

TITLE OF THE INVENTION

APPARATUS AND METHOD FOR OPTIMIZING SWAP TIME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority to U.S. Provisional Application No. 63/523,942, filed on June 29, 2023, the entire contents of which are herein incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to a robotic apparatus, robotic handling system, and method for transporting a workpiece between various positions.

Discussion of the Background

[0003] Automated transfer devices significantly improve the efficiency, speed, and reliability at which workpieces such as semiconductor wafers are processed. Automation is particularly useful in clean room environments. When robots are used for wafer transferring should quickly and precisely transfer a wafer between various locations to reduce manufacturing time and ensure sufficient yield.

[0004] A need exists for devices that can increase the yield of a manufacturing operation, thereby reducing cost and increasing output over time.

SUMMARY OF THE INVENTION

[0005] The present disclosure advantageously describes a robotic apparatus comprising an arm member, a first end effector, a second end effector, at least one drive unit, and a control unit. The arm member is configured to pivot about a first axis. The first end effector is pivotably connected to the arm member about a second axis, and the first end effector has a first surface upon which a first workpiece can be received. The second end effector is pivotably connected to the arm member about the second axis, and the second end effector has a second surface upon which a second workpiece can be received. The at least one drive unit is configured to drive the arm member to pivot about the first axis. The at least one drive unit is configured to drive the first end effector to pivot about the second axis, and to drive the second end effector to pivot about the second axis. The control unit is configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector to perform a swapping operation that includes the first end effector and the second end effector swapping arc positions disposed at opposite ends of an arc having a constant radius of curvature. The control unit is configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector such that the first workpiece received on the first end effector and the second workpiece received on the second end effector each travel at equal and constant velocities along the arc.

[0006] The present disclosure advantageously describes a method of transporting workpieces with a robotic apparatus, comprising: providing a robotic apparatus having: an arm member configured to pivot about a first axis; a first end effector pivotably connected to

the arm member about a second axis, the first end effector having a first surface upon which a first workpiece can be received; a second end effector pivotably connected to the arm member about the second axis, the second end effector having a second surface upon which a second workpiece can be received; at least one drive unit configured to drive the arm member to pivot about the first axis, the at least one drive unit being configured to drive the first end effector to pivot about the second axis, the at least one drive unit being configured to drive the second end effector to pivot about the second axis; and a control unit configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector. The method further comprises controlling the at least one drive unit to move the arm member, the first end effector and the second end effector to perform a swapping operation that includes the first end effector and the second end effector swapping arc positions disposed at opposite ends of an arc having a constant radius of curvature, wherein the at least one drive unit is controlled to move the arm member, the first end effector and the second end effector such that the first workpiece received on the first end effector and the second workpiece received on the second end effector each travel at equal and constant velocities along the arc.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] A more complete appreciation of the invention and many of the attendant advantages thereof will become readily apparent with reference to the following detailed description, particularly when considered in conjunction with the accompanying drawings, in which:

[0008] FIGS. 1A-1H are plan views of arms that can be employed with a robot according to exemplary embodiments of the present invention;

[0009] FIG. 2 is a diagram illustrating a robot and a control unit according to an exemplary embodiment of the present invention;

[0010] FIG. 3 is a block diagram illustrating a control unit and drive units according to an exemplary embodiment of the present invention;

[0011] FIGS. 4A-4E are plan views of a workspace of a wafer processing apparatus showing a wafer swap operation using a dual blade robot;

[0012] FIG. 5 depicts first and second end effectors performing a portion of the wafer swapping operation according to an exemplary embodiment of the present invention;

[0013] FIG. 6 is a graph of an acceptable radius of curvature as a function of tangential velocity for a commanded acceleration of 1 g;

[0014] FIG. 7 depicts first and second end effectors during a portion of the wafer swapping operation according to an exemplary embodiment of the present invention;

[0015] FIG. 8 depicts the end effectors at a central or coincident position while performing the wafer swapping operation according to an exemplary embodiment of the present invention;

[0016] FIG. 9 is a flowchart of possible swap motion operations depending upon line segment lengths according to exemplary embodiments of the present invention;

[0017] FIG. 10 depicts first and second end effectors during a portion of the wafer swapping operation for explanatory purposes according to an exemplary embodiment of the present invention;

[0018] FIG. 11 depicts first and second end effectors during a portion of the wafer swapping

operation for explanatory purposes according to an exemplary embodiment of the present invention;

[0019] FIGS. 12A-12L depict examples of symmetric motion profiles of first and second end effectors during wafer swapping operations with varying gamma values according to exemplary embodiments of the present invention;

[0020] FIG. 13 depicts first and second end effectors during a portion of the wafer swapping operation for explanatory purposes according to an exemplary embodiment of the present invention;

[0021] FIG. 14 depicts an example of a nonsymmetric motion profile of first and second end effectors during a wafer swapping operation with unequal length line segments for explanatory purposes according to an exemplary embodiment of the present invention;

[0022] FIG. 15 depicts first and second end effectors during a portion of the wafer swapping operation for explanatory purposes according to an exemplary embodiment of the present invention;

[0023] FIG. 16 is a graph of z move time as a function of acceleration for different blade pitch distances; and

[0024] FIG. 17 depicts an end effector for purposes of a discussion of wrist acceleration according to an embodiment of the present invention.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS OF THE INVENTION

[0025] Embodiments of the present invention will be described hereinafter with reference to

the accompanying drawings. In the following description, the constituent elements having substantially the same function and arrangement are denoted by the same reference numerals, and repetitive descriptions will be made only when necessary.

