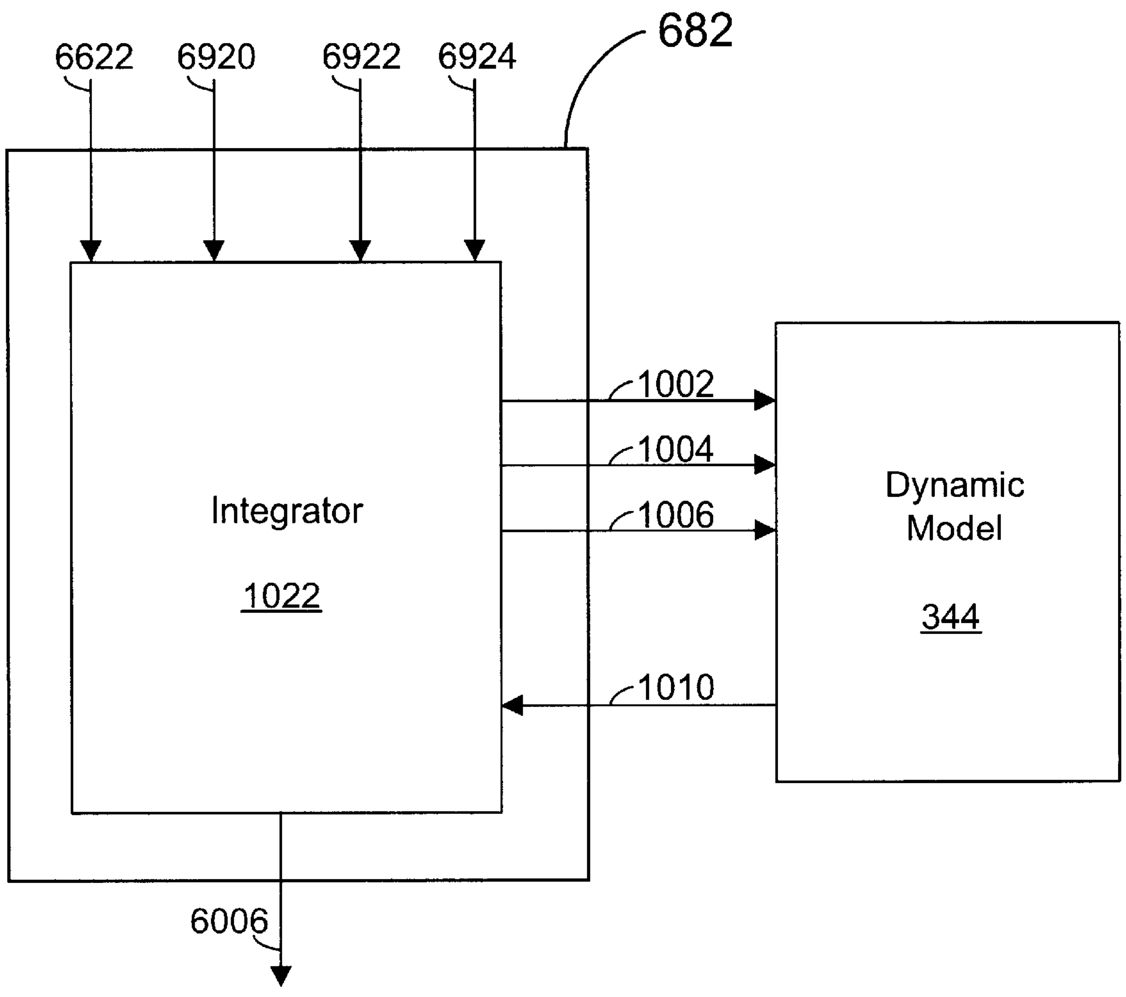
682
6622
6920
6922
6924
Integrator
1022
1002
1004
1006
1010
Dynamic Model
344
6006

FIG. 10

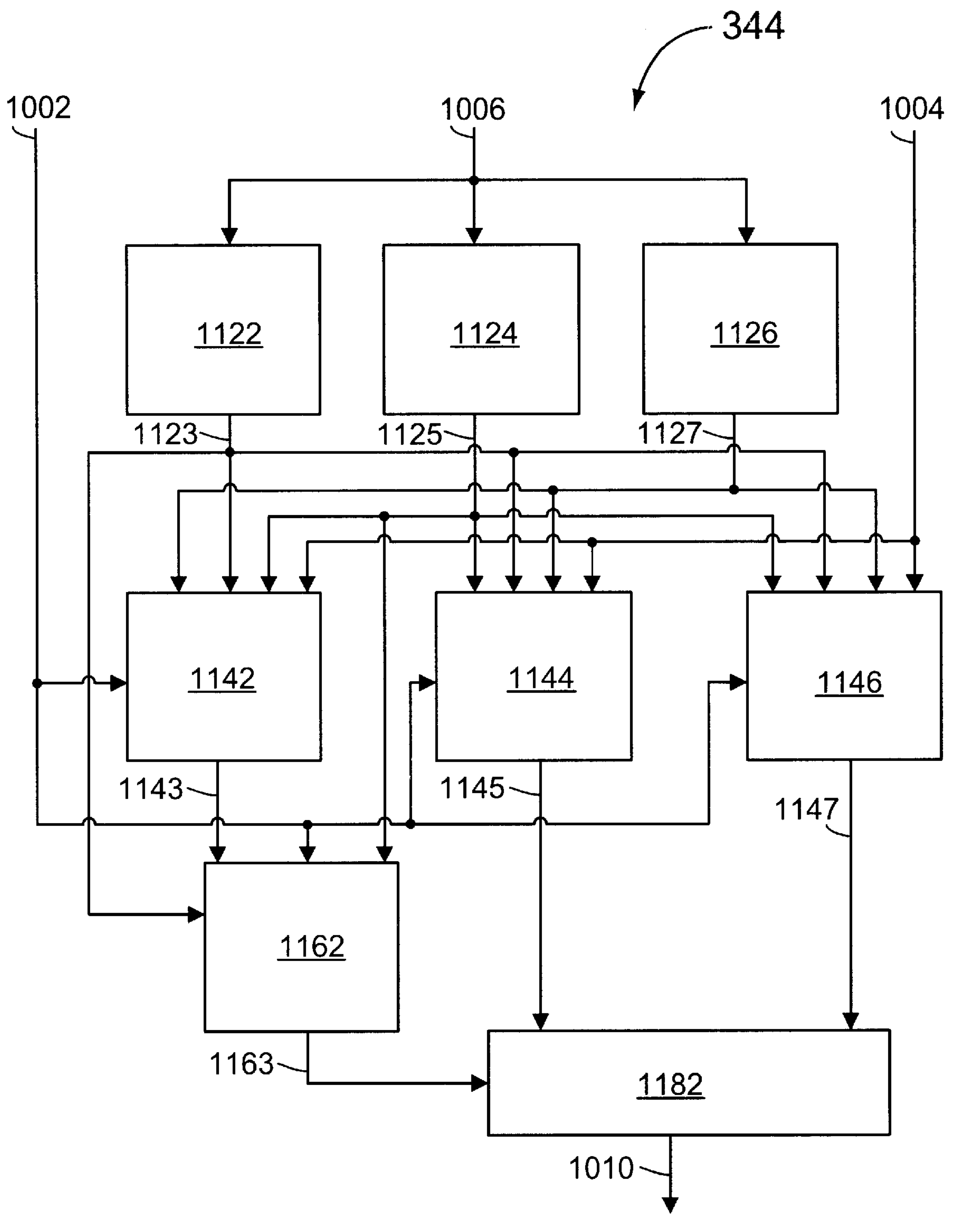
344
1002
1006
1004
1122
1124
1126
1123
1125
1127
1142
1144
1146
1143
1145
1147
1162
1163
1182
1010

FIG. 11

METHOD AND SYSTEM FOR DYNAMICALLY FILTERING THE MOTION OF ARTICULATED BODIES

RELATED APPLICATIONS

This application claims priority under 35 U.S.C. §119(e), to U.S. patent application Ser. No. 60/198,947 entitled "Method and System For Dynamically Filtering the Motion of Articulated Bodies" by Anderson filed Apr. 21, 2000, which is assigned to the current assignee hereof and is incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates in general to methods, data processing system readable storage media, and articles, and more particularly, to methods of filtering motion of a body, data processing system readable media having software code for carrying out those methods, and articles comprising output information related to a body, wherein the output information is generated using those methods.

