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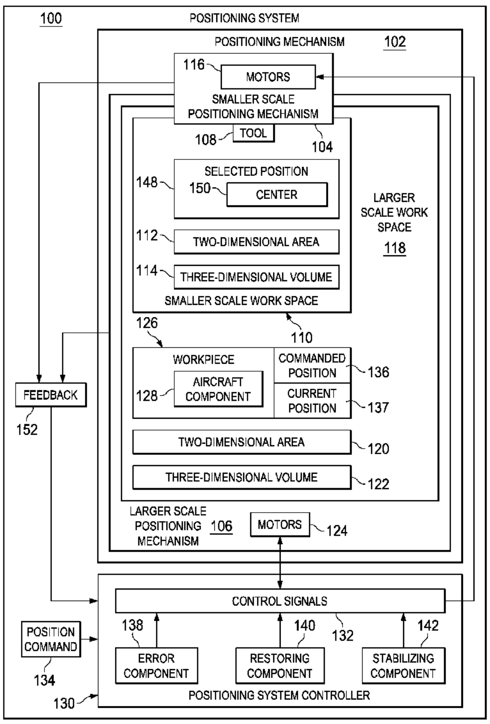
(54) **Title**: POSITION CONTROL FOR A POSITIONING SYSTEM COMPRISING LARGER SCALE AND SMALLER SCALE POSITIONING MECHANISMS

FIG. 1



(57) Abstract: A method and apparatus for controlling a positioning mechanism comprising a smaller scale positioning mechanism for moving a tool within a smaller scale work space and a larger scale positioning mechanism for changing a position of the smaller scale work space within the larger scale work space. A commanded position for the tool is received by a processor unit. An error component is determined using a difference between the commanded position and a current position of the tool in the larger scale work space. A restoring component configured to move the tool toward a selected position in the smaller scale work space is determined. Control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position are generated using the error component and the restoring component.

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POSITION CONTROL FOR A POSITIONING SYSTEM COMPRISING LARGER SCALE AND SMALLER SCALE POSITIONING MECHANISMS

BACKGROUND INFORMATION

Background:

An automated positioning system may be used to perform a variety of manufacturing and other tasks. An automated positioning system may include a tool attached to a computer controlled positioning mechanism. The positioning mechanism may be configured to move the tool to various positions in a work space. For example, the positioning mechanism may be controlled to move the tool to various positions in the work space to perform various operations on a workpiece in the work space. A robotic arm is one example of a positioning mechanism that may be used in an automated positioning system.

For example, automated positioning systems are used in direct digital manufacturing. Direct digital manufacturing also may be referred to as additive manufacturing, additive free-form fabrication, solid free-form fabrication, rapid prototyping, layered manufacturing, or three-dimensional printing. Direct digital manufacturing machines may be used to produce three-dimensional solid objects from three-dimensional digital models of the objects. To produce an object, the direct digital manufacturing machine may lay down successive layers of liquid, powder, or sheet material corresponding to virtual cross sections from the digital model of the object. The layers are joined together or fused automatically to create the final object. Objects of almost any shape or having any geometric feature may be made using a direct digital manufacturing machine. A direct digital manufacturing machine also may be referred to as a three-dimensional printer.

Current direct digital manufacturing machines may have working volumes of approximately one cubic meter. It may be desirable to have direct digital manufacturing machines with larger working volumes to produce larger objects. For example, without limitation, it may be desirable to have direct digital manufacturing machines with working volumes of approximately ten cubic meters.

Efficiency of direct digital manufacturing processes may be improved if the nozzle or other tool for laying down material in a direct digital manufacturing machine may be moved throughout the working volume of the machine at relatively high speed and with relatively high acceleration. For example, without limitation, efficient direct digital manufacturing may be achieved with speeds of approximately 2 meters per second and accelerations of approximately 40 meters per second per second.

Larger volume versions of current direct digital manufacturing machine designs may require significantly stiffer and more massive linkages in the positioning mechanism to move the nozzle or other tool through the working volume at the higher speeds and accelerations desirable for efficiency. Larger motors may be required to move the larger linkages at the desired speeds and accelerations. As a result, such a machine may require more expensive components and may use more energy than current direct digital manufacturing machines.

Accordingly, it would be beneficial to have a method and apparatus that takes into account one or more of the issues discussed above as well as possibly other issues.

SUMMARY

A first illustrative embodiment provides an apparatus comprising a smaller scale positioning mechanism, a larger scale positioning mechanism, and a positioning system controller. The smaller scale positioning mechanism is configured to move a tool

within a smaller scale work space. The larger scale positioning mechanism is configured to change a position of the smaller scale work space within a larger scale work space. The positioning system controller is configured to receive a position command identifying a commanded position for the tool within the larger scale work space, determine an error component using a difference between the commanded position and a current position of the tool in the larger scale work space, determine a restoring component configured to move the tool toward a selected position in the smaller scale work space, and generate control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position using the error component and the restoring component.

Another illustrative embodiment provides a method for controlling a positioning mechanism. A position command identifying a commanded position for a tool within a larger scale work space is received by a processor unit. A smaller scale positioning mechanism is configured to move the tool within a smaller scale work space. A larger scale positioning mechanism is configured to change a position of the smaller scale work space within the larger scale work space. An error component is determined by the processor unit using a difference between the commanded position and a current position of the tool in the larger scale work space. A restoring component configured to move the tool toward a selected position in the smaller scale work space is determined by the processor unit. Control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position are generated using the error component and the restoring component.

Another illustrative embodiment provides another method for controlling a positioning mechanism. A position command identifying a commanded position for a tool within a larger scale work space is received by a processor unit. A smaller scale positioning mechanism is configured to move the tool within a smaller scale work space. A larger scale positioning mechanism is configured to change a position of the smaller scale work space within the larger scale work space. An estimated velocity for the commanded position and an estimated acceleration for the commanded position are determined by the processor unit. A position of the smaller scale positioning mechanism, an integral of the position of the smaller scale positioning mechanism, a velocity of the smaller scale positioning mechanism, a position of the larger scale positioning mechanism, and a velocity of the larger scale positioning mechanism are determined by the processor unit. An error component is determined by the processor unit using a first difference between the commanded position and a first sum of the position of the smaller scale positioning mechanism and the position of the larger scale positioning mechanism and a second difference between the estimated velocity for the commanded position and a second sum of the velocity of the smaller scale positioning mechanism and the velocity of the larger scale positioning mechanism. A restoring component is determined by the processor unit using the integral of the position of the smaller scale positioning mechanism and the position of the smaller scale positioning mechanism. An acceleration for the smaller scale positioning mechanism and an acceleration for the larger scale positioning mechanism are determined using the error component, the restoring component, and the estimated acceleration for the commanded position. Control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position are generated using the acceleration for the smaller scale positioning mechanism and the acceleration for the larger scale positioning mechanism.

The features, functions, and benefits may be achieved independently in various embodiments of the present disclosure or may be combined in yet other embodiments in which further details can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the illustrative embodiments are set forth in the appended claims. The illustrative embodiments, however, as well as a preferred mode of use, further objectives, and features thereof will best be understood by reference to the following detailed description of illustrative embodiments of the present disclosure when read in conjunction with the accompanying drawings, wherein:

Figure 1 is an illustration of a block diagram of a positioning system in accordance with an illustrative embodiment;

Figure 2 is an illustration of a positioning mechanism in accordance with an illustrative embodiment;

Figure 3 is a schematic illustration of another positioning mechanism in accordance with an illustrative embodiment;

Figure 4 is an illustration of controlling a positioning system in accordance with an illustrative embodiment;

Figure 5 is an illustration of a flowchart of a process for controlling a positioning system in accordance with an illustrative embodiment;

Figure 6 is an illustration of a flowchart of another process for controlling a positioning system in accordance with an illustrative embodiment; and

Figure 7 is an illustration of a block diagram of a data processing system in accordance with an illustrative embodiment.

DETAILED DESCRIPTION

The different illustrative embodiments recognize and take into account a number of different considerations. "A number," as used herein with reference to items, means one or more items. For example, "a number of different considerations" means one or more different considerations.

The different illustrative embodiments recognize and take into account that the working volume of most current direct digital manufacturing machines may be relatively small. For example, the working volume of most current direct digital manufacturing machines may not exceed 1 cubic meter. Current direct digital manufacturing machines that have larger working volumes may operate relatively slowly and with relatively low accelerations. As a result, larger current direct digital manufacturing machines may not be efficient enough for practical industrial use.

