radiation within the workpiece, by conversion of kinetic energy of incident electrons or ions into heat within the workpiece, by workpiece erosion, etc.) are herein individually and collectively referred to as the "tool tip," and any region of the workpiece that is ultimately processed by the tool (e.g., at the tool tip) is herein referred to as the "tooling region." In embodiments in which the tool is a mechanical structure that is rotatable about an axis that intersects the workpiece (e.g., as with a router bit, a drill bit, etc.), or in which the tool is energy or a stream or jet of matter directed onto the workpiece along an axis that intersects the workpiece, an angle of such an axis relative to the portion of the surface of the workpiece intersected by the axis is herein referred to as a "tooling angle."

The multi-axis machine tool includes one or more actuators to position the tool tip, to position the workpiece, to move the tool tip relative to the workpiece, to move the workpiece relative to the tool tip, or any combination thereof. Thus, the positioning of the tooling region on or within the workpiece can be changed upon imparting relative movement between the tool tip and the workpiece. Each actuator may be arranged or otherwise configured to position the tooling region or otherwise impart relative movement between the tooling region and the workpiece along at least one linear axis, along at least one rotary axis, or any combination thereof. As is known in the art, examples of linear axes include an X-axis, a Y-axis (orthogonal to the X-axis) and a Z-axis (orthogonal to the X- and Y-axes), and examples of rotary axes include an A-axis (i.e., defining rotation about an axis parallel to the X-axis), a B-axis (i.e., defining rotation about an axis parallel to the Y-axis) and a C-axis (i.e., defining rotation about an axis parallel to the Z-axis).

Actuators arranged or configured to position the tooling region or otherwise impart relative movement between the tooling region and the workpiece along a linear axis may be generally referred to as "linear actuators." Actuators arranged or configured to position the tooling region or otherwise impart relative movement between the tooling region and the workpiece along a rotary axis may be generally referred to as "rotary actuators." Examples of linear actuators that may be included within the multi-axis machine tool include one or more X-axis actuators (i.e., actuators arranged or configured to impart motion along the X-axis), one or more Y-axis actuators (i.e., actuators arranged or configured to impart motion along the Y-axis) and one or more Z-axis actuators (i.e., actuators arranged or configured to impart motion along

the relatively-high bandwidth X-axis actuator 108, relatively-high bandwidth Y-axis actuator 110 and relatively-high bandwidth Z-axis actuator 112 in the serial tool tip positioning assembly may be configured to provide continuous or stepped (incremental) motion.

A tool fixture (not shown) may be mechanically coupled to the serial tool tip positioning assembly (e.g., at the relatively-high bandwidth Z-axis actuator 112) to hold, retain, carry, etc., a mechanical structure (e.g., a router bit, a drill bit, a tool bit, a grinding bit, a blade, etc.) in any suitable or desired manner. Accordingly, the mechanical structure can be coupled to the serial tool tip positioning assembly by way of a tool fixture, which may be provided as one or more chucks or other clamps, clips, or other fastening devices (e.g., bolts, screws, pins, retaining rings, straps, ties, etc.). If the tool to be used includes a stream or jet of matter (e.g., water, air, sand or other abrasive particles, paint, metallic powder, or the like or any combination thereof, provided by a source of water, air, sand, particles, paint, powder, or the like or any combination thereof, as is known in the art), then the nozzle, head, etc., from which the stream or jet is ejected can be characterized as the tool fixture.

ii. Embodiments Concerning the Parallel Tool Tip Positioning Assembly

In one embodiment, a parallel tool tip positioning assembly can be employed when the tool to be used is a beam of directed energy, etc. Within a parallel tool tip positioning assembly, the nature and configuration of one or more of the relatively-high bandwidth X-axis actuator 108, relatively-high bandwidth Y-axis actuator 110 and relatively-high bandwidth Z-axis actuator 112 will depend upon the tool to be used.