DESCRIPTION OF THE RELATED ART

Computer models of the human body have been used since the early 1970's to estimate in-vivo quantities, such as muscle forces, which then and now cannot be measured except by invasive means. In the case of muscle forces, the difficulty arises because there are more muscles in the body than degrees of freedom, thus allowing multiple control strategies for a single observed body motion. As a result, an inverse dynamic analysis (i.e., an analysis that solves for the net muscular joint moments given body segmental accelerations derived from experimental measures) leads to an indeterminant set of equations for the muscle forces. Two approaches have been commonly employed to resolve this indeterminacy: static optimization and dynamic optimization.

Static optimization, based on the results of an inverse dynamic analysis, postulates that the net muscular joint moments are distributed across muscles so as to minimize a postulated performance criterion. The static optimization method is computationally feasible, but it has a number of shortcomings. First, in the static optimization technique, all quantities are treated as time independent variables. This assumption can lead to non-physiological predictions of muscle force because the dynamic properties of muscle are not taken into account. Second, the static optimization technique is highly dependent on the accurate collection and processing of kinematic data. The reason is that an inverse dynamic analysis requires twice differentiating displacement data to obtain accelerations, which amplifies any noise present in the displacement data. Third, because an inverse dynamics approach alone is taken, the static optimization process is not capable of generating novel motion.

Dynamic optimization is based on a forward dynamics approach. In a forward dynamics approach, one develops a detailed dynamic model of the musculoskeletal system and uses this model to execute computer-based simulations of movement that are driven by a set of actuator controls (e.g., joint torques, muscle excitation signals, and the like). Like static optimization, dynamic optimization postulates a performance criterion to resolve the indeterminant force distribution problem. However, performance criteria for dynamic optimization are time dependent and their evaluation is accomplished by numerically integrating the equations of motion over the duration of the simulation. As a result,

dynamic optimization incurs great computational expense, so much so that relatively few dynamic optimization problems have been solved for complex activities like walking. Only recently, with the advent of parallel supercomputers, has it become feasible to solve large-scale dynamic optimization problems for human movement. Even with the use of parallel supercomputers, solutions can take more than 100 hours for motion that is less than one second in duration.

In the field of computer animation, obtaining realistic, life-like character motion is often an important objective. There are two general methods by which this task is currently approached: 1) motion capture and 2) key-framing. In motion capture, the motion of an actor or apparatus is digitally recorded (e.g., using markers and video cameras). Then, an inverse kinematic problem is often solved to drive a computer model through the same motion. This method has several drawbacks: 1) motion capture data frequently has errors, 2) motion capture sessions are typically limited to a small volume which requires that motion capture sequences be spliced together, and 3) it is sometimes not possible to use motion capture for certain animation sequences (e.g., locomotion of imaginary creatures, violent crashes, or space flight). In key-framing, an animator uses software to compose a series of animation frames, separated in time by some interval, which together comprise an animation sequence. The drawback of this method is that the realism of the sequence depends heavily on the experience and skill of the animator. For complex three-dimensional movements, an animator might be required to manually specify more than 30 variables per key-frame, and it is extraordinarily difficult to capture the subtle nuances exhibited by real-life characters.

Filtering techniques have been devised to reduce error in motion capture data, but these techniques typically omit knowledge of the dynamic properties of the character's body and of the actuators which drive the body. For example, inverse kinematic techniques have been implemented which can serve to reduce error in motion capture data when the motion of a character is constrained (e.g., a part of the body is known to be in contact with an obstacle or is known to articulate with another part of the body by a particular kind of joint, such as ball-and-socket). These same inverse kinematic techniques can also be used to reduce the burden on the animator when a key-framing methodology is used. However, in many instances an inverse kinematics technique is not sufficient for imbuing character animation with life-like dynamic realism.

Several physics-based animation techniques have been developed. Popovic and Witkin (SIGGRAPH 99, Los Angeles, Aug. 8–13, 1999) used an optimal control (or dynamic optimization) technique for improving the dynamic realism of character movement in computer animations. However, their technique is labor intensive, requires a high-level of skill from the animator, normally requires a simplified dynamic representation of the character, and can be computationally costly. Zordan and Hodgins (*Computer Animation and Simulation*, 1999) have employed proportional-derivative ("PD") control techniques to introduce dynamic realism into computer animation. While their technique appears to require less labor than that of Popovic and Witkin (1999), it does have several shortcomings. First, being a PD controller, the actuation of their dynamic models is based solely on error between the trajectory of the model and the desired kinematic trajectory, and therefore, has no feed-forward control. Without feed-forward control, non-physiological generalized forces are often demanded to make the dynamic model track the desired trajectories.

Second, because this approach does not use optimization when computing controls for the actuators, it cannot be used to reduce an indeterminate control problem to a determinant one and cannot be used to predict unmeasured or unspecified kinematic variables.

SUMMARY OF THE INVENTION

Methods can be used to filter the motion of a body so that the motion can be consistent with the laws of classical dynamics. Estimates of the generalized forces (i.e., forces and torques), which give rise to the filtered motion, can also be produced. In one embodiment, given a dynamic model that represents a system of articulated bodies and given a set of tunable filter parameters, an optimization-based inverse dynamics process can be used to compute a set of controls that drive a forward dynamic simulation toward a set of specified kinematic trajectories. To the extent that the actuators of the dynamic model are capable of applying the needed generalized forces, the specified kinematic trajectories can be reproduced. To the extent the actuators are not capable of applying the needed generalized forces, the specified kinematic trajectories can be filtered in a manner consistent with the dynamic properties of the articulated bodies.

The coupling of the optimization-based inverse dynamics algorithm with a forward dynamic simulation process has several benefits compared to prior art. In contrast to static optimization, the methods and system described herein 1) can account for the time dependent properties of the actuators, 2) can be less sensitive to errors in the specified kinematics, 3) and can generate novel motion. In contrast to dynamic optimization (i.e., optimal control methods for solving spacetime constraint problems), at least some of the embodiments of the present invention may require substantially less computation time. In contrast to other physics-based animation techniques, those embodiments may not require simplification of the dynamic model, does not require a high level of expertise from the animator, can reduce indeterminate control problems to determinant ones, and can predict unmeasured or unspecified kinematic variables. In addition, depending on how the filtering problem is phrased, the methods and system can be used to solve the inverse kinematics problem implicitly rather than depending on a prior explicit inverse kinematic solution. The methods and system can be useful in the areas of medicine, ergonomics, computer animation, or any other areas where it is of benefit for the motion of objects, real or imaginary, to follow the laws of classical dynamics.

In one set of embodiments, a method of filtering motion of a body can comprise accessing specified kinematics of the body, a dynamic property of the body, and a state of the body. The method can also comprise determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property. The method can further comprise advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

In another set of embodiments, a data processing system readable medium can have code embodied within it. The code can include instructions executable by a data processing system. The instructions may be configured to cause the data processing system to perform the methods described herein.

In other embodiments, an article can comprise an output information related to a body. More specifically, the article can comprise a data processing system readable medium and a code embodied within the data processing system readable medium. The code may include the output information. The output information may be generated by: accessing specified kinematics of the body, a dynamic property of the body, and a state of the body; determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property; and advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

The foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example and not limitation in the accompanying figures, in which like references indicate the same elements, and in which:

FIG. **1** includes an illustration of a schematic representation of a data processing system;

FIG. **2** includes an illustration of a data processing system storage medium including software code;

FIG. **3** includes an illustration of a system that can be used in filtering motion of articulated bodies in accordance with an embodiment;

FIGS. **4–5** include illustrations of an implementation for using filter factors, weights, and bounds;

FIG. **6** includes an illustration of a dynamic filter module;

FIG. **6A** includes a flow diagram of a portion of the software code;

FIG. **7** includes an illustration showing an implementation of using an optimizing unit;

FIGS. **8** and **9** include illustrations showing details of portions of the optimizing unit; and

FIGS. **10** and **11** include illustrations of an implementation of a forward dynamic simulator.