It has been proposed to use relatively large linear motors in the positioning mechanisms of larger volume direct digital manufacturing machines. The use of such motors may improve the speed and acceleration performance, and thus the efficiency, of such machines. However, the use of large linear motors in direct digital manufacturing machines may have undesirable drawbacks.

Linear motors may be more expensive than conventional motors and ball screws used in the positioning mechanisms of conventional direct digital manufacturing machines. Linear motors may only produce linear motion. Therefore, the use of linear motors may limit the use of articulated structures in the positioning mechanisms of direct digital manufacturing machines. Furthermore, linear motors may use more energy than the conventional motors used in conventional direct digital manufacturing machines. Therefore, the use of linear motors in a direct digital manufacturing machine may result in a higher cost of operation.

The different illustrative embodiments recognize and take into account that direct digital manufacturing processes typically may be characterized by the desire for relatively short bursts of high acceleration of a positioning mechanism over a relatively small envelope of acceleration in the working volume of a direct digital manufacturing machine. For example, such short bursts of high acceleration may be used at the start and stop of a trajectory segment. A relatively short burst of high acceleration also may be desired in turning a relatively small radius corner.

The different illustrative embodiments also recognize and take into account that a positioning mechanism comprising a joint larger scale positioning mechanism and a smaller scale positioning mechanism may be used to improve dynamic performance and efficiency in a direct digital manufacturing machine with a relatively large working volume. In such a positioning mechanism, a tool to be moved to desired positions in the working volume may be attached to the smaller scale positioning mechanism. The smaller scale positioning mechanism may use relatively small high-dynamic motors to move the tool around in a smaller scale work space. The smaller scale positioning mechanism may be attached to the larger scale positioning mechanism. The larger scale positioning mechanism may use relatively efficient low-dynamic motors to move the smaller scale positioning mechanism, and thus the smaller scale work space, around in a larger scale work space corresponding to the working volume of the direct digital manufacturing machine. Such a positioning mechanism may be referred to as a macro/mini machine.

The different illustrative embodiments also recognize and take into account that, in order to achieve desired speed and efficiency of operation of a positioning mechanism including a joint larger scale positioning mechanism and a smaller scale positioning mechanism, it may be desirable that relatively short bursts of acceleration over a relatively small envelope of acceleration are achieved primarily by operation of the smaller scale positioning mechanism. However, the smaller scale positioning mechanism may not be able to provide such acceleration if the position of the tool in the smaller scale work space at the start of the acceleration is not appropriate. In this case, the slower larger scale positioning mechanism may need to be relied upon to move the tool, thereby increasing the time to perform an operation and reducing efficiency.

For example, following a move to the left, a tool may be positioned at or near the left edge of the smaller scale work space of the smaller scale positioning mechanism. If the positioning mechanism is commanded to move the tool to the left again, the smaller scale positioning mechanism will not be able to accelerate the tool in the desired direction. In this case, the slower larger scale positioning mechanism must be relied upon to move the tool by moving the smaller scale positioning mechanism, and thus the smaller scale work space, in the desired direction.

In accordance with an illustrative embodiment, a positioning system may include a smaller scale positioning mechanism and a larger scale positioning mechanism. The smaller scale positioning mechanism may be configured to move a tool within a smaller scale work space. The larger scale positioning mechanism may be configured to change the position of the smaller scale work space within a larger scale work space. A positioning system controller may be configured to control the smaller scale positioning mechanism and the larger scale positioning mechanism to move the tool from a current position to a commanded position in the larger scale work space in a manner such that relatively short and high accelerations of the tool are provided by the smaller scale positioning mechanism.

The positioning system controller may use a restoring component to generate control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism in a manner such that the position of the tool in the smaller scale work space is also driven toward a center of the smaller scale work space. Use of the restoring component in this manner may help to ensure that the tool is in an appropriate position in the smaller scale work space for the next acceleration in any direction.

Turning now to **Figure 1**, an illustration of a block diagram of a positioning system is depicted in accordance with an illustrative embodiment. Positioning system **100** may be used to perform any appropriate process. For example, without limitation, positioning system **100** may be used for manufacturing, assembly, disassembly, inspection, testing, rework, or any other appropriate process or combination of processes. For example, positioning system **100** may be part of a direct digital manufacturing machine used for direct digital manufacturing.

Positioning system **100** may include positioning mechanism **102**. Positioning mechanism **102** may include smaller scale positioning mechanism **104** and larger scale positioning mechanism **106**. Smaller scale positioning mechanism **104** may be referred to as a mini positioning mechanism. Larger scale positioning mechanism **106** may be referred to as a macro positioning mechanism. Positioning mechanism **102** may be referred to as a macro/mini positioning mechanism.

Tool **108** may be attached to smaller scale positioning mechanism **104**. Tool **108** may include any appropriate device or structure that may be used for any appropriate purpose. For example, without limitation, tool **108** may include a nozzle, a tape laying head, or any other device or structure for depositing or applying any appropriate material. As another example, tool **108** may include a drill, a saw, a scraper, a sander, a sand blaster, or any other device or structure for removing any appropriate material. As a further example, tool **108** may include a lens, a sensor, or any other device or structure for destructive or non-destructive inspection or testing of any appropriate material. Tool **108** may include various devices or structures in any appropriate combination.

Smaller scale positioning mechanism **104** may be configured to move tool **108** within smaller scale work space **110.** Smaller scale work space **110** may be two-dimensional area **112** or three-dimensional volume **114.** Two-dimensional area **112** may be referred to as a first two-dimensional area. Three-dimensional volume **114** may be referred to as a first three-dimensional volume.

Positions in smaller scale work space **110** may be defined with reference to smaller scale positioning mechanism **104.** Smaller scale positioning mechanism **104** may be configured to move tool **108** into any appropriate position in smaller scale work space **110.** The position of tool **108** in smaller scale work space **110** may refer to the location of tool **108** in smaller scale work space **110,** the orientation of tool **108** in smaller scale work space **110,** or both.

Smaller scale positioning mechanism **104** may include any appropriate devices and structures that may be configured to move tool **108** in any number of degrees of freedom within smaller scale work space **110.** Smaller scale positioning mechanism **104** may use motors **116** for moving tool **108** in smaller scale work space **110.** Motors **116** may be relatively high dynamic motors that may be configured to move tool **108** at relatively high speeds and with relatively high rates of acceleration.

Larger scale positioning mechanism **106** may be configured to change the relative position of smaller scale work space **110** in larger scale work space **118.** Larger scale work space **118** may correspond to the work space for positioning mechanism **102.** Larger scale work space **118** may be two-dimensional area **120** or three-dimensional volume **122**. Two-dimensional area **120** may be referred to as a second two-dimensional area. Three-dimensional volume **122** may be referred to as a second three-dimensional volume. The relative position of smaller scale work space **110** in larger scale work space **118** may refer to the location of smaller scale work space **110** in larger scale work space **118**, the orientation of smaller scale work space **110** in larger scale work space **118**, or both.

Larger scale positioning mechanism **106** may include any appropriate devices and structures that may be configured to change the relative position of smaller scale work space **110** in larger scale work space **118** in any number of degrees of freedom. For example, smaller scale positioning mechanism **104** may be attached to larger scale positioning mechanism **106**. In this case, larger scale positioning mechanism **106** may be configured to move smaller scale positioning mechanism **104** within larger scale work space **118** to change the position of smaller scale work space **110** in larger scale work space **118**. Alternatively, larger scale positioning mechanism **106** may be configured to move larger scale work space **118** with respect to smaller scale positioning mechanism **104** to change the position of smaller scale work space **110** in larger scale work space **118**.

Larger scale positioning mechanism **106** may use motors **124** to change the relative position of smaller scale work space **110** in larger scale work space **118**. For example, motors **124** may be larger and slower than motors **116** in smaller scale positioning mechanism **104**.

Workpiece **126** may be positioned in larger scale work space **118**. Workpiece **126** may include any structure and any material that may be operated on in any appropriate manner using tool **108**. For example, without limitation, workpiece **126** may be aircraft component **128**. Aircraft component **128** may include any part or portion of any type of aircraft. For example, aircraft component **128** may include an entire aircraft.

Positioning system controller **130** may be configured to control the movement of tool **108** throughout larger scale work space **118.** For example, positioning system controller **130** may be configured to generate control signals **132.** Control signals **132** may be configured for controlling motors **116** in smaller scale positioning mechanism **104** and motors **124** in larger scale positioning mechanism **106** in a manner such that smaller scale positioning mechanism **104** and larger scale positioning mechanism **106** together move tool **108** to desired positions in larger scale work space **118.**

Positioning system controller **130** may be configured to receive position command **134.** Position command **134** may identify commanded position **136** in larger scale work space **118.** Commanded position **136** is a position in larger scale work space **118** to which tool **108** is to be moved. For example, without limitation, commanded position **136** may correspond to a position on or in workpiece **126** in larger scale work space **118.**

Position command **134** may be provided to positioning system controller **130** from any appropriate source. For example, position command **134** may be provided by a human operator, a machine, or a human operator in combination with a machine.