[0026] Dual blade robots can be used to perform a wafer swap from a processing stage of a processing chamber or other location at which a wafer is placed and retrieved. U.S. Application No. 15/644,828, which issued as U.S. Patent No. 10,580,681 discloses a robotic apparatus and method for transport of a workpiece that provides background teaching of an apparatus and method that the present invention can be utilized in conjunction with, and therefore the disclosure in U.S. Application No. 15/644,828 is hereby incorporated herein and included herewith. For example, the robot and the control unit illustrated in FIG. 1 of U.S. Application No. 15/644,828 in conjunction with the robot arm shown, for example, in FIG. 4f thereof and/or the robot arms shown in FIGS. 1A-H of the present application, can be utilized in conjunction with the present invention. Additionally, the control unit and drive units illustrated in FIG. 2 of U.S. Application No. 15/644,828 can be utilized in conjunction with the present invention.

[0027] FIGS. 1A-1H depict a series of exemplary dual blade robot configurations according to embodiments of the present invention.

[0028] FIG. 1A depicts a dual blade robot having a first arm 16 and two second arms (also referred to as blades or end effectors) 18a, 18b. The blades 18a, 18b are each pivotally coupled to the first arm 16 about pivot axis (also referred to herein as a second axis) PA1, also referred to as a wrist of the dual blade robot, and the first arm 16 is pivotally coupled at a fixed location about pivot axis (also referred to herein as a first axis) PA2. The blades 18a, 18b can

each hold or receive a wafer, for example, blade 18a holds or receives wafer W1 and blade 18b holds or receives wafer W2. For example, blade 18a could be retrieving wafer W1 from a supply/output station/chamber for delivery to a processing station/chamber (process position), and, at the same time (i.e., simultaneously or at least partially in an overlapping manner), blade 18b could be retrieving wafer W2 from the processing station for delivery to the supply/output station, thus performing a wafer swapping operation.

[0029] FIG. 1B depicts a dual blade robot similar to the dual blade robot in FIG. 1A; however, in the embodiment of FIG. 1B, the dual blade robot includes a track 28 for translational motion of the dual arm robot along the track 28. The track 28 can be linear or curved. In the embodiment of FIG. 1B, the first arm 16 is pivotally coupled to a translating member 28a about pivot axis PA2, and the translating member 28a is movable along the track 28.

[0030] FIG. 1C depicts a dual blade robot similar to the dual blade robot in FIG. 1A; however, in the embodiment of FIG. 1C, the dual blade robot includes a base 30 for rotational motion about a Z axis (independent of or in combination with the rotational motion of the first arm 16 at axis PA2) coinciding with axis PA2 and/or Z-axis translational motion of the dual arm robot along axis PA2.

[0031] FIG. 1D depicts a dual blade robot similar to the dual blade robot in FIG. 1C; however, in the embodiment of FIG. 1D, the dual blade robot includes a track 28 for translational motion of the base 30 and the dual arm robot along the track 28. The track 28 can be linear or curved. In the embodiment of FIG. 1D, the first arm 16 is pivotally coupled to a translating member 28a about pivot axis PA2, and the translating member 28a is movable along the track 28. Additionally, in the embodiment of FIG. 1D, the dual blade robot includes the base 30 for

rotational motion about a Z axis coinciding with axis PA2 and/or Z-axis translational motion of the dual arm robot along axis PA2.

[0032] FIG. 1E depicts a dual blade robot similar to the dual blade robot in FIG. 1A; however, in the embodiment of FIG. 1E, the dual blade robot includes arm 16a and arm 16b. The blades 18a, 18b are each pivotally coupled to the arm 16a about pivot axis PA1, the arm 16a is pivotally coupled to the arm 16b about pivot axis PA2, and the arm 16b is pivotally coupled at a fixed location about pivot axis PA3.

[0033] FIG. 1F depicts a dual blade robot similar to the dual blade robot in FIG. 1E; however, in the embodiment of FIG. 1F, the dual blade robot includes a track 28 for translational motion of the dual arm robot along the track 28. The track 28 can be linear or curved. In the embodiment of FIG. 1F, the arm 16b is pivotally coupled to a translating member 28a about pivot axis PA3, and the translating member 28a is movable along the track 28.

[0034] FIG. 1G depicts a dual blade robot similar to the dual blade robot in FIG. 1E; however, in the embodiment of FIG. 1G, the dual blade robot includes a base 30 for rotational motion about a Z axis (independent of or in combination with the rotational motion of the arm 16b at axis PA3) coinciding with axis PA3 and/or Z-axis translational motion of the dual arm robot along axis PA3.

[0035] FIG. 1H depicts a dual blade robot similar to the dual blade robot in FIG. 1G; however, in the embodiment of FIG. 1H, the dual blade robot includes a track 28 for translational motion of the base 30 and the dual arm robot along the track 28. The track 28 can be linear or curved. In the embodiment of FIG. 1H, the arm 16b is pivotally coupled to a translating member 28a

about pivot axis PA3, and the translating member 28a is movable along the track 28. Additionally, in the embodiment of FIG. 1H, the dual blade robot includes the base 30 for rotational motion about a Z axis coinciding with axis PA3 and/or Z-axis translational motion of the dual arm robot along axis PA3.

[0036] Additional arms can be added in addition to arms 16a, 16b if needed or desired.

[0037] Each member (i.e., arm, blade, translating member, base, etc.) of the dual blade robots in FIGS. 1A-1H is actively controlled by drive unit(s) and controlled by one or more control units in the manner disclosed in U.S. Application No. 15/644,828.

[0038] There is a need for an apparatus and method that can achieve an optimal wafer swap time while not exceeding a maximum acceleration, for example, in a case of friction grip handling or vacuum handling.

[0039] A configuration of a robotic apparatus 10 will be described according to an exemplary embodiment of the invention. FIG. 2 is an exemplary robotic apparatus 10 that includes a transfer robot (or robot) 12 and a robot controller (or control unit) 22. The robot 12 includes a plurality of arm members that are rotatable with respect to each other. The robot 12 shown in FIG. 2 incorporates elements from, for example, the dual blade robot shown in FIG. 1E.