For example, if the tool to be used is a beam of electrons or ions (e.g., generated from an electron or ion source, not shown, as is known in the art), the relatively-high bandwidth X-axis actuator 108, the relatively-high bandwidth Y-axis actuator 110 and the relatively-high bandwidth Z-axis actuator 112 may be provided as one or more magnetic lenses, cylinder lenses, Einzel lenses, quadropole lenses, multipole lenses, or the like or any combination thereof.

In another example, if the tool to be used is laser light (e.g., manifested as a series of pulses, as a continuous or quasi-continuous beam of laser light, or any combination thereof, generated from one or more laser sources as is known in the art), each of the relatively-high bandwidth X-axis actuator 108 and the relatively-high bandwidth Y-axis actuator 110 may be provided as a galvanometer-driven mirror system, a fast-steering mirror system (e.g., a mirror

actuated by a voice-coil motor, a piezoelectric actuator, an electrostrictive actuator, a magnetostrictive actuator, etc.), microelectromechanical systems (MEMS) mirror system, an adaptive optical (AO) system, an electro-optic deflector (EOD) system, an acousto-optic deflector (AOD) system (e.g., arranged and configured to diffract laser light along an axis, such as the X- or Y-axis, in response to an applied RF signal), or the like or any combination thereof. If the tool is to be provided as a focused beam of laser light (in which case the "tool tip" is a region of the focused beam having a fluence sufficiently high to process the workpeice), then a relatively high-bandwidth Z-axis actuator 112 can be provided as one or more AOD systems (e.g., arranged and configured to diffract laser light along two axes, such as the X- and Y-axes, in response to one or more applied, chirped RF signals), a fixed focal-length lens disposed in path in which the laser light propagates (i.e., a "propagation path") that is coupled to an actuator (e.g., a voice-coil) configured to move the lens along the propagation path, a variable-focal length lens (e.g., a zoom lens, or a so-called "liquid lens" incorporating technologies currently offered by COGNEX, VARIOPTIC, etc.) disposed in the propagation path, or the like or any combination thereof.

FIG. 3 schematically illustrates one embodiment of a parallel tool tip positioning assembly configured to position or otherwise move a tool tip associated with a focused beam of laser light. Referring to FIG. 3, the parallel tool tip positioning assembly 300 optionally includes a scan lens 302 (e.g., f-theta lens, a telecentric lens, an axicon lens, etc.) configured to focus a ~~bream~~ of laser light propagating along a propagation path 304, which has been deflected by a first galvanometer-driven mirror system (provided here as the relatively-high bandwidth X-axis actuator 108) and a second galvanometer-driven mirror system (provided here as the relatively-high bandwidth Y-axis actuator 110). As illustrated, the first galvanometer-driven mirror system includes a mirror 306a coupled to a motor 308a (e.g., via a shaft), which is configured to rotate the mirror 306a about the Y-axis (e.g., so as to permit deflection of the beam of laser light along the X-axis). Similarly, the second galvanometer-driven mirror system includes a mirror 306b coupled to a motor 308b (e.g., via a shaft), which is configured to rotate the mirror 306b about the X-axis (e.g., so as to permit deflection of the beam of laser light along the Y-axis). As a relatively-high bandwidth Z-axis actuator 112, the parallel tool tip positioning assembly 300 may also include a lens coupled to an actuator (e.g., a voice-coil, not shown),

actuated by a voice-coil motor, a piezoelectric actuator, an electrostrictive actuator, a magnetostrictive actuator, etc.), microelectromechanical systems (MEMS) mirror system, an adaptive optical (AO) system, an electro-optic deflector (EOD) system, an acousto-optic deflector (AOD) system (e.g., arranged and configured to diffract laser light along an axis, such as the X- or Y-axis, in response to an applied RF signal), or the like or any combination thereof. If the tool is to be provided as a focused beam of laser light (in which case the "tool tip" is a region of the focused beam having a fluence sufficiently high to process the workpeice), then a relatively high-bandwidth Z-axis actuator 112 can be provided as one or more AOD systems (e.g., arranged and configured to diffract laser light along two axes, such as the X- and Y-axes, in response to one or more applied, chirped RF signals), a fixed focal-length lens disposed in path in which the laser light propagates (i.e., a "propagation path") that is coupled to an actuator (e.g., a voice-coil) configured to move the lens along the propagation path, a variable-focal length lens (e.g., a zoom lens, or a so-called "liquid lens" incorporating technologies currently offered by COGNEX, VARIOPTIC, etc.) disposed in the propagation path, or the like or any combination thereof.