For example, without limitation, position command **134** may comprise a sequence of positions in larger scale work space **118.** The sequence of positions may correspond to interpolation points for a desired trajectory of tool **108** in larger scale work space **118.** For example, the interpolation points may begin at current position **137** of tool **108** in larger scale work space **118** and may be spaced continuously in time. In this case, commanded position **136** may be determined from the next position in the sequence of positions. In this example, position command **134** may be generated and provided by a trajectory interpolator.

Positioning system controller **130** may be configured to generate control signals **132** for moving tool **108** from current position **137** to commanded position **136** using one or more of error component **138**, restoring component **140**, and stabilizing component **142**, in any appropriate combination. For example, without limitation, positioning system controller **130** may be configured to determine an acceleration for smaller scale positioning mechanism **104** and an acceleration for larger scale positioning mechanism **106** using one or more of error component **138**, restoring component **140**, and stabilizing component **142** in combination with an estimated acceleration for commanded position **136**. Positioning system controller **130** may be configured to generate control signals **132** using the acceleration for smaller scale positioning mechanism **104** and the acceleration for larger scale positioning mechanism **106**.

Error component **138** may be configured to drive the position of tool **108** toward commanded position **136**. Positioning system controller **130** may be configured to determine error component **138** using the difference between commanded position **136** and current position **137** of tool **108** in larger scale work space **118**. For example, without limitation, positioning system controller **130** may be configured to determine error component **138** using a first difference between commanded position **136** and a sum of a position of smaller scale positioning mechanism **104** and a position of larger scale positioning mechanism **106** and a second difference between an estimated velocity for commanded position **136** and a sum of a velocity of smaller scale positioning mechanism **104** and a velocity of larger scale positioning mechanism **106**.

Restoring component **140** may be configured to drive the position of tool **108** toward selected position **148** in smaller scale work space **110**. For example, without limitation, selected position **148** may be center **150** of smaller scale work space **110**. In this example, restoring component **140** may be used to help ensure that tool **108** is in an appropriate position in smaller scale work space **110** for the next acceleration of tool **108** in any direction in larger scale work space **118**. For example, without limitation, positioning system controller **130** may be configured to determine restoring component **140** using an integral of the position of smaller scale positioning mechanism **104** and the position of smaller scale positioning mechanism **104.**

Stabilizing component **142** may be configured to prevent unstable self-motion of larger scale positioning mechanism **106.** Self-motion refers to motion of larger scale positioning mechanism **106** that causes no motion of tool **108.** In a general acceleration minimization scheme, the velocities associated with self-motion are unstable. Stabilizing larger scale positioning mechanism **106** may stabilize positioning mechanism **102** as a whole.

Positioning system controller **130** may be configured to determine stabilizing component **142** to provide a feedback loop to stabilize the self-motion velocities of larger scale positioning mechanism **106.** For example, without limitation, positioning system controller **130** may be configured to determine stabilizing component **142** using a velocity of larger scale positioning mechanism **106.**

Current position **137** of tool **108** and other current parameters of smaller scale positioning mechanism **104** and larger scale positioning mechanism **106** may be determined using feedback **152** from smaller scale positioning mechanism **104** and larger scale positioning mechanism **106.** Any appropriate device or method may be used to provide feedback **152** for desired current parameters of smaller scale positioning mechanism **104** and larger scale positioning mechanism **106** to positioning system controller **130.**

In the present application, including in the claims, and unless stated otherwise, the position, velocity, and acceleration of smaller scale positioning mechanism **104** refers to the position, velocity, and acceleration, respectively, of tool **108** or of a portion of smaller scale positioning mechanism **104** to which tool **108** is attached. In the present application, including in the claims, and unless stated otherwise, the position, velocity, and acceleration of larger scale positioning mechanism **106** refers to the position, velocity, and acceleration, respectively, of smaller scale work space **110** with respect to larger scale work space **118.** In the present application, including in the claims, "position" may refer to location or orientation or both, "velocity" may refer to linear velocity or angular velocity or both, and "acceleration" may refer to linear acceleration or angular acceleration or both.

The illustration of **Figure 1** is not meant to imply physical or architectural limitations to the manner in which illustrative embodiments may be implemented. Other components in addition to, in place of, or both in addition to and in place of the ones illustrated may be used. Some components may be unnecessary in some illustrative embodiments. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined or divided into different blocks when implemented in different illustrative embodiments.

Turning now to **Figure 2**, an illustration of a positioning mechanism is depicted in accordance with an illustrative embodiment. In this example, positioning mechanism **200** is an example of one implementation of positioning mechanism **102** in **Figure 1.**

Positioning mechanism **200** may include larger scale positioning mechanism **202** and smaller scale positioning mechanism **204.** Smaller scale positioning mechanism **204** is attached to larger scale positioning mechanism **202.** Tool **206** is attached to smaller scale positioning mechanism **204.** Smaller scale positioning mechanism **204** may be configured to move tool **206** within a smaller scale work space defined with respect to smaller scale positioning mechanism **204.** Larger scale positioning mechanism **202** may be configured to move smaller scale positioning mechanism **204** in a larger scale work space. Thus, positioning mechanism **200** is an example of a positioning mechanism wherein a larger scale positioning mechanism moves a smaller scale work space within a larger scale work space to change the relative position of the smaller scale work space in the larger scale work space.

Turning now to **Figure 3**, a schematic illustration of another positioning mechanism is depicted in accordance with an illustrative embodiment. In this example, positioning mechanism **300** is example of one implementation of positioning mechanism **102** in **Figure 1.** Positioning mechanism **300** is an example of a positioning mechanism wherein a larger scale work space is moved with respect to a smaller scale work space to change the position of the smaller scale work space in the larger scale work space.

Positioning mechanism **300** includes larger scale positioning mechanism **302** and smaller scale positioning mechanism **304.** Larger scale positioning mechanism **302** may be configured to move table **306** in a number of directions. In this example, the surface of table **306** may define a larger scale work space. Workpiece **308** may be positioned on table **306.**

Tool **310** may be attached to smaller scale positioning mechanism **304.** Smaller scale positioning mechanism **304** may be configured to move tool **310** in a number of directions within a smaller scale work space defined by smaller scale positioning mechanism **304.** Smaller scale positioning mechanism **304** may be supported in a fixed position on support structure **312.** Thus, the smaller scale work space is fixed in position in positioning mechanism **300.**

Turning now to **Figure 4**, an illustration of controlling a positioning system is depicted in accordance with an illustrative embodiment. In this example, larger scale work space **400** is an example of larger scale work space **118** in **Figure 1** and smaller scale work space **402** is an example of smaller scale work space **110** in **Figure 1.**

In this example, point **404** indicates the center of smaller scale work space **402.** Point **406** indicates the current position of a tool in larger scale work space **400** and smaller scale work space **402.** Point **408** indicates a point in larger scale work space **400** to which the tool is commanded to move.

In accordance with an illustrative embodiment, the control signals for controlling movement of the tool include a component indicated by arrow **410** for moving smaller scale work space **402** toward point **408,** a component indicated by arrow **412** for moving the tool in smaller scale work space **402** in the direction of point **408,** and a component indicated by arrow **414** for moving the tool in the smaller scale work space in the direction of point **404.**

Turning now to **Figure 5**, an illustration of a flowchart of a process for controlling a positioning system is depicted in accordance with an illustrative embodiment. The process of **Figure 5** may be used to control a positioning system comprising a smaller scale positioning mechanism configured to move a tool within a smaller scale work space and a larger scale positioning mechanism configured to change a position of the smaller scale work space within a larger scale work space. For example, the process of **Figure 5** may be implemented in positioning system controller **130** to control positioning system **100** in **Figure 1.**

The process may begin by receiving a position command identifying a commanded position for the tool in the larger scale work space (operation **502**). An error component may be determined using a difference between a current position of the tool in the larger scale work space and the commanded position (operation **504**). A restoring component may be determined, wherein the restoring component is configured to move the tool toward a selected position in the smaller scale work space (operation **506**). For example, the restoring component may be configured to move the tool toward the center of the smaller scale work space. A stabilizing component may be determined, wherein the stabilizing component is configured to prevent unstable self-motion of the larger scale positioning mechanism (operation **508**). Control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position then may be generated using the error component, the restoring component, and the stabilizing component (operation **510**), with the process terminating thereafter.