[0040] The robot 12 of FIG. 2 includes a torso 14, arm 16b, arm 16a, first end effector 18a, and second end effector 18b, which are each exemplary arm members, each of which is rotated by a drive unit, such as drive units 24A-24D (collectively referenced as drive units) provided therein or in association therewith. In the embodiment shown in FIG. 2, both the first end effector 18a and the second end effector 18b are rotated by drive unit 24D in opposite rotational

directions from one another using a gear arrangement or two separate drive units can be provided that each respectively rotates one of the first end effector 18a and the second end effector 18b.

[0041] As illustrated in FIG. 2, the torso 14 is rotatable about pivot axis PA4, the arm 16b is rotatable about pivot axis PA3, the arm 16a is rotatable about pivot axis PA2, and the first end effector 18a and the second end effector 18b are each rotatable about pivot axis PA1. The first end effector 18a is connected to a distal end of the arm 16a and includes a surface S1 that supports a substrate W1, such as a semiconductor wafer. The second end effector 18b is connected to a distal end of the arm 16a and includes a surface S2 that supports a substrate W2, such as a semiconductor wafer. Substrates W1 and W2 are examples of workpieces. Workpieces other than semiconductor wafers can be transported in the manner discussed below. The first end effector 18a and the second end effector 18b can each include at least one device, DV1 and DV2, respectively, such as an edge-gripping device and/or a suction device in order to help retain the wafer on the supporting surface S1 and S2, respectively, during movement.

[0042] The arm 16a is connected to a distal end of arm 16b. The arm 16b is connected to a distal end of torso 14, which is in turn connected to base 66. Therefore, base 66 supports torso 14, arm 16b, arm 16a, the first end effector 18a, and the second end effector 18b. The base 66 includes a housing 60A, the torso 14 includes a housing 60B, the arm 16b includes a housing 60C, the arm 16a includes a housing 60D, the first end effector 18a includes a housing 60E, and the second end effector 18b includes a housing 60F (collectively referenced as housing). Robot 12 can be formed as a Selective Compliance Assembly robot (SCARA robot), for example.

[0043] Control unit 22 outputs commands to bring each of the torso 14, arm 16b, arm 16a, first end effector 18a, and second end effector 18b into motion, as will be described in further detail below. Control unit 22 can be included outside the housing of robot 12 as depicted in FIG. 2, or inside the housing of robot 12. Control unit 22 communicates with robot 12 and the drive units directly, or in conjunction with an intermediate control device, which can include an amplifier. When an amplifier is included as an intermediate device, control unit 22 is configured to issue commands to the amplifier, which in turns generates control signals for one or more of the drive units. Control unit 22 can also receive instructions from a higher-level device such as a programmable logic controller, for example.

[0044] As illustrated in FIG. 2, the torso 14 is rotatable about pivot axis PA4, the arm 16b is rotatable about pivot axis PA3, the arm 16a is rotatable about pivot axis PA2, and the first end effector 18a and the second end effector 18b are rotatable about pivot axis PA1. This rotational motion is accomplished by a corresponding drive unit constituted by a motor drive or servo motor, for example. Control unit 22 is configured to control the drive units for each of the torso 14, arm 16b, arm 16a, and first end effector 18a and the second end effector 18b. Each drive unit provides feedback that indicates at least a position of the drive unit to control unit 22. The position feedback is provided directly from the respective drive units, which perform torque-sensing, from an external sensor 120, or any combination of torque-sensing drive units and external sensors. External sensor 120 can include some components. Control unit 22 controls the operation of drive units in accordance with the feedback information to control the position of each of the torso 14, arm 16b, arm 16a, first end effector 18a, and the second end effector 18b.

[0045] FIG. 3 illustrates an exemplary configuration of the control unit 22. As illustrated in FIG. 3, the drive units are each in communication with control unit 22. Although four drive units 24A-24D are depicted in FIG. 3, additional drive units can be provided for each respective axis, including torso 14, arm 16b, arm 16a, first end effector 18a, and the second end effector 18b. Control unit 22 includes a processing unit 112 and a memory 114. Processing unit 112 is a processing device such as a microprocessor or CPU and communicates with memory 114 and executes instructions (e.g., software programs) provided by motion limit unit 104, which is stored in memory 114, which is a long-term non-volatile storage device such as a hard disk, solid state storage device, EEPROM, or other non-transitory storage medium. Motion limit unit 104 allows control unit 22 to command the drive units based on an allowable motion limits (velocity, acceleration, etc.) applied when robot 12 is brought into motion in order to transport substrates W1, W2.

[0046] Control unit 22 is in communication with a user interface that includes an input device 34 and a display 36 that can include a visual display and audio input/output capabilities. Control unit 22 includes a wired and/or wireless communication interface 116 to communicate with input device 34 and display 36, and can also include a volatile memory. Communication interface 116 accepts input from input device 36, which can include a mouse and/or keyboard, and controls display 34 to display information to a user. Communication interface 116 can also receive feedback from each of the drive units and output commands to the respective drive units. If an external sensor 120 is used to provide position feedback, this feedback information is also received by communication interface 116. The issuance of commands to the drive units and the receipt of feedback can be accomplished by direct communication or through an

intermediate device such as an amplifier.

[0047] A user can interact with input device 36 to configure the allowable motion limits (velocity, acceleration, etc.) set by motion limit unit 104. Thus, a user can observe the allowable motion limits with display 34 and set and/or modify the allowable motion limits with input device 36. Input device 36 and display 34 can be components of control unit 22 or provided as parts of a separate personal computer that communicates with communication interface 116.

[0048] Communication interface 116 of control unit 22 can be configured to receive data from display 34, input device 36, and the drive units. Alternatively, a separate communication interface 116 can be provided for the drive units alone. In this case, communication interface 116 for the drive units receives feedback from the drive units, via a cable, for example, and provides this feedback to processing unit 112. The communication interface 116 for the drive units outputs commands to control the drive units directly or through an intermediate device such as an amplifier.