Skilled artisans appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated relative to other elements to help to improve understanding of embodiments of the present invention.

DETAILED DESCRIPTION

Reference is now made in detail to the exemplary embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts (elements).

In accordance with a set of embodiments of the present invention, a method can be used to filter the motion so that it is more dynamically realistic. Input can comprise a complete or under-specified set of desired kinematic trajectories for a body or a system of articulated bodies, a dynamic model that represents the body or the system of articulated bodies, and a set of tunable filter parameters. Output information can comprise a complete set of filtered kinematic trajectories and any states of the dynamic model that were generated during the filtering process, such as muscle forces, muscle activation levels, motor torques, external forces, and the like.

The filtering can be accomplished by coupling an optimization-based inverse dynamics process with a forward dynamic simulation process. In particular, by minimizing a specified performance criterion and satisfying a set of optionally specified constraints, the optimization-based inverse dynamics process can generate a set of controls that drives the forward dynamic simulation process so that the dynamic model tracks the input set of desired kinematic trajectories and possibly so that some other aspect of performance is minimized or maximized (e.g., the sum of muscle stress, peak motor torques, etc.). The various embodiments of the present invention may have advantages over prior art methods including static optimization, dynamic optimization (i.e., optimal control methods for solving spacetime constraint problems), and physics-based computer animation techniques, or the like. The embodiments may be useful in the technological areas of biomechanics, medicine, ergonomics, computer animation, or other motion-related areas where motion is to follow the laws of classical dynamics and where estimates of the generalized forces (i.e., forces and torques) that give rise to a particular motion are desired.

FIG. **1** includes an illustration of a data processing system **100** that includes a processor, which is bi-directionally coupled to input/output devices including a monitor **142**, a keyboard **144**, and a pointer device **146** (e.g., a mouse, a track ball, or the like). The pointer device can be connected to the keyboard **144** as shown in FIG. **1** or may be connected as a separate input/output device (not shown). The processor **122** is bi-directionally coupled to a storage device **162** (e.g., a hard disk, floppy diskette, CD-ROM, or other nonvolatile memory) and random access memory (RAM) **164** (e.g., static random access memory, dynamic random access memory, or the like). To execute a file, the processor **122** typically reads the file within the storage device **162** and loads it into RAM **164**. The processor **122** principally controls the software program during its execution.

The methods described herein may be implemented in suitable software code that may reside within ROM, RAM **164**, or the storage device **162**. FIG. **2** illustrates a combination of software code elements **204**, **206**, and **208** that are embodied within a data processing system readable medium **202** of the storage device **162**. In addition to the types of memories described above, the instructions in an embodiment may be contained on a data storage device with a different data processing system readable storage medium. Alternatively, the instructions may be stored as software code elements on a DASD array, magnetic tape, conventional hard disk drive, electronic read-only memory, optical storage device, CD ROM, a floppy diskette or other appropriate data processing system readable medium or storage device.

In an illustrative embodiment of the invention, the computer-executable instructions may be lines of compiled C^{++}, Java, or other language code. Other architectures may be used. A server-client or other network architecture (not shown) could be used. Some or all of the functions of the data processing system **100** may be incorporated into a server computer or other computer remote to the data processing system **100**.

Communications between the components within the data processing system **100** can be accomplished using electronic or optical signals. When a user (human) is at the data processing system **100**, the device may convert the signals to a human understandable form when sending a communication to the user and may convert input from a human to appropriate electronic or optical signals to be used by the data processing system **100** or other computers.

Attention is now directed to a system that can be used in accordance with embodiments of the present invention. FIG. **3** includes a flow diagram showing a high level representation of a software configuration **300** for dynamically filtering the motions of articulated bodies. The configuration **300** can include a kinematic input (specified kinematics) **322**, an articulated-bodies description **326**, and tunable filter parameters **324**. A user may interact with the data processing system **100** to define the data for these components. The kinematic input **322** can be accessed and processed to generate a set of curve fits. The articulated-bodies description **326** can be used to generate a dynamic model **344**. The processed kinematics **342** and tunable filter parameters **324** are fed to a software component.**362** to dynamically filter the data. The dynamic filter **362** accesses the dynamic model **344**. The dynamic filter **362** can then generate output **382** that includes kinematic output which is similar to the kinematic input **322** but modified according to the tunable filter parameters **324** and the articulated-bodies description **326**. In addition, the output **382** can include the generalized forces and auxiliary states which generated a particular kinematic output. Information regarding each of the blocks is given below in more detail.

Much of the discussion below uses examples from the science of biomechanics. However, the present invention is not limited to biomechanics. The principles described below can be used for many different physical or imaginary (computer animation) systems.

Before proceeding, it is useful to clarify some of the notational conventions used. An arrow over a symbol expresses a vector or an array of quantities. A double headed arrow over a symbol expresses a matrix of quantities. A subscript e on a symbol expresses that the quantity or quantities represented by the symbol is from the kinematic input **322**. A subscript d on a symbol expresses that the quantity or quantities represented by the symbol is a desired processed kinematic input originating from process kinematics **342**. If a generalized coordinate, or a time derivative thereof, or a function of generalized coordinates, or a time derivative thereof, does not have a subscript, it pertains to the dynamic model. Finally, in what follows, the term body (bodies) is meant to refer to the mathematical representation in the dynamic model of a physical or imaginary body (bodies).

The kinematic inputs **322** can include a set of curves (or sets of points that define a set of curves) that represent time histories of displacements or orientations. Some of the input displacements or orientations, $\vec{q}_e$, can correspond directly to a subset of the generalized coordinates of the dynamic model, $\vec{q}$. Other of the input displacements or orientations, $\vec{\Phi}_e$, which may be the position of a video marker in the inertial frame or the like, may not correspond directly to a subset of the generalized coordinates of the dynamic model, but rather correspond to functions of the generalized coordinates, $\vec{\Phi}(\vec{q})$.

As is known by skilled artisans, the choice of which generalized coordinates $\vec{q}$ are used to specify the configuration of a model is somewhat arbitrary and often based on convenience. A model should have as many generalized coordinates as it has degrees of freedom; however, one may also define more generalized coordinates than degrees of freedom. This line of discussion is pursued to point out that the distinction between $\vec{q}$ and $\vec{\Phi}(\vec{q})$ is a matter of definition. That is, one can suitably define a set of generalized coordinates, $\vec{q}$, for a model such that all $\vec{\Phi}(\vec{q})$ are eliminated. If this redefinition were performed, then the kinematic inputs **322** would be described entirely by $\vec{q}_e$. In practice, this approach may not be the most practical approach to filtering the kinematic inputs **322**. Rather, one would likely choose an unconstrained and convenient $\vec{q}$ for the model and leave many of the kinematic inputs **322** expressed as functions of the generalized coordinates, $\vec{\Phi}_e(\vec{q})$. For example, one might choose a generalized coordinate of the model to represent hip flexion angle, q^{hip}, and ask the dynamic filter to track the inertial position a video marker placed on the thigh, $\Phi_e^{mark}(q^{hip})$ which is a function of q^{hip}. By posing the problem in this way, solving the inverse kinematic problem explicitly (i.e., using $\Phi_e^{mark}(q^{hip})$ to first infer q_e^{hip}) can be bypassed in favor of solving the inverse kinematic problem implicitly as a part of the dynamic filtering process.

A $\vec{q}_e$ specified by the user need not entirely specify all the generalized coordinates, $\vec{q}$, of the model. Data can be unspecified (i.e., omitted) for a q_e over the entire time interval of a motion or for a portion or portions of the time interval of the motion. If q_e is unspecified for a time interval, then the corresponding q is also considered to be unspecified for the time interval. Any number of $\vec{\Phi}_e(\vec{q})$ may be specified, including zero and including many more than the number of $\vec{q}$ of the dynamic model. A $\vec{\Phi}_e(\vec{q})$ may also be unspecified, but this does not imply that a q is unspecified.