Turning now to **Figure 6**, an illustration of a flowchart of another process for controlling a positioning system is depicted in accordance with an illustrative embodiment. The process of **Figure 6** may be used to control a positioning system comprising a smaller scale positioning mechanism configured to move a tool within a smaller scale work space and a larger scale positioning mechanism configured to change a position of the smaller scale work space within a larger scale work space. For example, the process of **Figure 6** may be implemented in positioning system controller **130** to control positioning system **100** in **Figure 1.**

The process may begin by receiving a position command identifying a commanded position for the tool within the larger scale work space (operation **602**). An estimated velocity and acceleration for the commanded position may be determined (operation **604**). A joint state of the positioning mechanism may be determined (operation **606**).

An error component may be determined using a difference between the commanded position state and the joint state of the positioning mechanism (operation **608**). For example, without limitation, the error component may be determined using a first difference between the commanded position and a first sum of the position of the smaller scale positioning mechanism and the position of the larger scale positioning mechanism and a second difference between the estimated velocity for the commanded position and a second sum of the velocity of the smaller scale positioning mechanism and the velocity of the larger scale positioning mechanism.

A restoring component may be determined (operation **610**). The restoring component may be configured to move the tool toward the center of the smaller scale work space. For example, without limitation, the restoring component may be determined using an integral of the position of the smaller scale positioning mechanism and the position of the smaller scale positioning mechanism.

A stabilizing component may be determined (operation **612**). The stabilizing component may be configured to prevent unstable self-motion of the larger scale positioning mechanism. For example, without limitation, the stabilizing component may be determined using the velocity of the larger scale positioning mechanism.

Joint acceleration for the positioning mechanism may be determined using the error component, the restoring component, and the stabilizing component (operation **614**). For example, without limitation, acceleration for the smaller scale positioning mechanism and acceleration for the larger scale positioning mechanism may be determined using the error component, the restoring component, the stabilizing component, and the estimated acceleration of the commanded position. Control signals for the positioning mechanism then may be generated from the joint acceleration (operation **616**), with the process terminating thereafter. For example, control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position may be generated using the acceleration for the smaller scale positioning mechanism and the acceleration for the larger scale positioning mechanism.

Turning now to **Figure 7**, an illustration of a block diagram of a data processing system is depicted in accordance with an illustrative embodiment. In this example, data processing system **700** is an example of one implementation of a data processing system for implementing positioning system controller **130** in **Figure 1.**

In this illustrative example, data processing system **700** includes communications fabric **702.** Communications fabric **702** provides communications between processor unit **704,** memory **706,** persistent storage **708,** communications unit **710,** input/output (I/O) unit **712,** and display **714.** Memory **706,** persistent storage **708,** communications unit **710,** input/output (I/O) unit **712,** and display **714** are examples of resources accessible by processor unit **704** via communications fabric **702.**

Processor unit **704** serves to run instructions for software that may be loaded into memory **706.** Processor unit **704** may be a number of processors, a multi-processor core, or some other type of processor, depending on the particular implementation. Further, processor unit **704** may be implemented using a number of heterogeneous processor systems in which a main processor is present with secondary processors on a single chip. As another illustrative example, processor unit **704** may be a symmetric multi-processor system containing multiple processors of the same type.

Memory **706** and persistent storage **708** are examples of storage devices **716.** A storage device is any piece of hardware that is capable of storing information, such as, for example, without limitation, data, program code in functional form, and other suitable information either on a temporary basis or a permanent basis. Storage devices **716** also may be referred to as computer readable storage devices in these examples. Memory **706,** in these examples, may be, for example, a random access memory or any other suitable volatile or non-volatile storage device. Persistent storage **708** may take various forms, depending on the particular implementation.

For example, persistent storage **708** may contain one or more components or devices. For example, persistent storage **708** may be a hard drive, a flash memory, a rewritable optical disk, a rewritable magnetic tape, or some combination of the above. The media used by persistent storage **708** also may be removable. For example, a removable hard drive may be used for persistent storage **708.**

Communications unit **710,** in these examples, provides for communications with other data processing systems or devices. In these examples, communications unit **710** is a network interface card. Communications unit **710** may provide communications through the use of either or both physical and wireless communications links.

Input/output (I/O) unit **712** allows for input and output of data with other devices that may be connected to data processing system **700.** For example, input/output (I/O) unit **712** may provide a connection for user input through a keyboard, a mouse, and/or some other suitable input device. Further, input/output (I/O) unit **712** may send output to a printer. Display **714** provides a mechanism to display information to a user.

Instructions for the operating system, applications, and/or programs may be located in storage devices **716,** which are in communication with processor unit **704** through communications fabric **702.** In these illustrative examples, the instructions are in a functional form on persistent storage **708.** These instructions may be loaded into memory **706** for execution by processor unit **704.** The processes of the different embodiments may be performed by processor unit **704** using computer-implemented instructions, which may be located in a memory, such as memory **706.**

These instructions are referred to as program instructions, program code, computer usable program code, or computer readable program code that may be read and executed by a processor in processor unit **704.** The program code in the different embodiments may be embodied on different physical or computer readable storage media, such as memory **706** or persistent storage **708.**

Program code **718** is located in a functional form on computer readable media **720** that is selectively removable and may be loaded onto or transferred to data processing system **700** for execution by processor unit **704.** Program code **718** and computer readable media **720** form computer program product **722** in these examples. In one example, computer readable media **720** may be computer readable storage media **724** or computer readable signal media **726.**

Computer readable storage media **724** may include, for example, an optical or magnetic disk that is inserted or placed into a drive or other device that is part of persistent storage **708** for transfer onto a storage device, such as a hard drive, that is part of persistent storage **708.** Computer readable storage media **724** also may take the form of a persistent storage, such as a hard drive, a thumb drive, or a flash memory, that is connected to data processing system **700.** In some instances, computer readable storage media **724** may not be removable from data processing system **700.**

In these examples, computer readable storage media **724** is a physical or tangible storage device used to store program code **718** rather than a medium that propagates or transmits program code **718.** Computer readable storage media **724** is also referred to as a computer readable tangible storage device or a computer readable physical storage device. In other words, computer readable storage media **724** is a media that can be touched by a person.

Alternatively, program code **718** may be transferred to data processing system **700** using computer readable signal media **726.** Computer readable signal media **726** may be, for example, a propagated data signal containing program code **718.** For example, computer readable signal media **726** may be an electromagnetic signal, an optical signal, and/or any other suitable type of signal. These signals may be transmitted over communications links, such as wireless communications links, optical fiber cable, coaxial cable, a wire, and/or any other suitable type of communications link. In other words, the communications link and/or the connection may be physical or wireless in the illustrative examples.

In some illustrative embodiments, program code **718** may be downloaded over a network to persistent storage **708** from another device or data processing system through computer readable signal media **726** for use within data processing system **700.** For instance, program code stored in a computer readable storage medium in a server data processing system may be downloaded over a network from the server to data processing system **700.** The data processing system providing program code **718** may be a server computer, a client computer, or some other device capable of storing and transmitting program code **718.**

The different components illustrated for data processing system **700** are not meant to provide architectural limitations to the manner in which different embodiments may be implemented. The different illustrative embodiments may be implemented in a data processing system including components in addition to and/or in place of those illustrated for data processing system **700.** Other components shown in **Figure 7** can be varied from the illustrative examples shown. The different embodiments may be implemented using any hardware device or system capable of running program code. As one example, data processing system **700** may include organic components integrated with inorganic components and/or may be comprised entirely of organic components excluding a human being. For example, a storage device may be comprised of an organic semiconductor.

In another illustrative example, processor unit **704** may take the form of a hardware unit that has circuits that are manufactured or configured for a particular use. This type of hardware may perform operations without needing program code to be loaded into a memory from a storage device to be configured to perform the operations.

For example, when processor unit **704** takes the form of a hardware unit, processor unit **704** may be a circuit system, an application specific integrated circuit (ASIC), a programmable logic device, or some other suitable type of hardware configured to perform a number of operations. With a programmable logic device, the device is configured to perform the number of operations. The device may be reconfigured at a later time or may be permanently configured to perform the number of operations. Examples of programmable logic devices include, for example, a programmable logic array, a programmable array logic, a field programmable logic array, a field programmable gate array, and other suitable hardware devices. With this type of implementation, program code **718** may be omitted, because the processes for the different embodiments are implemented in a hardware unit.