[0049] One of the basic robot motions for a dual blade robot is the wafer swap operation at a wafer processing apparatus 300, as can be seen in FIGS. 4A-4E. Typically, a wafer will start at a process position, from which the wafer is to be removed by an active blade (i.e., the blade inside of the processing chamber). On the inactive (passive) blade (i.e., the blade outside of the processing chamber, but within a supply/output chamber), the robot will have possession of a wafer to be placed at the process station. For the purpose of this discussion, it is assumed that an empty blade has been inserted into the processing chamber, a move that was previously optimized, for example, for a friction grip in U.S. Application No. 15/644,828. It is also assumed that the robot has moved in a Z direction (i.e., height

direction) and picked the processed wafer off the process pedestal or pins. The processed wafer is now ready to be swapped for the unprocessed wafer on the inactive blade. The motion is roughly as shown in FIG. 4A, which is a first figure in a sequence of figures including FIGS. 4A-4E.

[0050] Thus, FIG. 4A shows a processed wafer, which in FIG. 4A is substrate (or wafer) W2, at a processing location that is in processing chamber 310 of the wafer processing apparatus 300, and an unprocessed wafer, which in FIG. 4A is substrate (or wafer) W1, at a supply/output location that is in supply/output chamber 320 of the wafer processing apparatus 300. In FIG. 4A, the wafer W2 is provided on the second end effector 18b, which in FIG. 4A is considered to be an active blade (i.e., the blade inside of the processing chamber 310) 18b1, while the wafer W1 is provided on the first end effector 18a, which in FIG. 4A is considered to be an inactive blade (i.e., the blade outside of the processing chamber 310, but within the supply/output chamber 320) 18a1. It is noted that the processing chamber 310 and the supply/output chamber 320 of the wafer processing apparatus 300 are shown in simplified form, and some or all of the remaining components of the robotic apparatus 10 could be positioned within the wafer processing apparatus 300 (e.g., within the supply/output chamber 320 or an adjacent chamber) or outside of the wafer processing apparatus 300 such that the first end effector 18a and the second end effector 18b reach within the wafer processing apparatus 300 in the manner shown in FIGS. 4A-4E.

[0051] FIG. 4B shows a next orientation/location of the first end effector 18a and the second end effector 18b in the wafer swap operation after FIG. 4A. In FIG. 4B, the wafer W2 provided on the second end effector 18b is moving through an opening 330 between the

processing chamber 310 and the supply/output chamber 320, and the wafer W1 provided on the first end effector 18a is moving toward the opening 330.

[0052] FIG. 4C shows a next orientation/location of the first end effector 18a and the second end effector 18b in the wafer swap operation after FIG. 4B. In FIG. 4C, the wafer W2 provided on the second end effector 18b has moved out of the opening 330 into the supply/output chamber 320, and the wafer W2 on the second end effector 18b is directly above (and obscuring the view of) the wafer W1 provided on the first end effector 18a that is moving toward the opening 330.

[0053] FIG. 4D shows a next orientation/location of the first end effector 18a and the second end effector 18b in the wafer swap operation after FIG. 4C. In FIG. 4D, the wafer W2 provided on the second end effector 18b has moved toward the supply/output location of the supply/output chamber 320, and the wafer W1 on the first end effector 18a is moving through the opening 330 into the processing chamber 310.

[0054] FIG. 4E shows a next orientation/location of the first end effector 18a and the second end effector 18b in the wafer swap operation after FIG. 4D. In FIG. 4E, the wafer W2 provided on the second end effector 18b has moved to the supply/output location of the supply/output chamber 320, and the wafer W1 on the first end effector 18a has moved to the processing location in the processing chamber 310. In this orientation/location, the wafer W1 can be processed within the processing chamber 310, and the wafer W2 can be left at the supply/output chamber 320 such that a subsequent wafer can be picked up by the second end effector 18b in order to prepare for another (subsequent) wafer swap operation. In FIG. 4E, the first end effector 18a is considered to be the active blade (i.e., the blade inside of the

processing chamber 310) 18a1, while the second end effector 18b is considered to be the inactive blade (i.e., the blade outside of the processing chamber 310, but within the supply/output chamber 320) 18b2.

[0055] It is noted that, in performing the motion shown in FIGS. 4A-4E, there are at least two primary collisions to be concerned with given the spatial limitations (in addition to the collision with the opening 330 between the processing chamber 310 and the supply/output chamber 320). First, the inactive wafer (i.e., the wafer on the inactive blade that is outside of the processing chamber, but within the supply/output chamber) may hit either a top wall (not shown but above bottom wall 324) of the supply/output chamber or a back wall 322 of the supply/output chamber 320. Secondly, the wrist (i.e., the first end effector 18a and the second end effector 18b joined at pivot axis PA1) may collide with a bottom wall 324 of the supply/output chamber 320.

[0056] As will be discussed in further detail below, there are four degrees of freedom associated with the kinematics of a dual blade swap. When a linear motion profile is applied to the active blade (i.e., the blade inside of the processing chamber) at the wafer being extracted from the process station, then this accounts for two degrees of freedom. The third degree of freedom is the orientation of the active blade. Often times, the orientation will be held fixed but it can also vary through movement. The inactive blade, that which is holding the unprocessed wafer, will follow a line constraint that will intersect at a point with the line defining the active blade. The point of intersection is represented in FIG. 4C. At this point (which is at a point of singularity), the extraction portion has been completed and the velocity of both blades is zero. The robot then proceeds to insert the unprocessed wafer into

the station and clears the processed wafer using the same paths as before, simply applied to the different blades.

[0057] In such a movement (paths of motion) as are shown in FIGS. 4A-4E, the fact that the wafers need to come to rest at their point of coincidence represents an unfortunate loss of time. An improvement over such a motion is needed, as is discussed below. Such motion should allow a robot used for wafer transferring to quickly and precisely transfer a wafer between various locations to reduce manufacturing time and ensure sufficient yield. A need exists for devices that can increase the yield of a manufacturing operation, thereby reducing cost and increasing output over time.