FIG. 3 schematically illustrates one embodiment of a parallel tool tip positioning assembly configured to position or otherwise move a tool tip associated with a focused beam of laser light. Referring to FIG. 3, the parallel tool tip positioning assembly 300 optionally includes a scan lens 302 (e.g., f-theta lens, a telecentric lens, an axicon lens, etc.) configured to focus a beam of laser light propagating along a propagation path 304, which has been deflected by a first galvanometer-driven mirror system (provided here as the relatively-high bandwidth X-axis actuator 108) and a second galvanometer-driven mirror system (provided here as the relatively-high bandwidth Y-axis actuator 110). As illustrated, the first galvanometer-driven mirror system includes a mirror 306a coupled to a motor 308a (e.g., via a shaft), which is configured to rotate the mirror 306a about the Y-axis (e.g., so as to permit deflection of the beam of laser light along the X-axis). Similarly, the second galvanometer-driven mirror system includes a mirror 306b coupled to a motor 308b (e.g., via a shaft), which is configured to rotate the mirror 306b about the X-axis (e.g., so as to permit deflection of the beam of laser light along the Y-axis). As a relatively-high bandwidth Z-axis actuator 112, the parallel tool tip positioning assembly 300 may also include a lens coupled to an actuator (e.g., a voice-coil, not shown),

PRECESSION ELEPHANT and PRECESSION ELEPHANT 2 series of scan heads offered by ARGES GmbH, the LASERTEC product line offered by DMG MORI AKIENGESELLSHAFT/DMG MORI COMPANY LIMITED. Further, and notwithstanding the above, it should be recognized that the tool tip positioning assembly can, in some embodiments, be provided as described in any of U.S. Patent No. 8,121,717 or ~~as described in~~ International Patent Pub. No. WO 2014/009150 A1, each of which is incorporated herein by reference in its entirety, or as described in FIGS. 5A-5C of aforementioned U.S. Patent No. 8,392,002.

Having exemplarily described certain components of one embodiment of a multi-axis machine tool above, an algorithm for processing and generating actuator commands to control the multi-axis machine tool, as implemented by the control system 100, now be discussed in greater detail with reference to FIG. 1.

D. Embodiments Concerning Processing of Actuator Commands

Referring to FIG. 1, the control system 100 receives preliminary actuator commands (e.g., obtained or otherwise derived from a computer file or a computer program as discussed above). As shown, the preliminary actuator commands include preliminary linear actuator commands: preliminary X-axis actuator command (i.e., X_prelim.), preliminary Y-axis actuator command (i.e., Y_prelim.), and preliminary Z-axis actuator command (i.e., Z_prelim.); and preliminary rotary actuator commands: preliminary B-axis actuator command (i.e., B_prelim.) and preliminary C-axis actuator command (i.e., C_prelim.). In one embodiment, at least one of the preliminary actuator commands will have non-negligible frequency content that exceeds the threshold frequency of a corresponding relatively-low bandwidth actuator. For example, the preliminary X-axis actuator command (i.e., X_prelim.) may have non-negligible frequency content that exceeds the threshold frequency of a corresponding relatively-low bandwidth X-axis actuator 102, the preliminary Y-axis actuator command (i.e., Y_prelim.) may have non-negligible frequency content that exceeds the threshold frequency of a corresponding relatively-low bandwidth Y-axis actuator 104, the preliminary Z-axis actuator command (i.e., Z_prelim.) may have non-negligible frequency content that exceeds the threshold frequency of a corresponding relatively-low bandwidth Z-axis actuator 106, the preliminary B-axis actuator command (i.e., B_prelim.) may have non-negligible frequency content that exceeds the threshold frequency of a corresponding relatively-low bandwidth B-axis actuator 114, the preliminary C-