In still another illustrative example, processor unit **704** may be implemented using a combination of processors found in computers and hardware units. Processor unit **704** may have a number of hardware units and a number of processors that are configured to run program code **718**. With this depicted example, some of the processes may be implemented in the number of hardware units, while other processes may be implemented in the number of processors.

In another example, a bus system may be used to implement communications fabric **702** and may be comprised of one or more buses, such as a system bus or an input/output bus. Of course, the bus system may be implemented using any suitable type of architecture that provides for a transfer of data between different components or devices attached to the bus system.

Additionally, communications unit **710** may include a number of devices that transmit data, receive data, or both transmit and receive data. Communications unit **710** may be, for example, a modem or a network adapter, two network adapters, or some combination thereof. Further, a memory may be, for example, memory **706**, or a cache, such as that found in an interface and memory controller hub that may be present in communications fabric **702**.

The flowcharts and block diagrams described herein illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various illustrative embodiments. In this regard, each block in the flowcharts or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function or functions. It should also be noted that, in some alternative implementations, the functions noted in a block may occur out of the order noted in the figures. For example, the functions of two blocks shown in succession may be executed substantially concurrently, or the functions of the blocks may sometimes be executed in the reverse order, depending upon the functionality involved.

The description of the different illustrative embodiments has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. Further, different illustrative embodiments may provide different benefits as compared to other illustrative embodiments. The embodiment or embodiments selected are chosen and described in order to best explain the principles of the embodiments, the practical application, and to enable others of ordinary skill in the art to understand the disclosure for various embodiments with various modifications as are suited to the particular use contemplated.

Further, the disclosure comprises embodiments according to the following clauses:

Clause 17. A method for controlling a positioning mechanism comprising:

receiving, by a processor unit, a position command identifying a commanded position for a tool within a larger scale work space, wherein a smaller scale positioning mechanism is configured to move the tool within a smaller scale work space and a larger scale positioning mechanism is configured to change a position of the smaller scale work space within the larger scale work space;

determining, by the processor unit, an estimated velocity for the commanded position and an estimated acceleration for the commanded position;

determining, by the processor unit, a position of the smaller scale positioning mechanism, an integral of the position of the smaller scale positioning mechanism, a velocity of the smaller scale positioning mechanism, a position of the larger scale positioning mechanism, and a velocity of the larger scale positioning mechanism;

determining, by the processor unit, an error component using a first difference between the commanded position and a first sum of the position of the smaller scale positioning mechanism and the position of the larger scale positioning mechanism and a second difference between the estimated velocity for the commanded position and a second sum of the velocity of the smaller scale positioning mechanism and the velocity of the larger scale positioning mechanism;

determining, by the processor unit, a restoring component using the integral of the position of the smaller scale positioning mechanism and the position of the smaller scale positioning mechanism;

determining an acceleration for the smaller scale positioning mechanism and an acceleration for the larger scale positioning mechanism using the error component, the restoring component, and the estimated acceleration for the commanded position; and

generating control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from a current position to the commanded position using the acceleration for the smaller scale positioning mechanism and the acceleration for the larger scale positioning mechanism.

Clause 18. The method of clause 17 further comprising:

determining a stabilizing component using the velocity of the larger scale positioning mechanism; and

determining the acceleration for the smaller scale positioning mechanism and the acceleration for the larger scale positioning mechanism using the error component, the restoring component, the estimated acceleration for the commanded position, and the stabilizing component.

Clause 19. The method of clause 17, wherein the smaller scale positioning mechanism is attached to the larger scale positioning mechanism and the larger scale positioning mechanism is configured to move the smaller scale positioning mechanism within the larger scale work space to change the position of the smaller scale work space within the larger scale work space.

Clause 20. The method of clause 17, wherein the larger scale positioning mechanism is configured to move the larger scale work space with respect to the smaller scale positioning mechanism to change the position of the smaller scale work space within the larger scale work space.

CLAIMS:

What is claimed is:

1. An apparatus, comprising:

a smaller scale positioning mechanism configured to move a tool within a smaller scale work space;

a larger scale positioning mechanism configured to change a position of the smaller scale work space within a larger scale work space; and

a positioning system controller configured to receive a position command identifying a commanded position for the tool within the larger scale work space, determine an error component using a difference between the commanded position and a current position of the tool in the larger scale work space, determine a restoring component configured to move the tool toward a selected position in the smaller scale work space, and generate control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position using the error component and the restoring component.

2. The apparatus of claim 1, wherein the selected position is a center of the smaller scale work space.

3. The apparatus of claims 1-2, wherein the positioning system controller is further configured to:

determine a stabilizing component configured to prevent unstable self-motion of the larger scale positioning mechanism, and

generate the control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position using the error component, the restoring component, and the stabilizing component.

4. The apparatus of claims 1-3, wherein the positioning system controller is configured to:

determine an estimated velocity for the commanded position and an estimated acceleration for the commanded position;

determine a position of the smaller scale positioning mechanism, an integral of the position of the smaller scale positioning mechanism, a velocity of the smaller scale positioning mechanism, a position of the larger scale positioning mechanism, and a velocity of the larger scale positioning mechanism;

determine the error component using a first difference between the commanded position and a sum of the position of the smaller scale positioning mechanism and the position of the larger scale positioning mechanism and a second difference between the estimated velocity for the commanded position and a sum of the velocity of the smaller scale positioning mechanism and the velocity of the larger scale positioning mechanism;

determine the restoring component using the integral of the position of the smaller scale positioning mechanism and the position of the smaller scale positioning mechanism;

determine an acceleration for the smaller scale positioning mechanism and an acceleration for the larger scale positioning mechanism using the error component, the restoring component, and the estimated acceleration for the commanded position; and

generate the control signals using the acceleration for the smaller scale positioning mechanism and the acceleration for the larger scale positioning mechanism.

5. The apparatus of claims 1-4, wherein the smaller scale positioning mechanism is attached to the larger scale positioning mechanism and the larger scale positioning mechanism

is configured to move the smaller scale positioning mechanism within the larger scale work space to change the position of the smaller scale work space within the larger scale work space.

6. The apparatus of claims 1-5, wherein the larger scale positioning mechanism is configured to move the larger scale work space with respect to the smaller scale positioning mechanism to change the position of the smaller scale work space within the larger scale work space.

7. The apparatus of claims 1-6, wherein the smaller scale work space is selected from a first two-dimensional area and a first three-dimensional volume and the larger scale work space is selected from a second two-dimensional area and a second three-dimensional volume.

8. The apparatus of claims 1-7 further comprising:

an aircraft component positioned in the larger scale work space and wherein the control signals are configured to control the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool to the commanded position on the aircraft component.

9. A method for controlling a positioning mechanism comprising:

receiving, by a processor unit, a position command identifying a commanded position for a tool within a larger scale work space, wherein a smaller scale positioning mechanism is configured to move the tool within a smaller scale work space and a larger scale positioning mechanism is configured to change a position of the smaller scale work space within the larger scale work space;

determining, by the processor unit, an error component using a difference between the commanded position and a current position of the tool in the larger scale work space;

determining, by the processor unit, a restoring component configured to move the tool toward a selected position in the smaller scale work space; and

generating control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position using the error component and the restoring component.

10. The method of claim 9, wherein the selected position is a center of the smaller scale work space.

11. The method of claims 9-10 further comprising:

determining a stabilizing component configured to prevent unstable self-motion of the larger scale positioning mechanism, and

generating the control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool from the current position to the commanded position using the error component, the restoring component, and the stabilizing component.

12. The method of claims 9-11 further comprising:

determining an estimated velocity for the commanded position and an estimated acceleration for the commanded position;

determining a position of the smaller scale positioning mechanism, an integral of the position of the smaller scale positioning mechanism, a velocity of the smaller scale positioning mechanism, a position of the larger scale positioning mechanism, and a velocity of the larger scale positioning mechanism;

determining the error component using a first difference between the commanded position and a sum of the position of the smaller scale positioning mechanism and the position of the larger scale positioning mechanism and a second difference between the estimated velocity for the commanded position and a sum of the velocity of the smaller scale positioning mechanism and the velocity of the larger scale positioning mechanism;

determining the restoring component using the integral of the position of the smaller scale positioning mechanism and the position of the smaller scale positioning mechanism;

determining an acceleration for the smaller scale positioning mechanism and an acceleration for the larger scale positioning mechanism using the error component, the restoring component, and the estimated acceleration for the commanded position; and

generating the control signals using the acceleration for the smaller scale positioning mechanism and the acceleration for the larger scale positioning mechanism.