[0058] Kinematics

[0059] There are four degrees of freedom in the planar, dual blade kinematics. We can command the x-y position of both the active wafer and the passive wafer. Both wafers can be driven simultaneously so long as the distance between the wafers is less than twice the end effector length. When the two wafers come in close proximity with one another, the position of the wrist can vary wildly as the wrist position is indeterminate when the wafers are coincident, as this represents a point of singularity. This can lead to unacceptable accelerations at the wrist.

[0060] Thus, we want to command linear wafer acceleration on both wafers until the wafers come in close proximity with one another. We then want to transition to a model that keeps the wrist acceleration and position stable. We can do so by applying some symmetry of motion between the two wafers. As shown in FIG. 5, from position ① to

position ②, the wafer (in this depiction wafer W1) will accelerate and potentially decelerate along a linear path. At position ②, the active wafer will enter into an arc segment (from position ②, through position ③, to position ④) of radius, R, with velocity, V. Simultaneously, the passive wafer (in this depiction wafer W2) will enter at the other side of the same arc at position ④ with the same velocity, V. The wrist of the robot will be on a line of symmetry passing through the center of the arc at position ③. The wrist will move along this line of symmetry during this move segment, as can be seen by the location of the pivot axis as it moves from pivot axis PA1(1) (when first end effector 18a(1) is at position ② and second end effector 18b(1) is at position ④) to pivot axis PA1(2) (when first end effector 18a(2) is at position ③ and second end effector is also at position ③ but obscured from view by the first end effector 18a(2) above it). The wafers move along the arc at constant tangential speed, experiencing no tangential acceleration. Given the symmetry, the wafers will be instantaneously coincident at position ③. The previously active wafer will exit the arc with the same velocity. Note that, in FIG. 5, the first end effector 18a(1) has a center of a workpiece holding position that is located at position ②, which also corresponds to a center of the workpiece W1 supported by the first end effector 18a(1). Similarly, note that, in FIG. 5, the second end effector 18b(1) has a center of a workpiece holding position that is located at position ④, which also corresponds to a center of the workpiece W2 supported by the second end effector 18b(1).

[0061] For a given arc entrance velocity, V, and commanded acceleration, A, we can determine the minimum radius of curvature,

$$R = V^2/A$$

where A is the allowable acceleration. In this case, for zero tangential acceleration and constant velocity, the acceleration is purely centripetal and optimized. FIG. 6 is a graph of an acceptable radius of curvature as a function of tangential velocity for a commanded acceleration of 1 g.

[0062] Wrist Kinematics Through Arc

[0063] The constant velocity motion of the wafer on the arc is easily defined by the angle, β . Given the designed symmetry of the motion through the arc segment, the wrist will always remain on the line of symmetry as shown by pivot axis PA1 in FIG. 7. In FIG. 7, the first end effector 18a with wafer W1 is moving along the arc ARC from position ② to position ③ and the second end effector 18b with wafer W2 is moving along the arc ARC from position ④ to position ③. We want to determine the location of the wrist as the wafers move along the arc. In FIG. 7, position ① can be considered a first start position (or a second end position), position ② can be considered a first arc position, position ③ can be a central or coincident position (or a third arc position), position ④ can be considered a second arc position, and position ⑤ can be considered a second start position (or a first end position).

[0064] From FIG. 7, we can see from the law of cosines,

$$L_4^2 = R^2 + C^2 - 2 \cdot R \cdot C \cdot \cos(\gamma/2 - \beta).$$

[0065] Where C is the distance from the center of curvature to the wrist.

$$a = 1$$

$$b = 2 \cdot R \cdot \cos(\gamma/2 - \beta)$$

$$c = R^2 - L_4^2$$

[0066] We can use the quadratic equation,

$$C = (-2*R*\cos(\gamma/2-\beta)+\sqrt{4*R^2*\cos^2(\gamma/2-\beta)-4*(R^2-L_4^2)})/2$$

$$C = -R*\cos(\gamma/2-\beta)+\sqrt{R^2*\cos^2(\gamma/2-\beta)-R^2+L_4^2}.$$

[0067] Once we have C, χ is easily found from the law of cosines.

[0068] Wrist Limitation Given Environment

[0069] In the following and in conjunction with FIG. 8, we consider spatial considerations given the geometry of the blades, the wafers, and the surrounding environment.

[0070] The process station can be a distance, B, from a side wall. Given the length of the end effector, L_4 , the minimum allowable clearance, s, and the radius of the robot wrist, r_{wrist} , the following must be maintained.

$$(R+L_4)*\cos(\gamma/2) < R+B-r_{wrist}-s$$

[0071] From this, we can determine the minimum angle, gamma.

$$\gamma_{min} > 2*\cos^{-1}((R+B-r_{wrist}-s)/(R+L_4)).$$

[0072] Swap Motion

[0073] In the above, we consider a line – arc – line segment approach (i.e., line between point ① and point ②, arc between point ② and point ④, and line between point ④ and point ⑤). It should be noted that a line-arc-arc segment is also a possibility. But considering two line segments, their respective lengths can be either equal or unequal.

[0074] We will review possible swap motion operations for both below, as depicted in a flowchart in FIG. 9. As shown in FIG. 9, upon start of swap motion operation it will be determined at step S102 whether the line segments are of equal length or unequal length. If the line segments are of equal length, then the process will move to step 104, and, if the line segments are of unequal length, then the process will move to step 108.

[0075] Equal Length Line Segments: Symmetric Motion

[0076] For unequal length line segments, we need to determine the geometric relationship between the intended path and the end effectors. However, we consider a simplified scheme where the line segments are equal in length and the starting position of the end effectors are aligned with the path as shown in FIG. 10 where the wrist will always stay on the line of symmetry. For equal length line segments, a symmetric motion can be performed in step S106.

[0077] First, we see that they are readily defined by the following relationship with the end effector length,

$$L_4 = D + R \cdot \tan(\gamma/2).$$

[0078] This can be an equation considered to be of two unknowns, D and R.

[0079] Second, we see that the value of $D_{1 \rightarrow 2}$ (i.e., distance between point ① and point ②) and $D_{5 \rightarrow 4}$ (i.e., distance between point ⑤ and point ④) are equal and, more importantly, the acceleration profile for both wafers can be the same. The motion can be symmetric about the line that passes through the center of the radius of curvature and the starting point of the wrist.