In motion capture processes, leaving generalized coordinates unspecified is of benefit if certain displacements or orientations of the articulated bodies are difficult to measure accurately or if, for example, video markers become obscured. In key framing, leaving generalized coordinates unspecified is of benefit, for example, because it can reduce the amount of work demanded from the animator. If the generalized coordinates of the model are left unspecified, they are predicted by the dynamic filtering process.

The process kinematics component **342** can be used to curve fit $\vec{q}_e$ and $\vec{\Phi}_e$ in time to produce analytical expressions for the desired generalized coordinates $\vec{q}_d$ and the desired kinematic functions of the generalized coordinates $\vec{\Phi}_d(\vec{q})$. The curve fitting may be performed using any suitable mathematical representation including polynomials, Fourier series, linear interpolation, splines, or the like. The quantities $\vec{q}_d$ and $\vec{\Phi}_d(\vec{q})$ can be differentiated with respect to time (t) to estimate desired generalized speeds ($\dot{q}_d$, $\dot{\Phi}_d(\vec{q}$, $\dot{q}$)) and desired accelerations ($\ddot{q}_d$, $\Phi_d(\vec{q}$, $\dot{q}$, $\ddot{q}$)).

Unless stated otherwise, hereafter, the dependence of the $\vec{\Phi}$'s on the $\vec{q}$'s will often be omitted and treated as though it is understood. It is also noted that in the field of dynamics the relation between a generalized coordinate and a generalized speed need not be the one implied, namely that $\dot{q}=d\vec{q}/dt$. It is well known to skilled artisans in the field that many relationships between the generalized coordinates and speeds other than the one implied herein may be posed. However, for the sake of simplicity, the above simple relationship, namely $\dot{q}=d\vec{q}/dt$, is adopted throughout.

This differentiation of the kinematic input **322** can be carried out numerically or analytically. Having analytical expressions of $\vec{q}_d$, $\dot{q}_d$, $\ddot{q}$, $\vec{\Phi}_d(\vec{q})$, $\dot{\Phi}_d$, Φ_d, and Φ_d can allow the kinematic information to be queried for any arbitrary time (t), which may be beneficial during integration that will be performed later, particularly if the integration involves advancing in time by variable step lengths. The $\vec{q}_d$, $\dot{q}_d$, $\ddot{q}_d$, $\vec{\Phi}_d(\vec{q})$, $\dot{q}_d$, and $\vec{\Phi}_d$ can be sent to the software component **362** as input for dynamic filtering.

The articulated-bodies description **326** can include information that may vary depending on the use. For the example in biomechanics, the articulated bodies may represent a leg of a human, and the information may include:

body moments of inertia and masses;

how the bodies are connected to one another in terms of joint types and locations of the joints with respect to the centers of masses of the bodies (the joint types generally determine which generalized coordinates $\vec{q}$ are used);

the mechanics of passive joint structures;

constraints on the generalized coordinates ($\vec{q}$);

force interaction with an external environment;

controls ($\vec{x}$)(e.g., muscle excitation levels);

actuator properties (e.g., mathematical representations of muscle mechanics and dynamics);

auxiliary states and their properties ($\vec{a}$) (e.g., muscle activation and fatigue states);

and the like.

More, fewer, or different parameters can be used depending on the system and the desired specificity chosen by the user. Information from the articulated-body description **326** can be used to generate the dynamic model **344** that is described in more detail later. Information generated from the dynamic model **344** can be used by the software component **362** that dynamically filters the data.

The controls, $\vec{x}$, generally pertain to the actuation of the articulated bodies as represented by the dynamic model. The controls may include generalized forces that are applied to the articulated bodies. However, the controls may also include variables which pertain to actuation of the articulated bodies more indirectly than generalize forces, such as a neural excitation level of a muscle, an electrical current or voltage sent to a motor, an extent of depression of an accelerator pedal of a vehicle, and the like.

The states of the articulated bodies ($\vec{y}$) as represented by the dynamic model can comprise all integrated quantities, which generally include the generalized coordinates ($\vec{q}$) and generalized speeds ($\dot{q}$), but may also include actuator generalized forces ($\vec{F}_A$), external generalized forces ($\vec{F}_E$), and any number of auxiliary states ($\vec{a}$) which are used in support of the simulation process, and the like. Thus, often the states take the form:

$$\vec{y} = \begin{bmatrix} \vec{q} \\ \dot{\vec{q}} \\ \vec{F}_A \\ \vec{F}_E \\ \vec{a} \\ \vdots \end{bmatrix}$$

The software component **362** also receives input from the tunable filter parameters **324**. Some of the details of the tunable filter parameters **324** can be seen in FIGS. **4** and **5**.

For each generalized coordinate, q^i, there can be a corresponding pair of correction factors, k_q^i and $k_{\dot{q}}^i$, and a corresponding weight, w_q^i, as shown in section **402** in FIG. **4**. Note that the correction factors and weights can change with time (horizontal axis). The higher k_q^i the more aggressively tracking error between q^i and q_d^i is corrected. The higher $k_{\dot{q}}^i$ the more aggressively tracking error between $\dot{q}^i$ and $\dot{q}_d^i$ is corrected. Each weight can be used to determine which generalized coordinates are more important. The track switches in FIG. **4** can allow the tracking of generalized coordinates to be turned on and off as desired by the user. If the box is checked, the generalized coordinate can be tracked according to its correction factors and weight. If the box is not checked, the generalized coordinate may be left to vary freely during the dynamic filtering process as though it had not been specified.

Section **404** in FIG. **4** illustrates an entirely analogous set of filter parameters for each Φ_d^i.

FIG. **5** includes a table **500** showing upper and lower bounds for the controls $(\vec{x})$. If a box in FIG. **5** is checked, its corresponding control will be entirely unbounded. Otherwise, the upper and lower limits can change over time (horizontal axis) as shown in FIG. **5**.

Other parameters that may be specified include performance weights $(\vec{wx}, \vec{wa}$, etc.) used for terms in calculating the performance criterion, constraint weights $(\vec{wc})$, an integration tolerance (tol), and an optimization convergence criterion (eps). When tol and eps are large, the computations may be performed quickly but perhaps at the expense of accuracy. When tol and eps are small, the computations may take longer but the accuracy should improve. These other parameters are not shown in FIGS. **4** or **5**, but they may be part of the tunable filter parameters **324** that can be used in dynamically filtering the data (block **362**).

The dynamic filter component **362** is generally illustrated in FIG. **6**. The dynamic filter component can access information from the processed kinematic inputs **342** and the tunable filter parameters **324**, exchange information with the dynamic model **344**, and send information to the output **382**. As will become evident, the component **362** may perform functions iteratively. Many of the parameters used in the component **362** may be initialized on the first pass through the component **362**.

FIG. **6**A includes a flow diagram showing some of the acts performed by the component **362**. The method can include accessing a variety of information as shown in block **60**. The information may include the specified kinematics (such as positions, velocities, accelerations, orientations, angular velocities, angular accelerations, and the like), various dynamic properties available from the dynamic model **344** (such as dynamic properties of a body, states, forces, accelerations, and the like), and filter parameters (such as correction factors, weights, and the like). More or fewer variables may be accessed depending on the dynamic model and the user's desired specificity. The method can further include computing or otherwise determining corrected accelerations **62**. The corrected accelerations $(\ddot{q}_c)$ can be computed such that if achieved by the dynamic model, the model $\vec{q}$, $\dot{q}$, $\vec{\Phi}$, and $\dot{\Phi}$ will be driven toward $\vec{q}_d$, $\dot{q}_d$, $\vec{\Phi}_d$, and $\dot{\Phi}_d$.

The method can further include an optimization-based inverse dynamics process (block **64**) that determines values of the controls $(\vec{x})$ that minimize or maximize a user specified performance criterion (p) and optionally satisfy an additional set of constraints $(\vec{c})$. The performance criterion and constraints are chosen so as to produce an $\vec{x}$ which, when input to the forward dynamic simulation process (block **66**), results in beneficial filtering characteristics. The performance criterion and constraints may include any number of mathematical combinations of quantities such as tracking errors, actuator forces, external forces, auxiliary states, and the like. The optimization can be to minimize or maximize the value(s) of the performance criterion.