13. The method of claims 9-12, wherein the smaller scale positioning mechanism is attached to the larger scale positioning mechanism and the larger scale positioning mechanism is configured to move the smaller scale positioning mechanism within the larger scale work space to change the position of the smaller scale work space within the larger scale work space.

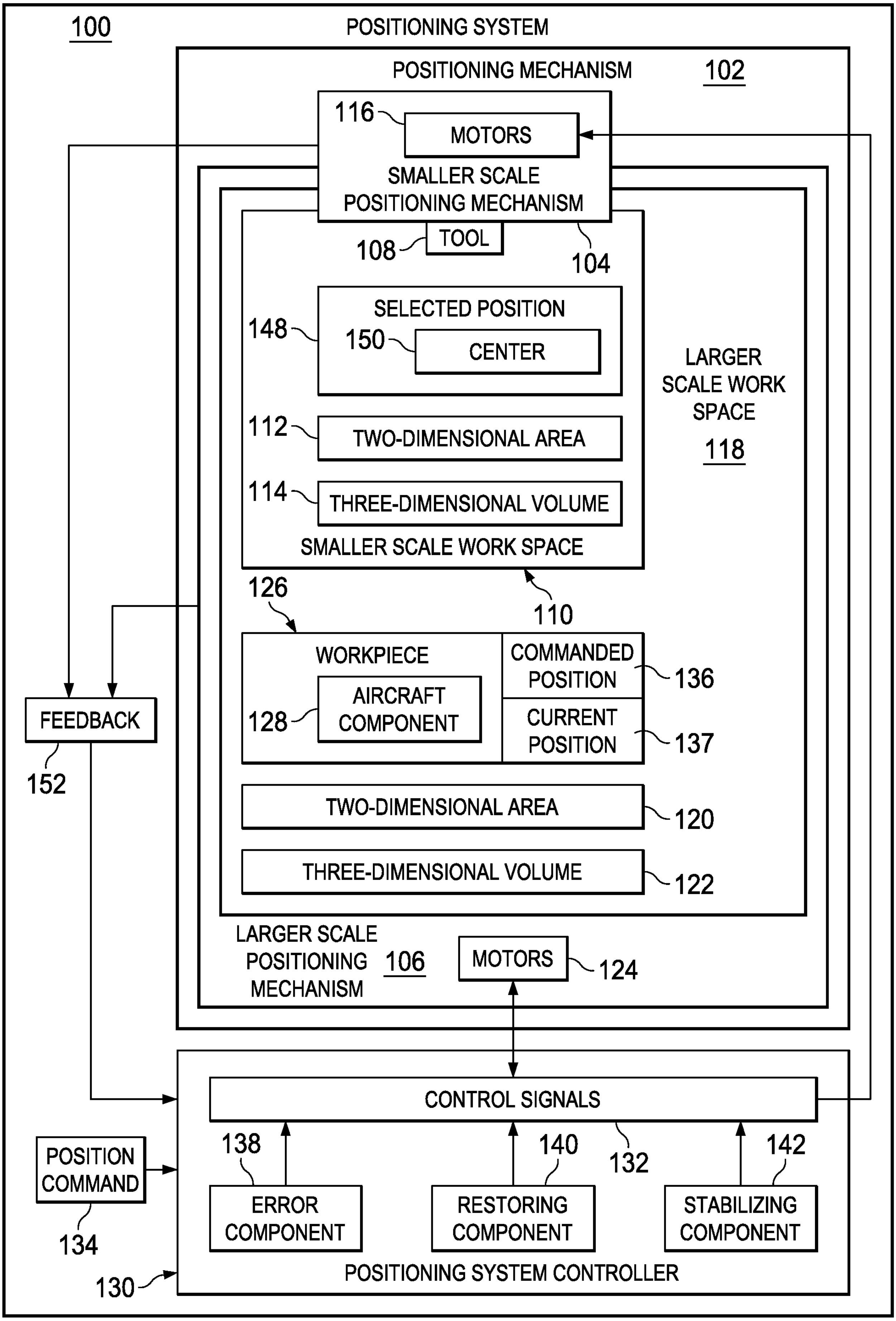
14. The method of claims 9-13, wherein the larger scale positioning mechanism is configured to move the larger scale work space with respect to the smaller scale positioning mechanism to change the position of the smaller scale work space within the larger scale work space.

15. The method of claims 9-14, wherein the smaller scale work space is selected from a first two-dimensional area and a first three-dimensional volume and the larger scale work space is selected from a second two-dimensional area and a second three-dimensional volume.

16. The method of claims 9-15 further comprising:

positioning an aircraft component in the larger scale work space and generating the control signals for controlling the smaller scale positioning mechanism and the larger scale positioning mechanism together to move the tool to the commanded position on the aircraft component.

FIG. 1



100
POSITIONING SYSTEM
POSITIONING MECHANISM
102
116
MOTORS
SMALLER SCALE POSITIONING MECHANISM
TOOL
108
104
SELECTED POSITION
148
150
CENTER
112
TWO-DIMENSIONAL AREA
114
THREE-DIMENSIONAL VOLUME
SMALLER SCALE WORK SPACE
LARGER SCALE WORK SPACE
118
126
110
WORKPIECE
128
AIRCRAFT COMPONENT
COMMANDED POSITION
136
CURRENT POSITION
137
FEEDBACK
152
TWO-DIMENSIONAL AREA
120
THREE-DIMENSIONAL VOLUME
122
LARGER SCALE POSITIONING MECHANISM
106
MOTORS
124
CONTROL SIGNALS
138
140
132
142
POSITION COMMAND
134
ERROR COMPONENT
RESTORING COMPONENT
STABILIZING COMPONENT
130
POSITIONING SYSTEM CONTROLLER