[0080] Given the symmetry, we assume now that both wafers will accelerate along the entire length, D. One does not need to slow for the other. Both wafers will accelerate with a magnitude A_{c1} to a maximum attainable velocity.

$$D = 1/2 \cdot A_{c1} \cdot t_1^2$$

[0081] We can solve for the acceleration time,

$$t_1 = \sqrt{2 \cdot D / A_c}.$$

[0082] We can then solve for the velocity at the entrance to the arc.

$$V_c = A_{c1} \cdot t_1$$

$$V_c = \sqrt{2 \cdot D \cdot A_{c1}}.$$

[0083] We must now be concerned for the centripetal acceleration of the wafer, traveling at a constant velocity V_c , as we move along the arc of radius, R .

$$A_{c2} = V^2/R = 2 \cdot D \cdot A_{c1}/R.$$

[0084] For constant acceleration, we can determine the relationship between D , R and the accelerations.

$$R = 2 \cdot D \cdot A_{c1}/A_{c2}.$$

[0085] If we assume that the linear acceleration and the centripetal acceleration should be the same magnitude, then the equation simplifies further,

$$R = 2 \cdot D.$$

[0086] This is a very elegant and useful simplification. We see that the design of the path can be completely independent of the acceleration.

[0087] Now having our relationship between R and D , we can solve for R and D using the first equation,

$$L_4 = D + R \cdot \tan(\gamma/2)$$

$$L_4 = R/2 + R \cdot \tan(\gamma/2)$$

$$R = 2 \cdot L_4 / (1 + 2 \cdot \tan(\gamma/2))$$

$$D = L_4 / (1 + 2 \cdot \tan(\gamma/2)).$$

[0088] The figure simplifies to FIG. 11.

[0089] Time For Symmetric Move

[0090] We wish to determine the time required for the total move. The distance traveled during the constant acceleration is defined by the following,

$$D = \frac{1}{2} A t_1^2$$

[0091] Solving for the acceleration time,

$$t_1 = \sqrt{2D/A}.$$

[0092] We know that the velocity is simply,

$$V = A t_1 = \sqrt{2D A}.$$

[0093] The time required for the wafers to travel about the arc is the following,

$$t_3 = R \gamma / V$$

$$t_3 = 2D \gamma / \sqrt{2D A}$$

$$t_3 = \gamma \sqrt{2D/A}.$$

[0094] The total move time can thus be found,

$$t_f = 2 t_1 + t_3$$

$$t_f = 2 \sqrt{2D/A} + \gamma \sqrt{2D/A}$$

$$t_f = \sqrt{2D/A} (2 + \gamma).$$

[0095] Minimum Distance

[0096] If the exiting wafer must travel a minimum distance to exit the station, we are essentially defining, D , as that minimum distance. We have a degree of freedom, γ , as shown in FIG. 11

$$L_4 = D_1 + 2 D_1 \tan(\gamma/2).$$

[0097] Solving for γ ,

$$\gamma = 2 \arctan((L_4 - D_1)/(2 D_1)).$$

[0098] As an example, we can see that when $L_4 = D_1$, $\gamma = 0$ which stands to reason.

[0099] If D_1 is greater than L_4 , γ would be negative which is not practical.

However, practically speaking, D_1 should never be greater than L_4 because by this time the wafer center will have crossed the starting location of the wrist. Which, even for a fully inserted end effector would not make sense for a wrist of some radius. The wafer would have already necessarily crossed the exit.

[00100] Examples

[00101] A few examples of symmetric motion with varying gamma are depicted in FIGS. 12A-12L, where $L_4 = 365$ mm.

[00102] Unequal Length Line Segments: General Case

[00103] In the following we consider a general case of line-arc-line (i.e., line between point ① and point ②, arc between point ② and point ④, and line between point ④ and point ⑤) where the lines (i.e., first line between point ① and point ②, and second line between point ⑤ and point ④) are not necessarily equal length. If the line segments are of unequal length, then the process will move to step 108 in FIG. 9, and two different methods can be used to compensate for the unequal lengths in step S110 or in step S112.

[00104] The blade having the longer line segment should be accelerating or decelerating at all times to optimize move time. For example, if the active blade has the longer linear move segment, it will accelerate along the line in the direction of point ② but may have to decelerate to, V , the speed attainable by the inactive wafer.

[00105] The inactive wafer, having the smaller distance to travel, can do a number of things. For one, it could hold position for some time delay, allowing the active blade to collapse the wrist. It would then accelerate at maximum acceleration to ensure that it attains the

matching velocity V at the point ④ at the same time as the active wafer. The benefit of this type of inactive wafer motion is that the wafers can never be separated by the starting distance. The active wafer is moving in the general direction of the inactive wafer and the inactive wafer is holding still for some time. Furthermore, the inactive blade will not come any closer to the rear wall.

[00106] Inactive Blade Pause (Step S110)

[00107] The active blade must travel the distance $D_{1 \rightarrow 2}$, arriving at a velocity, V . The inactive blade must travel a distance $D_{4 \rightarrow 5}$, arrive at the same velocity, V . The distance $D_{1 \rightarrow 2}$ will be greater than $D_{4 \rightarrow 5}$.

[00108] The active blades motion can be defined by an acceleration of A for t_1 seconds followed by a deceleration of A for t_2 seconds. The position and velocity of the active blade at the entry into the arc can be defined as in the following,

$$X_{1 \rightarrow 2} = \frac{1}{2} A t_1^2 + A t_1 t_2 - \frac{1}{2} A t_2^2$$

$$V_2 = A t_1 - A t_2 = V.$$

[00109] For the inactive blade, we will pause for t_3 seconds and then accelerate with a magnitude A for t_4 seconds.