i. Embodiments Concerning the Serial Tool Tip Positioning Assembly

Within a serial tool tip positioning assembly (e.g., as described above), any of the relatively-high bandwidth B-axis actuator 402 and the relatively-high bandwidth C-axis actuator 404 may include one or more components (e.g., stages, fixtures, chucks, rails, bearings, brackets, clamps, straps, bolts, screws, pins, retaining rings, ties, etc., not shown) to permit the relatively-high bandwidth B-axis actuator 402 and the relatively-high bandwidth C-axis actuator 404 to be mounted or otherwise mechanically coupled to one another or to any of the aforementioned actuators included within the serial tool tip.

Each of the relatively-high bandwidth B-axis actuator 402 and relatively-high bandwidth ~~B-axis~~ actuator 404 in the serial tool tip positioning assembly may be provided as one or more rotary stages (e.g., direct-drive stages, lead-screw stages, ball-screw stages, belt-driven stages, etc.), each driven by one or more hydraulic cylinders, one or more pneumatic cylinders, one or more servo motors, one or more voice-coil actuators, one or more piezoelectric actuators, one or more electrostrictive elements, or the like or any combination thereof. Moreover, any of the relatively-high bandwidth B-axis actuator 402 and relatively-high bandwidth C-axis actuator 404 in the serial tool tip positioning assembly may be configured to provide continuous or stepped (incremental) motion.

A tool fixture (not shown) may be mechanically coupled to the serial tool tip positioning assembly at the relatively-high bandwidth Z-axis actuator 112 (as discussed above), at the relatively-high bandwidth B-axis actuator 402 or at the relatively-high bandwidth C-axis actuator 404 to hold, retain, carry, etc., a mechanical structure (e.g., a router bit, a drill bit, a tool bit, a grinding bit, a blade, etc.), or other structure from which a stream or jet of matter is ejected (e.g., a nozzle, head, etc.), in any suitable or desired manner.

ii. Embodiments Concerning the Parallel Tool Tip Positioning Assembly

In one embodiment, the parallel tool tip positioning assembly includes a relatively-high bandwidth C-axis actuator 404, in addition to one or more of the relatively-high bandwidth X-axis actuator 108, the relatively-high bandwidth Y-axis actuator 110, and the relatively-high bandwidth Z-axis actuator 112, as exemplarily described above. In this case, the configuration of the relatively-high bandwidth C-axis actuator 404 will depend upon the tool to be used. Example embodiments discussed below relate to instances where the tool to be used includes

i. Embodiments Concerning the Serial Tool Tip Positioning Assembly

Within a serial tool tip positioning assembly (e.g., as described above), any of the relatively-high bandwidth B-axis actuator 402 and the relatively-high bandwidth C-axis actuator 404 may include one or more components (e.g., stages, fixtures, chucks, rails, bearings, brackets, clamps, straps, bolts, screws, pins, retaining rings, ties, etc., not shown) to permit the relatively-high bandwidth B-axis actuator 402 and the relatively-high bandwidth C-axis actuator 404 to be mounted or otherwise mechanically coupled to one another or to any of the aforementioned actuators included within the serial tool tip.

Each of the relatively-high bandwidth B-axis actuator 402 and relatively-high bandwidth C-axis actuator 404 in the serial tool tip positioning assembly may be provided as one or more rotary stages (e.g., direct-drive stages, lead-screw stages, ball-screw stages, belt-driven stages, etc.), each driven by one or more hydraulic cylinders, one or more pneumatic cylinders, one or more servo motors, one or more voice-coil actuators, one or more piezoelectric actuators, one or more electrostrictive elements, or the like or any combination thereof. Moreover, any of the relatively-high bandwidth B-axis actuator 402 and relatively-high bandwidth C-axis actuator 404 in the serial tool tip positioning assembly may be configured to provide continuous or stepped (incremental) motion.