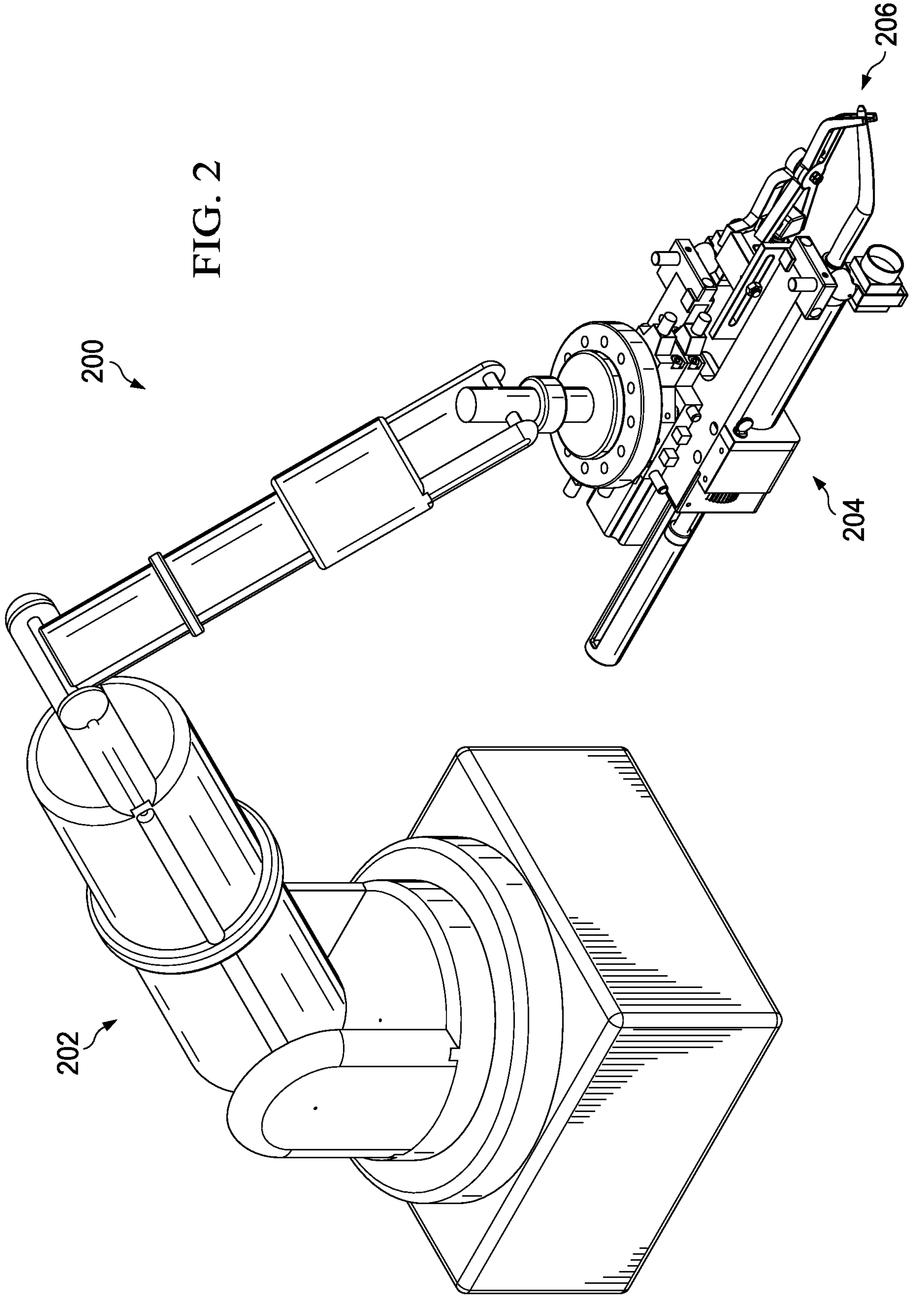


FIG. 2

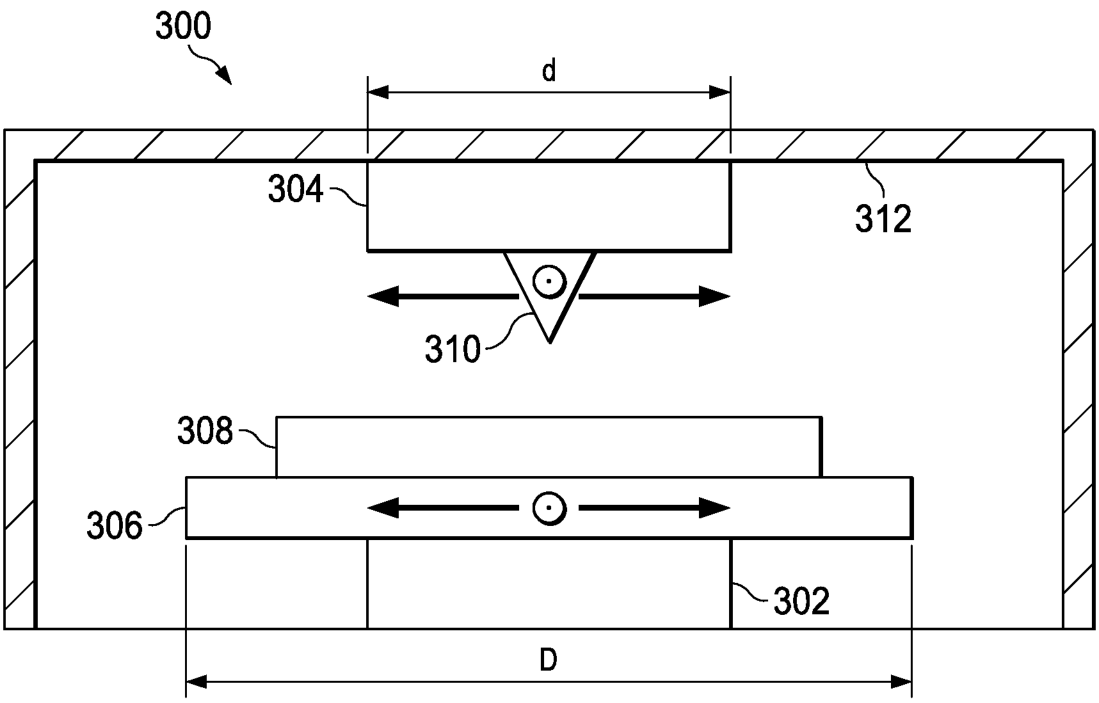
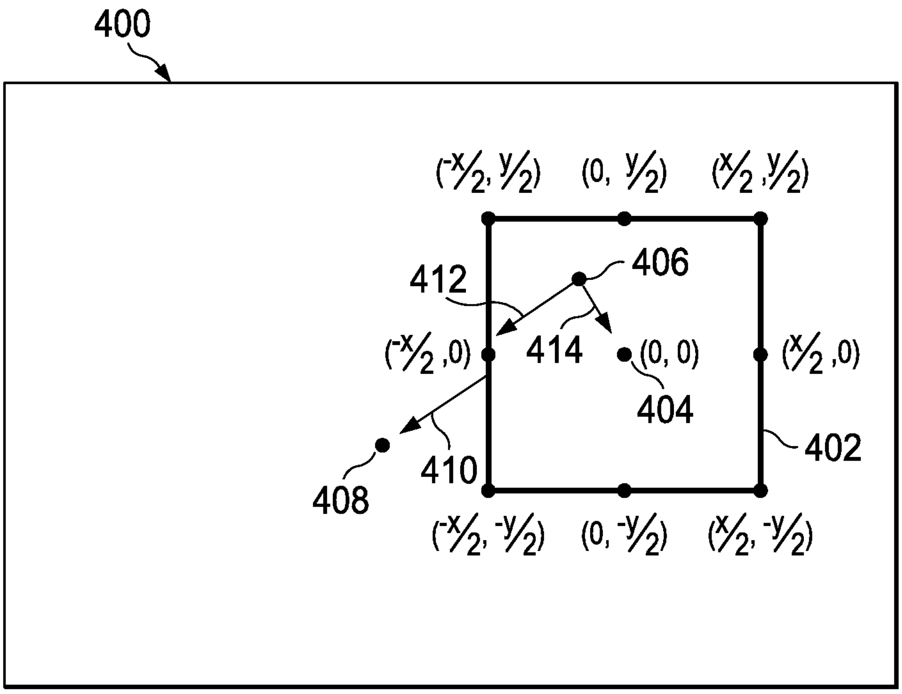

300
d
304
312
310
308
306
302
D

FIG. 3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(0, y/2)
(x/2, y/2)
406
412
414
(-x/2, 0)
(0, 0)
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402
410
408
(-x/2, -y/2)
(0, -y/2)
(x/2, -y/2)

FIG. 4

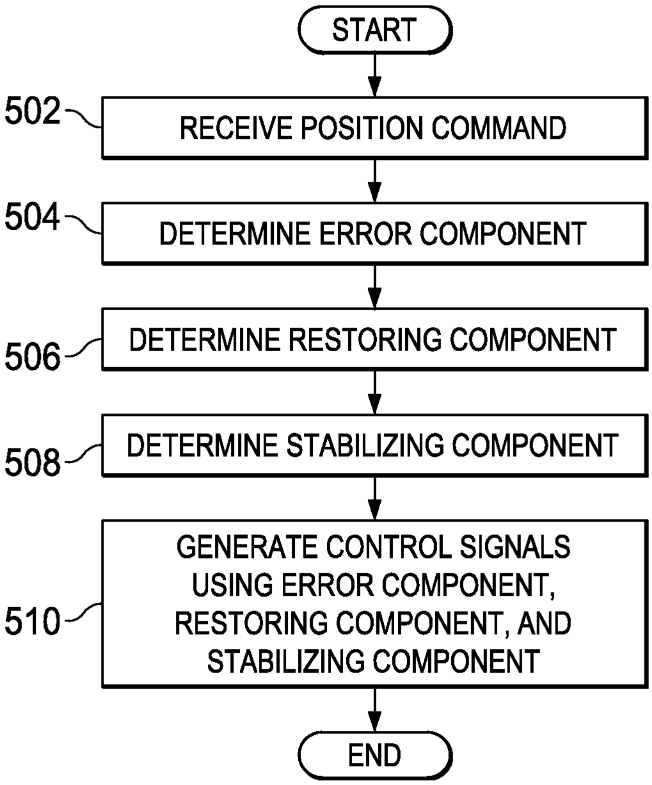

START
502 RECEIVE POSITION COMMAND
504 DETERMINE ERROR COMPONENT
506 DETERMINE RESTORING COMPONENT
508 DETERMINE STABILIZING COMPONENT
510 GENERATE CONTROL SIGNALS USING ERROR COMPONENT, RESTORING COMPONENT, AND STABILIZING COMPONENT
END