[00110] The position and velocity of the inactive blade at the entry into the arc can be defined as in the following,

$$X_{5 \rightarrow 4} = \frac{1}{2} A t_4^2 = D_{4 \rightarrow 5}$$

$$V_4 = A t_4 = V.$$

[00111] We know that that moves must start and stop at the same time,

$$t_1 + t_2 = t_3 + t_4.$$

[00112] We thus have five equations in four unknowns,

$$t_4 = \sqrt{2 \cdot D_{5 \rightarrow 4} / A}.$$

[00113] Inactive Wafer Travel Distance

[00114] For a given $D_{1 \rightarrow 2}$, R , and γ , we can find the orientation of the inactive blade along the entry line and the distance the inactive wafer will travel along the entry line, $D_{5 \rightarrow 4}$ (see FIG. 13).

[00115] The position vector associated with the point ④ is found through the following,

$$P_4 = D_{12} + R \cdot i + R \cdot \exp(i \cdot (\pi/2 - \gamma)).$$

[00116] The position of the wrist at the start of the move is the following,

$$P_w = L_4.$$

[00117] The value of b is the magnitude of the vector,

$$b = |P_4 - P_w|.$$

[00118] The value for the angle β is the following,

$$\beta = \text{atan2}(\text{imag}(P_4 - P_w), \text{real}(P_4 - P_w)).$$

[00119] We can then use the law of cosines to determine the following,

$$L_5^2 = D_{54}^2 + b^2 - D_{54} \cdot b \cdot \cos(\beta + \gamma).$$

[00120] From which we can solve the quadratic equation for $D_{5 \rightarrow 4}$.

[00121] We then have P_5 ,

$$P_5 = P_4 + D_{45} \cdot \exp(i \cdot g).$$

(See FIG. 14.).

[00122] Inactive Blade Back Up (Step S112)

[00123] Another option is for the inactive blade, having a shorter line segment, to take

advantage of the active blade moving towards it and to back up away from the active wafer, elongating the acceleration path, so that it can then subsequently accelerate along a longer distance to achieve a higher arc velocity.

[00124] Unequal Length, Simplified

[00125] We may wish to have the active wafer travel further from the station. The inactive wafer will travel at full acceleration along the length D. As developed above, we may know the required radius given a full linear acceleration, an equivalent centripetal acceleration, and a length D. (See FIG. 15.)

$$R = 2*D$$

[00126] From the above, we can write the relationship in x and y.

$$x: D_1 + 2*D*\sin(\gamma) + D*\cos(\gamma) = L_4 + L_5*\cos(q_5) \quad y:$$

$$2*D - 2*D*\cos(\gamma) + D*\sin(\gamma) = L_5*\sin(q_5)$$

[00127] We can isolate D on both sides of the equations,

$$(D_1 - L_4) + D*(2*\sin(\gamma) + \cos(\gamma)) = L_5*\cos(q_5) \quad D*(2 -$$

$$2*\cos(\gamma) + \sin(\gamma)) = L_5*\sin(q_5)$$

[00128] Squaring both sides and adding them together,

$$(D_1 - L_4)^2 + 2*D*(2*\sin(\gamma) + \cos(\gamma))*(D_1 - L_4) + D^2*(2*\sin(\gamma) + \cos(\gamma))^2 = L_5^2*\cos^2(q_5)$$

$$D^2*(2 - 2*\cos(\gamma) + \sin(\gamma))^2 = L_5^2*\sin^2(q_5)$$

[00129] Summing the two equations together and recognizing the identity,

$$(D_1 - L_4)^2 - L_5^2 + 2*D*(2*\sin(\gamma) + \cos(\gamma))*(D_1 - L_4) + D^2*[(2*\sin(\gamma) + \cos(\gamma))^2 + (2 - 2*\cos(\gamma) + \sin(\gamma))^2] = 0$$

[00130] From this, we can solve this quadratic equation in D. This has effectively eliminated the variable R by making it a function of D.

[00131] D will be shorter than D₁.

[00132] We also know the velocity as a function of D and the allowable acceleration.

$$V_c = \sqrt{2 \cdot D \cdot A_{c1}}$$

[00133] The time in arc is simply,

$$t_5 = R \cdot \gamma / V_c$$

$$t_5 = \sqrt{2 \cdot D / A_c} \cdot \gamma$$

[00134] Allowing For More Z Time

[00135] If you need more time to complete the z, the most important thing is to get into the safe zone as quickly as possible.

[00136] Superimposed Motion

[00137] Z Motion

[00138] The entry exit point is designed to be the point where the wafer can first deviate from the straight line on an arc. At around this same location, the wafer should be allowed to move in z. So, in general, the z move must be completed while the wafers are traveling on the arc.

The time required

$$t_z = 2 \cdot \sqrt{p / A_z} + t_f$$

where p is the blade pitch, A is the allowable acceleration in z, and t_f is the filter time constant.

(See FIG. 16.)

[00139] The time the wafers will spend on the arc is the following,

$$t_{\text{arc}} = R \cdot \gamma / V$$

[00140] In order for the move to be valid, the following must be true,

$$t_{\text{arc}} \geq t_z$$

[00141] This requirement may compel a longer R or gamma and a smaller, V.

[00142] Wrist Acceleration (see FIG. 17)

$$X_1 = L_4 \cdot \sin(\theta)$$

$$V_{x1} = \omega \cdot L_4 \cdot \cos(\theta)$$

$$A_{x1} = \alpha \cdot L_4 \cdot \cos(\theta) - \omega^2 \cdot L_4 \cdot \sin(\theta)$$

$$Y_w = L_4 \cdot (1 - \cos(\theta))$$

$$V_{yw} = \omega \cdot L_4 \cdot \sin(\theta)$$

$$A_{yw} = \alpha \cdot L_4 \cdot \sin(\theta) + \omega^2 \cdot L_4 \cdot \cos(\theta)$$

[00143] For $\theta = 0$ and $\alpha = 0$

$$A_{x1} = 0$$

$$A_{yw} = \alpha \cdot L_4 \cdot \sin(\theta) + \omega^2 \cdot L_4$$

[00144] It should be noted that the exemplary embodiments depicted and described herein set forth the preferred embodiments of the present invention, and are not meant to limit the scope of the claims hereto in any way. Numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention can be practiced otherwise than as specifically described herein.