The method can also include forward dynamic simulation process which, based on the $\vec{x}$ determined at block **64** using a forward dynamic simulator, advances the states of the model, $\vec{y}$, in time (block **66**). The processes outlined in FIG. **6**A are stopped when the time is advanced to or beyond the specified final time (tf).

Referring back to FIG. **6**, details regarding the data flow and software configuration of the component **362** are described in more detail. The processed kinematic inputs from block **342** can include the desired kinematics **6002** as functions of time. From this information as well as the current time t **6920**, the component **622** can determine the desired kinematics at time t, including information **6222** (i.e., a combination of $\vec{q}_d$ and $\vec{\Phi}_d$), information **6224** (i.e., a combination of $\dot{q}_d$ and $\dot{\Phi}_d$), and information **6226** (i.e., a combination of $\ddot{q}_d$ and Φ_d). The information **6222**, **6224**, and **6226** can be sent to and received by the acceleration correction component **624**.

From the tunable filter parameters from block **324** and the current time t **6920**, the component **642** can determine the current values of any tunable filter parameters **6422** at time t and send this information to the acceleration correction component **624**, the optimization-based inverse dynamics component **662**, and the forward dynamic simulation component **682**.

The acceleration correction component **624** can access or receive information **6222** **6224**, and **6226** from component **622**, and information **6422** from component **642**, as well as the current values of the model states $\vec{y}$ **6922** from a feedback loop coming from component **692**. From $\vec{y}$, $\vec{q}$ and $\dot{q}$ can be extracted and used together with correction factors $\vec{k}_q$, $\vec{k}_{\dot{q}}$, $\vec{k}_\Phi$, and $\vec{k}_\Phi$ from **6422** and information **6222**, **6224**, and **6626** from **622** to compute corrected accelerations $\ddot{q}_c$ and Φ_c. A common implementation follows:

$$\vec{\ddot{q}}_c = \vec{\ddot{q}}_d + \vec{k}_{\dot{q}}(\vec{\dot{q}}_d - \vec{\dot{q}}) + \vec{k}_q(\vec{q}_d - \vec{q}) \text{ and}$$

$$\Phi_c = \Phi_d + \vec{k}_\Phi(\dot{\Phi}_d - \dot{\Phi}) + \vec{k}_\Phi(\vec{\Phi}_d - \vec{\Phi}).$$

Other formulations for computing $\ddot{q}_c$ and Φ_c are likely possible. The output from the accelerator correction component **624** includes information **6242**, $\ddot{q}_c$ and Φ_c, that can be sent to and received by the optimization-based inverse dynamics component **662**.

The optimization-based inverse dynamics component **662** can be used at each time step t to determine or update the controls $(\vec{x})$ **6622** to optimize, including evaluate, a performance criterion (p) while satisfying any specified constraints $(\vec{c})$. To accomplish this task, the optimization based inverse dynamics component **662** may also receive some information **6422** from the query parameters component **642**. Information **6422** may, for example, include various weight factors, a convergence criterion, and other similar filter parameters. The component **662** may also receive the current time (t) **6920**, the current states $(\vec{y})$ **6922**, and the size of the last time increment (dt) **6924** from the time incrementing component **692**. The details of the component **662** are described later. The controls ($\vec{x}(t)$) **6622** can be sent to and received by the forward dynamic simulator **682**.

The forward dynamic simulator **682** can be used to advance the states $\vec{y}$ forward in time from the current time t to a new time t+dt. To accomplish this advancement, the forward dynamic simulator may implement any number of conventional integration techniques (e.g., Runge-Kutta, Runge-Kutta-Feldberg, algebraic integrators, implicit integrators, or the like). In addition to the controls ($\vec{x}$) **6622**, the simulator **682** may also receive the time (t) **6920**, the states ($\vec{y}$) **6922**, and time increment (dt) **6924** from the time incrementing component **692**. If integration is accomplished numerically, the simulator **682** advances the states to t+dt using time derivatives of $\vec{y}$ computed by making calls to the dynamic model **344**. The details of the component **682** are described later. The output of the simulator **682** can include t **6820**, new states $\vec{y}(t+dt)$ **6822**, and the time increment dt **6824** which can be sent to and received by the time incrementing component **692**.

The time incrementing component **692** may serve different functions. The component **692** can increment the time, so that the current time is changed from t to t+dt. If the incremented time is less than the final time of the motion, the process is allowed to continue. Otherwise the process is stopped. If the process is continued, the values from the simulator **682** are assigned to the current values ($\vec{y}(t)=\vec{y}(t+dt)$, etc.). The new current time (t) **6920**, the new current states **6922**, and time increment (dt) **6924** can be sent back to the components as shown in FIG. **6**.

At the end of the process or for each time increment, the controls ($\vec{x}$) and states ($\vec{y}$) may be stored in RAM **164** or storage device **162** of the data processing system **100**. When the finishing time is reached, information **6006** may be sent as output **382**. The output **382** may be sent to the monitor **142**, a printer (not shown in FIG. **1**) or stored on storage device **162** (if intermediate information is stored in RAM **164**) or a remote storage device via a network (not shown). In some embodiments, the output information related to the body may be part of an article. The article can comprise a data processing system readable medium and a code embodied within the data processing system readable medium. The code would include the output information that is generated by the methods described herein. At this point, the process can be complete or run again for a different time period or a different system.

Attention is now directed to details that may be performed by the optimization-based inverse dynamics component **662**. Referring to FIG. **7**, data flow and some of the parts of component **662** are described. The optimization-based inverse dynamics algorithm embodied in component **662** as described here utilizes a gradient-based optimization approach. Other optimization approaches may also be employed if desired (e.g., simplex, simulated annealing, etc.). The inputs may include controls ($\vec{x}$) **6622**, time (t) **6920**, states ($\vec{y}$) **6922**, time increment (dt) **6924**, and the corrected accelerations ($\ddot{q}_c$) **6242**. This information is used by the performance and constraint unit **702** and the performance and constraint differentiator **704**. Additional input can include filter parameters **6422** that can include, for example, a convergence criterion (eps), described below. More details of the unit **702** are described later. Unit **702** calculates a performance criterion (p) **7022** and constraints ($\vec{c}$) **7024**. The performance criterion **7022** and the constraints **7024** can be sent to and received by the differentiator **704** and the optimizer **722**.

The differentiator **704** can be used to compute derivatives of the performance criterion with respect to the controls ($\overrightarrow{dpdx}$) **7042** and derivatives of the constraints with respect to the controls

$(\overleftrightarrow{dcdx})$ 7044.

These derivatives can be computed analytically or numerically by conventional methods. The derivatives **7042** and **7044** can be sent to and received by the optimizer **722**.

Based on the quantities **7022**, **7024**, **7042**, and **7044**, and potentially other parameters that are commonly used by optimization algorithms, the optimizer **722** can determine the direction in which the controls ($\vec{x}$) should be changed in order to minimize or maximize p **7022** while satisfying the constraints $\vec{c}$ **7024**. A vector $\overrightarrow{dxda}$ **7222** represents this direction. Based on quantities that may include direction **7222**, the optimizer computes a convergence factor that can be compared to the input convergence criterion eps. Commonly if the computed convergence factor is not less than eps, the direction **7222** can be sent to and received by a line searching unit **762**. The line search unit **762** can determine an step length α in direction **7222** according the formula

$$\vec{x} = \vec{x} + \alpha \cdot \overrightarrow{dxd\alpha}$$

so that $\vec{x}$ is moved closer to an optimal solution. When $\vec{x}$ is updated in this manner, the performance criterion **7022** and constraints **7024** are recomputed based on the new values of $\vec{x}$. The process continues iteratively until the computed convergence factor is less than eps, at which point the controls **6622** are sent to the simulator **682**.