A tool fixture (not shown) may be mechanically coupled to the serial tool tip positioning assembly at the relatively-high bandwidth Z-axis actuator 112 (as discussed above), at the relatively-high bandwidth B-axis actuator 402 or at the relatively-high bandwidth C-axis actuator 404 to hold, retain, carry, etc., a mechanical structure (e.g., a router bit, a drill bit, a tool bit, a grinding bit, a blade, etc.), or other structure from which a stream or jet of matter is ejected (e.g., a nozzle, head, etc.), in any suitable or desired manner.

ii. Embodiments Concerning the Parallel Tool Tip Positioning Assembly

In one embodiment, the parallel tool tip positioning assembly includes a relatively-high bandwidth C-axis actuator 404, in addition to one or more of the relatively-high bandwidth X-axis actuator 108, the relatively-high bandwidth Y-axis actuator 110, and the relatively-high bandwidth Z-axis actuator 112, as exemplarily described above. In this case, the configuration of the relatively-high bandwidth C-axis actuator 404 will depend upon the tool to be used. Example embodiments discussed below relate to instances where the tool to be used includes

depend upon the tool to be used. Example embodiments discussed below relate to instances where the tool to be used includes laser light (e.g., manifested as a series of pulses, as a continuous or quasi-continuous beam of laser light, or any combination thereof, generated from one or more laser sources as is known in the art). When the tool to be used is laser light, the laser light can be directed (e.g., along the aforementioned propagation path) to illuminate a portion of the workpiece at or near the tooling region.

Referring now to FIG. 5, the relatively-high bandwidth B-axis actuator 402 can include a first AOD system 500 arranged and configured to diffract laser light along one axis (e.g., along the X-axis) in response to an applied RF signal, and a second AOD system 502 arranged and ~~to~~ disposed optically "downstream" of the ~~second~~ AOD system ~~502~~ and configured to diffract laser light along another axis (e.g., along the Y-axis) in response to an applied RF signal. The relatively-high bandwidth B-axis actuator 402 can include additional components, such as half-wave plates 501 and 503, and a polarizing beam splitter 505. When driven, the first AOD system 500 and the second AOD system 502 can deflect position or otherwise move an incident beam of laser light 510 to any number of positions (e.g., as indicated by deflected beams 512 and 514) within a scan range associated with the first AOD system 500 and second AOD system 502. Deflected beams, such as deflected beams 512 and 514, can be characterized by a deflection angle measured relative to the incident beam of laser light 510.

The relatively-high bandwidth B-axis actuator 402 can also include a set of lenses (e.g., relay lens 504 and scan lens 506) disposed optically downstream of the second AOD system 502. Relay lens 504 is used to transform the deflection angle of any deflected beams (e.g., deflected beams 512 and 514) to laterally displaced beams (e.g., laterally displaced beams 512' and 514') on the scan lens 506. The scan lens 506 then transforms any laterally displaced beams (e.g., laterally displaced beams 512' and 514') to incident beams (e.g., incident beams 512'' and 514'') which are delivered to the workpiece (illustrated here at 508). As illustrated, incident beams 512'' and 514'' illuminate the workpiece at the same (or at least substantially the same spot or tooling ~~region),~~ but at different tooling angles.

Based on the construction of the relatively-high bandwidth B-axis actuator 402 described above, it should be recognized that the speed with which the tooling angle of an incident beam of laser light can be changed corresponds to the refresh rate of the first and second AOD systems

depend upon the tool to be used. Example embodiments discussed below relate to instances where the tool to be used includes laser light (e.g., manifested as a series of pulses, as a continuous or quasi-continuous beam of laser light, or any combination thereof, generated from one or more laser sources as is known in the art). When the tool to be used is laser light, the laser light can be directed (e.g., along the aforementioned propagation path) to illuminate a portion of the workpiece at or near the tooling region.