WHAT IS CLAIMED IS:

1. A robotic apparatus comprising:

an arm member configured to pivot about a first axis;

a first end effector pivotably connected to the arm member about a second axis, the first end effector having a first surface upon which a first workpiece can be received;

a second end effector pivotably connected to the arm member about the second axis, the second end effector having a second surface upon which a second workpiece can be received;

at least one drive unit configured to drive the arm member to pivot about the first axis, the at least one drive unit being configured to drive the first end effector to pivot about the second axis, the at least one drive unit being configured to drive the second end effector to pivot about the second axis; and

a control unit configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector to perform a swapping operation that includes the first end effector and the second end effector swapping arc positions disposed at opposite ends of an arc having a constant radius of curvature, the control unit being configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector such that the first workpiece received on the first end effector and the second workpiece received on the second end effector each travel at equal and constant velocities along the arc.

2. The robotic apparatus of claim 1, wherein the control unit is configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector such that the equal and constant velocities produce centripetal acceleration values acting upon the first workpiece and the second workpiece along the arc that do not exceed a predetermined acceleration limit.

3. The robotic apparatus of claim 2, wherein the control unit is configured to control the at least one drive unit to move the arm member, the first end effector and the second end effector during the swapping operation without exceeding the predetermined acceleration limit to retain the first workpiece and the second workpiece on the first end effector and the second end effector, respectively, solely with surface friction without use of a suction device and without use of an edge gripping device.

4. The robotic apparatus of claim 1, wherein the first end effector and the second end effector each includes at least one of an edge-gripping device and a suction device.

5. The robotic apparatus of claim 1, wherein the swapping operation further includes at least one of:

moving the first end effector such that the first workpiece or a center of a workpiece holding position of the first end effector moves from a first start position to a first arc position of the arc positions; and

moving the second end effector such that the second workpiece or a center of a

workpiece holding position of the second end effector moves from a second start position to a second arc position of the arc positions.

6. The robotic apparatus of claim 5, wherein the movement of the first workpiece from the first start position to the first arc position includes straight linear movement and/or curved movement.

7. The robotic apparatus of claim 5, wherein the first start position is located within a processing chamber, and the second start position is located within a supply/output chamber.

8. The robotic apparatus of claim 5,
wherein the movement of the first workpiece from the first start position to the first arc position includes straight linear movement of a first length, and

wherein the movement of the second workpiece from the second start position to the second arc position includes straight linear movement of a second length.

9. The robotic apparatus of claim 8, wherein the control unit is configured to move the first end effector and the second end effector in symmetric motions during an entirety of the swapping operation when the first length is equal to the second length.

10. The robotic apparatus of claim 8, wherein the control unit is configured to move the first end effector and the second end effector in nonsymmetric motions during a portion of

the swapping operation when the first length is unequal to the second length.

11. A method of transporting workpieces with a robotic apparatus, comprising:

providing a robotic apparatus having:

an arm member configured to pivot about a first axis;

a first end effector pivotably connected to the arm member about a second axis,
the first end effector having a first surface upon which a first workpiece can be received;

a second end effector pivotably connected to the arm member about the second
axis, the second end effector having a second surface upon which a second workpiece can be
received;

at least one drive unit configured to drive the arm member to pivot about the first
axis, the at least one drive unit being configured to drive the first end effector to pivot about
the second axis, the at least one drive unit being configured to drive the second end effector to
pivot about the second axis; and

a control unit configured to control the at least one drive unit to move the arm
member, the first end effector and the second end effector; and

controlling the at least one drive unit to move the arm member, the first end effector
and the second end effector to perform a swapping operation that includes the first end effector
and the second end effector swapping arc positions disposed at opposite ends of an arc having
a constant radius of curvature,

wherein the at least one drive unit is controlled to move the arm member, the first end
effector and the second end effector such that the first workpiece received on the first end

effector and the second workpiece received on the second end effector each travel at equal and constant velocities along the arc.

12. The method of claim 11, wherein the at least one drive unit is controlled to move the arm member, the first end effector and the second end effector such that the equal and constant velocities produce centripetal acceleration values acting upon the first workpiece and the second workpiece along the arc that do not exceed a predetermined acceleration limit.

13. The method of claim 12, wherein the at least one drive unit is controlled to move the arm member, the first end effector and the second end effector during the swapping operation without exceeding the predetermined acceleration limit to retain the first workpiece and the second workpiece on the first end effector and the second end effector, respectively, solely with surface friction without use of a suction device and without use of an edge gripping device.

14. The method of claim 11, wherein the first end effector and the second end effector each includes at least one of an edge-gripping device and a suction device.

15. The method of claim 11, wherein the swapping operation further includes at least one of:

moving the first end effector such that the first workpiece or a center of a workpiece holding position of the first end effector moves from a first start position to a first arc position

of the arc positions; and

moving the second end effector such that the second workpiece or a center of a workpiece holding position of the second end effector moves from a second start position to a second arc position of the arc positions.

16. The method of claim 15, wherein the movement of the first workpiece from the first start position to the first arc position includes straight linear movement and/or curved movement.

17. The method of claim 15, wherein the first start position is located within a processing chamber, and the second start position is located within a supply/output chamber.

18. The method of claim 15,
wherein the movement of the first workpiece from the first start position to the first arc position includes straight linear movement of a first length, and
wherein the movement of the second workpiece from the second start position to the second arc position includes straight linear movement of a second length.

19. The method of claim 18, wherein the control unit is configured to move the first end effector and the second end effector in symmetric motions during an entirety of the swapping operation when the first length is equal to the second length.

20. The method of claim 18, wherein the control unit is configured to move the first end effector and the second end effector in nonsymmetric motions during a portion of the swapping operation when the first length is unequal to the second length.