Attention is now directed to the performance and constraints unit **702**, a portion of which is illustrated in FIG. **8**. The dynamic model **344** can be used to determine the accelerations of a body. In this embodiment, the model **344** can be used to calculate those accelerations in order to evaluate a performance criterion and constraints. The equations of motion can be represented in the following form, from which the accelerations can be calculated:

$$\ddot{\vec{q}} = \{I^{-1}(\vec{q})^{*}\{C(\vec{q}, \dot{\vec{q}}^{2}) + G(\vec{q}) + \vec{F}_{A}(\vec{q}, \dot{\vec{q}}, \vec{a}) + \vec{F}_{E}(\vec{q}, \dot{\vec{q}})\},$$

where:

$I^{-1}(\vec{q})$ can be an inverse of the system mass matrix;

$C(\vec{q}, \dot{q}^2)$ can be a vector of generalized active forces arising from centripetal forces;

$G(\vec{q})$ can be a vector of generalized active forces arising from gravitational forces;

$\vec{F}_A(\vec{q}, \dot{q}, \vec{a})$ can be a vector of generalized active forces arising from actuators; and

$\vec{F}_E(\vec{q}, \dot{q})$ can be a vector of generalized active forces arising from interaction with the external environment.

The actuator forces can be used in the equation and may be thought of an "internally generated" forces. In biomechanics, muscle forces may be examples of these actuator forces. The external environment term can account for forces that occur outside the system beyond centripetal and gravitational effects. External environmental forces can include forces due to fluids (e.g., wind, waves, etc.) or impacts with external objects. The external environment forces can be a function of the generalized coordinates and speeds.

Returning to FIG. **8**, a generalized force calculation unit **802** can be used to determine the generalized forces **8022**, which includes the actuator forces and the external forces. Inputs can include time **6920**, states **6922**, time increment **6924**, and controls **6622**. The details of the generalized force calculation are described later. The generalized forces can be sent to and received by the acceleration calculation unit **804**.

In addition to the generalized forces **8022**, the acceleration calculation unit **804** receives the generalized coordinates $\vec{q}$ **8062** and the generalized speeds $\dot{q}$ **8064**, which can be extracted from the states $\vec{y}$ **69226** using an extractor unit **806**. Note that $\vec{q}$ and $\dot{q}$ are just some of the information within the states. From the quantities **8022**, **8062**, and **8064**, the accelerations $\ddot{q}$ **8042** can be calculated using the equations of motion of the dynamic model **344**. Equations of motion can be generated by hand or by using a number of commercially available software programs, such as SD/Fast by Symbolic Dynamics, Inc., ADAMS by Mechanical Dynamics, Inc., or Autolev by Kane and Levinson.

The set of Φ corresponding to $\vec{\Phi}_d(\vec{q})$ can be evaluated using the kinematic computation unit **805**, based on the generalized coordinates **8022**, speeds **8064**, and accelerations **8042**.

A performance calculation unit **808** can be used to evaluate a performance criterion and constraints. In addition to receiving $\ddot{q}$ **8042** and Φ **8052**, the unit **808** may access the weights (e.g., W_q and W_x) from the tunable filter parameters and is shown as **6422** in FIG. **8**. The unit **808** may access any $\ddot{q}_c$ and any Φ_c from information **6242** from the output of the acceleration correction unit **624**. The unit **808** also has access to the time **6920**, the states **6922**, and the time increment **6924**. From all these quantities a range of forms of performance criteria and a range of forms of constraints can be calculated.

An important consideration in the choice of the forms of p and $\vec{c}$ is to drive the trajectory of the model ($\vec{q}$, $\dot{q}$) toward the desired kinematics ($\vec{q}_d$, $\dot{q}_d$, $\vec{\Phi}_d$, $\dot{\Phi}_d$). This consideration can be stated as follows: solve for $\vec{x}$ so that, when $\vec{x}$ is input to the forward dynamic simulator (block **682**) and the states are advanced in time by a time step, $\ddot{q}$ is approximately $\ddot{q}_c$ and Φ is approximately Φ_c over that time step. Other considerations can impact the choice of the forms of p and $\vec{c}$. These other considerations might include minimizing or maximizing actuator efforts, energy consumption, joint contact forces, acceleration of an unspecified generalized coordinate, and the like. When multiple considerations are expressed in p or in a combination of p and $\vec{c}$, the balance between the considerations is generally achieved with weight factors which can come from input **6422**. For example, when the following performance criterion is minimized it can have the effect of tracking the desired trajectories closely while at the same time minimizing a measure of actuator effort:

$$p = \underbrace{\sum_{i=1}^{nx} w_x^i (x^i)^2}_{\substack{\text{minimize} \\ \text{actuator} \\ \text{effort}}} + \underbrace{\sum_{i=1}^{nq} w_q^i (\ddot{q}_c^i - \ddot{q}^i)^2 + \sum_{i=1}^{n\Phi} w_\Phi^i \left(\ddot{\Phi}_c^i - \ddot{\Phi}^i\right)^2}_{\text{track trajectories closely}},$$

where $w_x{}^i$, $w_q{}^i$ and $w_\Phi{}^i$ are weight factors used to weight each consideration.

In the event that a $\ddot{q}^j$ is unspecified at a point in time or its tracking switch has been unchecked, the immediately preceding equation for p should omit the ($\ddot{q}_c{}^i - \vec{q}^{\,i}$) term from the summation for i=j. Numerous standard programming techniques can be used to accomplish this. The analogous procedure holds for an unspecified $\vec{\Phi}^j$.

The forms p and $\vec{c}$ can be posed in numerous ways. One phrasing of the parameter optimization problem might be appropriate for generating dynamically realistic computer animations, for which the animation artist wishes only to specify a few of the generalized coordinates through key-framing or motion capture. A different performance criterion could be used during medical simulations, which instead of minimizing the magnitudes of the unspecified accelerations, the magnitudes of the generalized forces (e.g., muscle forces) during a task like standing from a squat position can be minimized. Numerous variations can exist and are appreciated by skilled artisans after reading this specification.

After the calculation of the performance criterion **7022** and constraints **7024**, these quantities can be sent to and received by the performance and constraint differentiation unit **704** and the optimizer **722** in FIG. **7**.

The generalized forces unit **802** is illustrated in FIG. **9**. Inputs to an auxiliary state equation unit **902** may include time **6920**, states **6922**, time increment **6924**, and controls **6622**. The auxiliary state equation unit **902**, the equations of which derive from the dynamic model **344**, may be used to represent factors such as muscle activation, muscle fatigue, degradation of a motor, or the like. The calculations can be performed using any number of conventional techniques. The unit approximates auxiliary states $\vec{a}$(t+dt) **9022** that can be sent to and received by the actuator state equation unit **922**.

The states **6922** can include information regarding forces from actuators $\vec{F}_A$(t), displacements $\vec{q}$(t), speeds $\dot{q}$(t), and the like. Extracting unit **904** can be used to separate out forces $\vec{F}_A$(t) **9042** from the states, and extracting unit **906** can be used to separate out the displacements $\vec{q}$(t) **9062** and velocities $\dot{q}$(t) **9064** from the states.

The actuator state equation unit **922**, the equations of which derive from the dynamic model **344**, allows an estimation of the actuator forces at time t+dt (i.e., $\vec{F}_A$(t+dt)) **9222**. These actuator forces can include muscle forces, motor torques and the like. The actuator state unit may receive the forces $\vec{F}_A$(t) **9042**, the displacements $\vec{q}$(t) **9062**, velocities $\dot{q}$(t) **9064**, the auxiliary states $\vec{a}$(t+dt) **9022**, controls **6622**, time **6920**, and the time increment **6924**.

External forces are addressed by the external forces unit **924**, the equations of which derive from the dynamic model **344**. The inputs to unit **924** may include displacements $\vec{q}$(t) **9062**, velocities $\dot{q}$(t) **9064**, time **6920**, and time increment **6924**. That information can be used to approximate the external forces at time t+dt ($\vec{F}_E$(t+dt) **9242**). The information from units **922** and **924** can be concatenated by the concatenating unit **926** to give the generalized forces $\vec{F}$(t+dt) **8022**.

When determining controls using the optimization-based inverse dynamic algorithm (embodied in **662**), it is of benefit to estimate the generalized forces $\vec{F}$ at t+dt rather than at t for several reasons. First, it can allow for a better estimate of the accelerations that will occur when the states are advanced in time from t to t+dt, which can improve computational speed and can yield more realistic estimates of $\vec{F}$. Second, it can allow for better control of the center of mass for a system of articulated bodies which can be important for balance and navigation.