FIG. 5

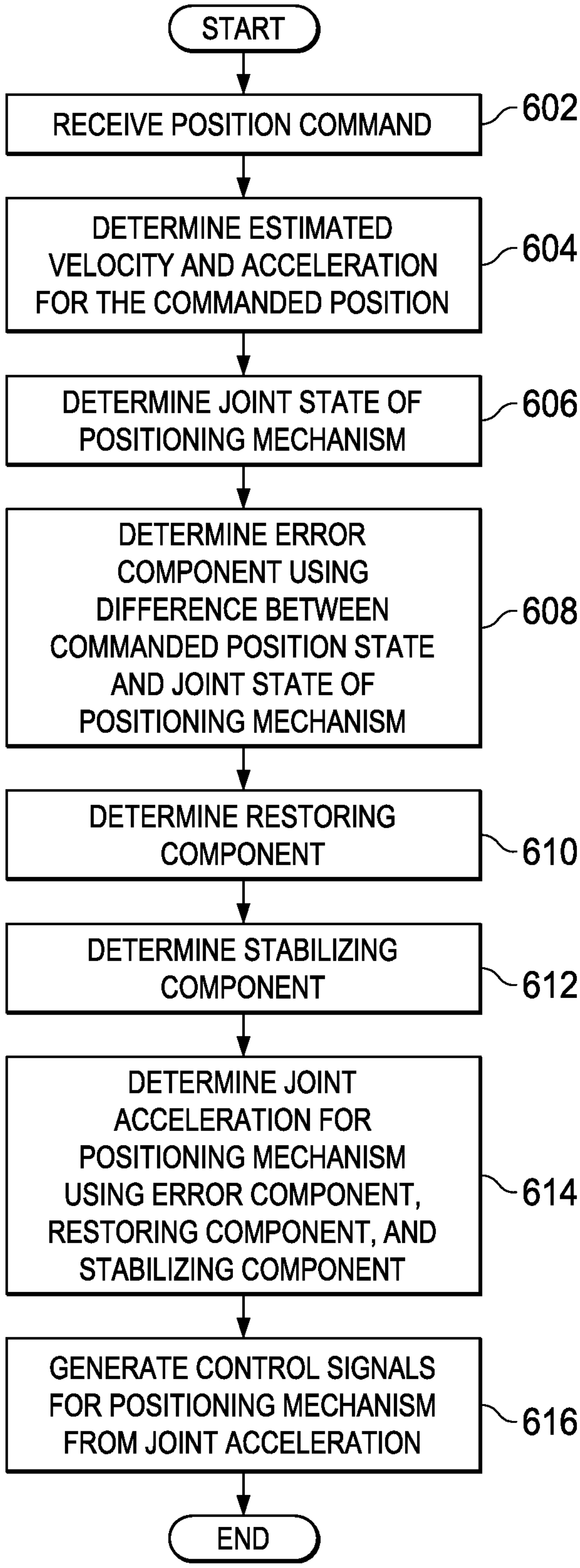
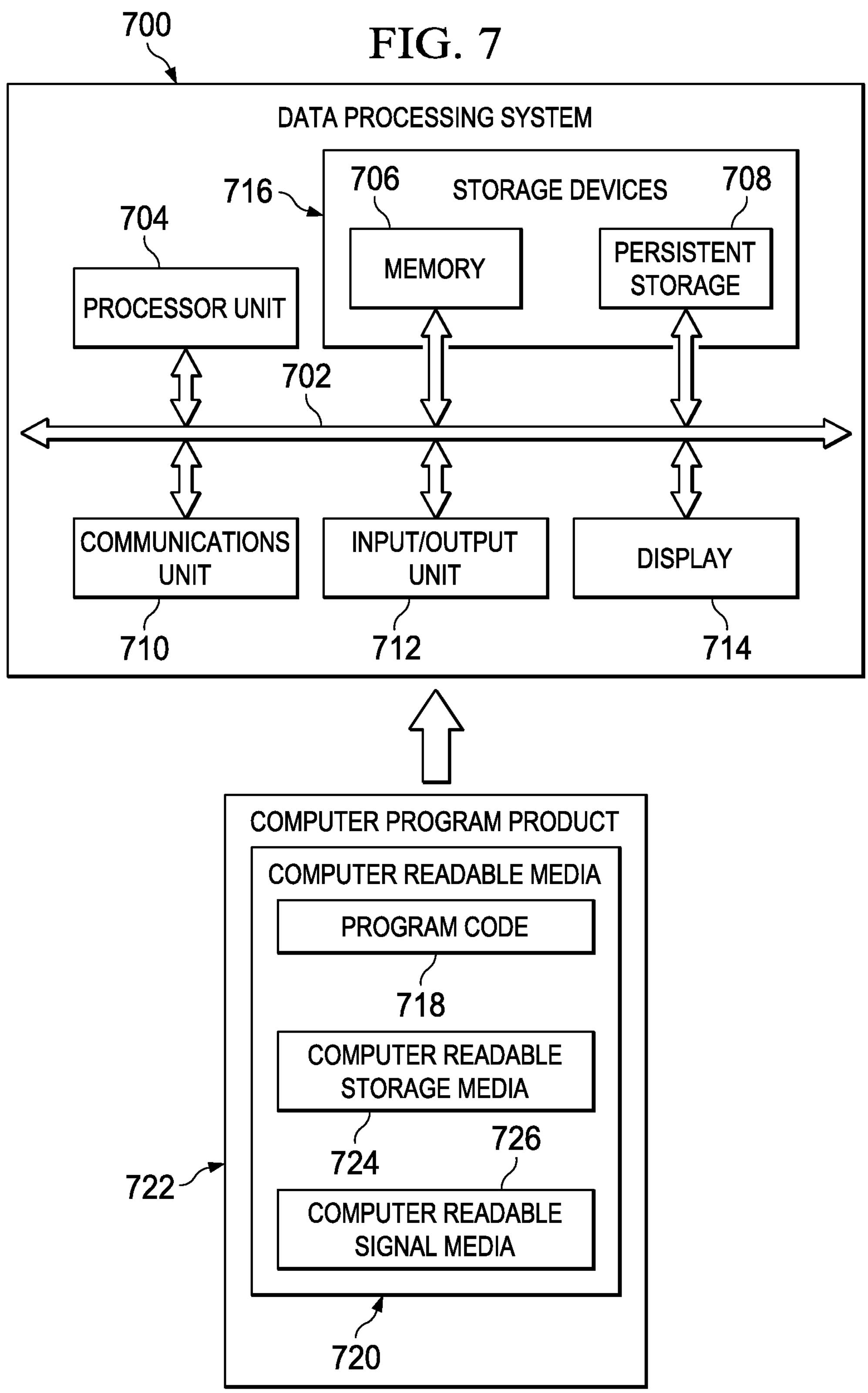

START
RECEIVE POSITION COMMAND 602
DETERMINE ESTIMATED VELOCITY AND ACCELERATION FOR THE COMMANDED POSITION 604
DETERMINE JOINT STATE OF POSITIONING MECHANISM 606
DETERMINE ERROR COMPONENT USING DIFFERENCE BETWEEN COMMANDED POSITION STATE AND JOINT STATE OF POSITIONING MECHANISM 608
DETERMINE RESTORING COMPONENT 610
DETERMINE STABILIZING COMPONENT 612
DETERMINE JOINT ACCELERATION FOR POSITIONING MECHANISM USING ERROR COMPONENT, RESTORING COMPONENT, AND STABILIZING COMPONENT 614
GENERATE CONTROL SIGNALS FOR POSITIONING MECHANISM FROM JOINT ACCELERATION 616
END

FIG. 6

FIG. 7


700
DATA PROCESSING SYSTEM
716
STORAGE DEVICES
706
708
704
MEMORY
PERSISTENT STORAGE
PROCESSOR UNIT
702
COMMUNICATIONS UNIT
INPUT/OUTPUT UNIT
DISPLAY
710
712
714
COMPUTER PROGRAM PRODUCT
COMPUTER READABLE MEDIA
PROGRAM CODE
718
COMPUTER READABLE STORAGE MEDIA
724
726
722
COMPUTER READABLE SIGNAL MEDIA
720

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/074450

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J9/16 G05B19/29
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G05B B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TANG WEN YANG ET AL: "Dynamic Compensation Control of Flexible Macroâ Micro Manipulator Systems", 1 January 2010 (2010-01-01), IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, PAGE(S) 143 - 151, XP011281072, ISSN: 1063-6536 page 143 page 146 - page 149 ----- -/--	1-16

[X] Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

* Special categories of cited documents :

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 April 2014	11/04/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Bassi, Luca

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2013/074450

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	AGATHE HODAC ET AL: "Decoupled macro/micro-manipulator for fast and precise assembly operations: design and experiments", SPIE CONFERENCE ON MICROROBOTICS AND MICROASSEMBLY, 1 September 1999 (1999-09-01), pages 122-130, XP055112051, DOI: http://dx.doi.org/10.1117/12.357816 the whole document -----	1-16