There are numerous standard methods which can be used to estimate $\vec{F}$(t+dt) in a computationally efficient manner. In the case of simple relationships between $\vec{F}$ and the states (e.g., linear springs), the problem can occasionally be solved analytically. In the case of more complicated relationships, the dependence of $\vec{F}$ on the states can be linearized and then perhaps solved analytically. Another option is using low-order integration (e.g., forward Euler, 2nd order Runge-Kutta). The simplest approximation is to assume that $\vec{F}$(t)=$\vec{F}$(t+dt), and this assumption is adequate for implementing a working embodiment of the invention.

The following illustrates a simple analytical example. Let the generalized force f be characterized by the following differential equation:

$$df/dt=(x-f)/k,$$

where x is a control and k is a constant. This equation is a separable and can be integrated analytically if x is also assumed to be constant over the interval of integration. The solution is:

$$f(t+dt)=x-(x-f(t))\exp[-dt/k],$$

where dt is taken as the interval of the integration.

Attention is now directed to the simulator **682** as shown in FIG. **10**. In one embodiment, the simulator **682** includes a numerical integrator **1022** that can receive the controls **6622**, time t **6920**, states **6922**, and the time increment dt **6924**. The process of numerical integration is conventional and has many accepted implementations. Many numerical integrators may make multiple evaluations of the time derivative of the states for each integration time step, each evaluation occurring at some altered time t'=t+δ, where δ can be a number that may be smaller or on the order of dt **6924**. The time t' **1002**, controls **1004** at time t', and states **1006** at time t' are sent to and received by the dynamic model **344** to determine the time derivatives of the states. The time derivatives of the states **1010** at time t' are sent to and received by the numerical integrator **1022**.

These multiple evaluations can be used to make a better approximation of the states at time t+dt. A 4th order Runge-Kutta numerical integrator, for example, can make four derivative evaluations in the process of advancing the states at time t to the states at time t+dt. For variable step integrators, the time step, dt, can vary. It may be useful to know the size of the time step during the optimization-based inverse dynamics algorithm previously described. Knowledge of the current size of dt can allow an estimation of the auxiliary states, actuator forces, and external forces at t+dt which can improve the determination of the controls **6622**. The outputs **6006** from the simulator **682** can include the states at time t+dt and the time increment dt.

FIG. **11** includes a portion of the dynamic model **344** that can be used to compute time derivatives of the states in conjunction with the numerical integrator **1022**. State information **1006** at time t' may be fed into extractor units **1122**, **1124**, and **1126**. Extractor unit **1122** separates the generalized coordinates and speed **1123** from the state information **1006**. Extractor unit **1124** separates the actuator forces **1125** from the state information **1006**, and extractor unit **1146** separates the auxiliary states **1127** from the state information **1006**.

The external forces software unit **1142** may use time t' **1002**, the controls **1004** at time t', the generalized coordinates and speeds **1123**, actuator forces **1125**, and auxiliary states **1127** to calculate the external forces **1143**. The external force vector **1143** can be sent to and received by the motion software unit **1162**.

The actuator dynamics software unit **1144** can determine **1145**, the time derivative of actuator forces ($\dot{F}_A$) Inputs to the unit **1144** may include the time t' **1002**, the controls **1004**, the generalized coordinates and speeds **1123**, the actuator forces **1125**, and the auxiliary states **1127**. The time derivative of actuator force **1145** can be sent to and received by an assembly unit **1182**.

The auxiliary state software unit **1146** can determine the time derivatives of the auxiliary states ($\dot{a}$) **1147**. Inputs to the unit **1146** may include the time t' **1002**, the controls **1004**, the generalized coordinates and speeds **1123**, the actuator forces **1125**, and the auxiliary states **1127**. The time derivative of the auxiliary states **1147** can be sent to and received by the assembly unit **1182**.

Software unit **1162** can determine equations of motion using conventional software. Inputs to the unit **1162** may include the time t' **1002**, the generalized coordinates and speeds **1123**, the actuator forces **1125**, and the external forces **1143**. The software unit **1162** can determine the accelerations $\ddot{q}$ **1163** at time t'. The accelerations **1163** can be sent to and received by an assembly unit **1182**. The assembly unit **1182** assembles the state time derivatives **1010** at time t' and returns that information back to the numerical integrator **1022**.

All the equations and calculations performed within the portion of the dynamic model **344** as shown in FIG. **11** are conventional and vary depending on the system of articulated bodies defined in the description **326**. However, skilled artisans appreciate this and can use equations and calculations that are tailored for their specific systems.

The data processing system **100** with the software components as described can be used to perform forward dynamics preceded by optimization-based inverse dynamics. Such a system may be useful in the prediction of unspecified generalized coordinates, resolution of redundant control in the context of solving a tracking problem, accounting for dynamic coupling in the equations of motion, or potentially other motion-related problems.

Clearly, the methods and system can be applied quite generally as a means of generating dynamically consistent motion for any system of articulated bodies for which dynamic equations of motion can be derived. Articulated bodies include humans, animals, imaginary creatures, robots, vehicles, space craft, and the like.

The process uses algorithmic components that are synergistically combined and employed. In particular, employing the optimization-based inverse dynamics algorithm in combination with a forward dynamic simulator can allow a) dynamically infeasible kinematics to be eliminated or filtered from the input kinematics, and b) novel motion to be generated for unspecified generalized coordinates of the equations of motion. Further, by leaving a q unspecified and by specifying a Φ_e that is a function of the q, an explicit solution of the inverse kinematics problem can by bypassed in favor of solving the inverse kinematic problem implicitly. That is, by tracking Φ_e values for q will be generated. The methods can be of value to anyone seeking to generate a) dynamically correct motion, b) motion which is achievable within the force generating capabilities of a physical system, c) displacements that cannot be measured accurately, d) novel motion, or the like.

The methods can be useful in the field of medicine. The methods can be used to produce accurate simulations of human kinetics as a means of estimating in-vivo muscle coordination patterns, muscle forces, and joint-contact forces. This information can be valuable for the diagnosis and treatment of movement pathologies and for the design of joint prostheses. In a biomechanics example, generalized forces can contribute to accelerations throughout the articulated linkage, not just to accelerations at joints that they span. Therefore, actuators can globally make up for insufficient accelerations of generalized coordinates they do not directly control. Further, the methods and system may be used in the field of ergonomics, particularly for quantifying repetitive stresses seen in the workplace.

The methods can be used as a computationally feasible method for producing accurate simulations of human or animal kinetics. These simulations can provide improved estimates of a wide range of in-vivo quantities, such as but not limited to, muscle coordination patterns, muscle forces, joint contact forces, and bone loading patterns. These quantities can be used in numerous ways, including:

1. in the study and treatment movement pathologies that arise from neurological trauma such as cerebral palsy, stroke, or the like;
2. in the study and treatment of disease processes which impact the musculoskeletal system such as diabetes, arthritis, or the like;
3. in the design of joint prostheses such as joint and limb replacements, braces, or the like;
4. in the design of sports equipment such as helmets, shoes, rackets, golf clubs, or the like;
5. in the design of suits for altered pressure or gravitational environments such as space, moons, unusual places on Earth, other planets, or the like;
6. in the design of machine-person interfaces such as vehicle or machine controls, or the like;
7. in the design of vehicle safety equipment such as seat belts, air bags, headrests, or the like; or
8. other designs or studies of motion of real or imaginary objects.

The methods can also be useful in the field of computer animation. The methods can be used to enhance the dynamic realism of computer animations that involve the motion of articulated bodies. Given a loose script of the motion a computer animator would like, the methods can be capable of generating motion that is close to the motion scripted by the computer animator but altered in order to conform with the physical laws of classical dynamics.

The methods and system can be used to improve the quality of animations or reduce the time or cost required to produce animations of similar quality. For example, the methods and system can be used:

1. to attenuate or filter errors in motion capture data;
2. to splice discrepant motion-capture or animation sequences together;
3. as an interactive tool for creating dynamically realistic animation sequences; or
4. for representing other systems where physical data for motion of the system cannot be empirically collected.

Note that the methods and system may depart from computed torque control as described herein. The control of a physical device is not intended. Rather, the control of an abstract, mathematical representation of an articulated linkage may constitute the full extent of the control problem. The abstract, mathematical representation of an articulated linkage need not have any correspondence with a real physical system. Rather, the user can be free to create an imaginary articulated linkage possessing exaggerated physical characteristics. The specification of exaggerated physical characteristics can be one of the ways dynamic filtering of motion facilitates a user's achievement of creative or artistic output. Additionally, deviations from the input kinematics may be desired. Whereas in robotics the reduction of trajectory errors is an essential consideration in the design of the robot and in the subsequent control of the robot, a feature of the dynamic filtering methods and system can include the generation of kinematic output that deviates, perhaps substantially, from the kinematic input. These deviations are generated based on the dynamical properties of a specified articulated linkage and dynamical properties of actuators that drive the articulated linkage. Further, control techniques in robotics do not typically contend with redundant control, a trait which is characteristic of the human body.

Skilled artisans appreciate that the methods may use generalized coordinates ($\vec{q}$), other displacements or orientations ($\vec{\Phi}$), or a combination thereof. When working only with generalized coordinates, one of the generalized coordinates may not be specified as part of the kinematic inputs **322**. The output information **382** can be generated to provide a value for that unspecified generalized coordinate. When working with $\vec{\Phi}$, a Φi may be a function of a generalized coordinate, but the generalized coordinate is not specified as part of the kinematic inputs **322**. The output information **382** can be generated to provide a value for that unspecified generalized coordinate.

In the foregoing specification, the invention has been described with reference to specific embodiments. However, one of ordinary skill in the art appreciates that various modifications and changes can be made without departing from the scope of the present invention as set forth in the claims below. Accordingly, the specification and figures are to be regarded in an illustrative rather than a restrictive sense, and all such modifications are intended to be included within the scope of present invention.

Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature or element of any or all the claims. As used herein, the terms "comprises," "comprising," or any other variation thereof, are intended to cover a non-exclusive inclusion, such that a process, method, article, or apparatus that comprises a list of elements does not include only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus.

What is claimed is:

1. A method of filtering motion of a body comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

accessing a filter parameter, wherein the filter parameter is part of a filter parameter set that includes a correction factor and a weight;

determining a desired acceleration using the specified kinematics;

determining a corrected acceleration using the filter parameter, the desired acceleration, and the state;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the corrected acceleration is used during the optimization-based inverse dynamics algorithm; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

2. A method of filtering motion of a body comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:

evaluating a performance criterion using the specified kinematics and the dynamic property; and

updating the control so as to minimize or maximize the performance criterion using an optimizer; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

3. A method of filtering motion of a body comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:

evaluating a constraint using the specified kinematics and the dynamic property; and

updating the control so as to satisfy the constraint using an optimizer; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

4. A method of filtering motion of a body comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:

estimating a generalize force at time t+dt; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

5. A method of filtering motion of a body comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body, wherein a generalized coordinate of the body is unspecified at a point in time;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state; and

generating output information, wherein the output information includes a generated value of the generalized coordinate at the point in time.

6. A method of filtering motion of a body comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body, wherein:

a q of the body is unspecified at a point in time; and

at least some of the specified kinematics comprises a Φ of the body at the point in time, wherein the Φ is a function of the q;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property;

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state; and

generating output information, wherein the output information includes a generated value of the q at the point in time.

7. A data processing system readable medium having code embodied therein, the code including instructions executable by a data processing system, wherein the instructions are configured to cause the data processing system to perform a method of filtering motion of a body, the method comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

accessing a filter parameter, wherein the filter parameter is part of a filter parameter set that includes a correction factor and a weight;

determining a desired acceleration using the specified kinematics;

determining a corrected acceleration using the filter parameter, the desired acceleration, and the state;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the corrected acceleration is used during the optimization-based inverse dynamics algorithm; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

8. A data processing system readable medium having code embodied therein, the code including instructions executable by a data processing system, wherein the instructions are configured to cause the data processing system to perform a method of filtering motion of a body, the method comprising:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic

property, wherein the optimization-based inverse dynamic algorithm comprises:
evaluating a performance criterion using the specified kinematics and the dynamic property; and
updating the control so as to minimize or maximize the performance criterion using an optimizer; and
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

9. A data processing system readable medium having code embodied therein, the code including instructions executable by a data processing system, wherein the instructions are configured to cause the data processing system to perform a method of filtering motion of a body, the method comprising:
accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;
determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:
evaluating a constraint using the specified kinematics and the dynamic property; and
updating the control so as to satisfy the constraint using an optimizer; and
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

10. A data processing system readable medium having code embodied therein, the code including instructions executable by a data processing system, wherein the instructions are configured to cause the data processing system to perform a method of filtering motion of a body, the method comprising:
accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;
determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:
estimating a generalize force at time t+dt; and
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

11. A data processing system readable medium having code embodied therein, the code including instructions executable by a data processing system, wherein the instructions are configured to cause the data processing system to perform a method of filtering motion of a body, the method comprising:
accessing specified kinematics of the body, a dynamic property of the body, and a state of the body, wherein a generalized coordinate of the body is unspecified at a point in time;
determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property;
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state; and
generating output information, wherein the output information includes a generated value of the generalized coordinate at the point in time.

12. A data processing system readable medium having code embodied therein, the code including instructions executable by a data processing system, wherein the instructions are configured to cause the data processing system to perform a method of filtering motion of a body, the method comprising:
accessing the specified kinematics accessing specified kinematics of the body, a dynamic property of the body, and a state of the body, wherein:
a q of the body is unspecified at a point in time; and
at least some of the specified kinematics comprises a Φ of the body at the point in time, wherein the Φ is a function of the q;
determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property;
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state; and
generating output information, wherein the output information includes a generated value of the q at the point in time.

13. An article comprising an output information related to a body, wherein the article comprises:
a data processing system readable medium; and
a code embodied within the data processing system readable medium, wherein the code includes the output information that is generated by:
accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;
accessing a filter parameter, wherein the filter parameter is part of a filter parameter set that includes a correction factor and a weight;
determining a desired acceleration using the specified kinematics;
determining a corrected acceleration using the filter parameter, the desired acceleration, and the state;
determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the corrected acceleration is used during the optimization-based inverse dynamics algorithm; and
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

14. An article comprising an output information related to a body, wherein the article comprises:
a data processing system readable medium; and
a code embodied within the data processing system readable medium, wherein the code includes the output information that is generated by;
accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;
determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:
evaluating a performance criterion using the specified kinematics and the dynamic property; and
updating the control so as to minimize or maximize the performance criterion using an optimizer; and
advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

15. An article comprising an output information related to a body, wherein the article comprises:

a data processing system readable medium; and

a code embodied within the data processing system readable medium, wherein the code includes the output information that is generated by:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:

evaluating a constraint using the specified kinematics and the dynamic property; and

updating the control so as to satisfy the constraint using an optimizers; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

16. An article comprising an output information related to a body, wherein the article comprises:

a data processing system readable medium; and

a code embodied within the data processing system readable medium, wherein the code includes the output information that is generated by:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property, wherein the optimization-based inverse dynamic algorithm comprises:

estimating a generalize force at time t+dt; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

17. An article comprising an output information related to a body, wherein the article comprises:

a data processing system readable medium; and

a code embodied within the data processing system readable medium, wherein the code includes the output information that is generated by:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body, wherein:

the output information is further generated by accessing the specified kinematics, wherein a generalized coordinate of the body is unspecified at a point in time; and

the output information includes a generated value of the generalized coordinate at the point in time;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

18. An article comprising an output information related to a body, wherein the article comprises:

a data processing system readable medium; and

a code embodied within the data processing system readable medium, wherein the code includes the output information that is generated by:

accessing specified kinematics of the body, a dynamic property of the body, and a state of the body, wherein:

the output information is further generated by accessing the specified kinematics, wherein:

a q of the body is unspecified at a point in time; and

at least some of the specified kinematics comprises a Φ of the body at the point in time, wherein the Φ is a function of the q; and

the output information includes a generated value of the q at the point in time;

determining a control pertaining to an actuation of the body using an optimization-based inverse dynamics algorithm, the specified kinematics, and the dynamic property; and

advancing the state in time using a forward dynamic simulator, the control, the dynamic property, and the state.

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