Referring now to FIG. 5, the relatively-high bandwidth B-axis actuator 402 can include a first AOD system 500 arranged and configured to diffract laser light along one axis (e.g., along the X-axis) in response to an applied RF signal, and a second AOD system 502 arranged and disposed optically "downstream" of the first AOD system 500 and configured to diffract laser light along another axis (e.g., along the Y-axis) in response to an applied RF signal. The relatively-high bandwidth B-axis actuator 402 can include additional components, such as half-wave plates 501 and 503, and a polarizing beam splitter 505. When driven, the first AOD system 500 and the second AOD system 502 can deflect position or otherwise move an incident beam of laser light 510 to any number of positions (e.g., as indicated by deflected beams 512 and 514) within a scan range associated with the first AOD system 500 and second AOD system 502. Deflected beams, such as deflected beams 512 and 514, can be characterized by a deflection angle measured relative to the incident beam of laser light 510.

The relatively-high bandwidth B-axis actuator 402 can also include a set of lenses (e.g., relay lens 504 and scan lens 506) disposed optically downstream of the second AOD system 502. Relay lens 504 is used to transform the deflection angle of any deflected beams (e.g., deflected beams 512 and 514) to laterally displaced beams (e.g., laterally displaced beams 512' and 514') on the scan lens 506. The scan lens 506 then transforms any laterally displaced beams (e.g., laterally displaced beams 512' and 514') to incident beams (e.g., incident beams 512'' and 514'') which are delivered to the workpiece (illustrated here at 508). As illustrated, incident beams 512'' and 514'' illuminate the workpiece at the same (or at least substantially the same) spot or tooling region, but at different tooling angles.

Based on the construction of the relatively-high bandwidth B-axis actuator 402 described above, it should be recognized that the speed with which the tooling angle of an incident beam of laser light can be changed corresponds to the refresh rate of the first and second AOD systems

500 and 502. The maximum ~~angle~~ tooling angle is proportional to the AOD deflection range and the focal length of the relay lens 504, and is inversely-proportional to the focal length of scan lens 506. The distance between the relay lens 504 and the scan lens 506 can be adjusted to ensure that different incident beams can be delivered to the same tooling region on the workpiece 508.

B. Additional Comments Concerning the Tool Tip Positioning Assembly

Notwithstanding the above, it should be recognized that any of the relatively-low bandwidth actuators described above as being incorporated within the workpiece positioning assembly (e.g., to position and/or move the workpiece) can, additionally or alternatively, be incorporated as part of a tool tip positioning assembly (e.g., to position and/or move the tool tip) that includes the relatively-high bandwidth B-axis actuator 402 or the relatively-high bandwidth C-axis actuator 404. Further, and notwithstanding the above, it should be recognized that the tool tip positioning assembly can, in some embodiments, be provided as any laser scanning or focusing assembly currently available in the industry, such as those found in the PRECESSION ELEPHANT and PRECESSION ELEPHANT 2 series of scan heads offered by ARGES GmbH. Further, and notwithstanding the above, it should be recognized that the tool tip positioning assembly can, in some embodiments, be provided as described in International Patent Pub. No. WO 2014/009150 A1, which is incorporated herein by reference in its entirety.

C. Embodiments Concerning Processing of Actuator Commands

Generally, the control system 400 may be implemented by one or more controllers as exemplarily described with respect to the control system 100, and operation of the control system 400 is the same as the operation of the control system 100 discussed above with respect to FIG. 1 with the exception of some additional processes and operations introduced to account for the presence of the relatively-high bandwidth B-axis actuator 402, the relatively-high bandwidth C-axis actuator 404, or a combination thereof. These additional processes and operations will now be described below.

The low-frequency content rotary actuator commands (e.g., B_low and C_low) are subtracted corresponding actuator commands in the preliminary rotary actuator commands (e.g., preliminary B-axis actuator command, B_prelim., and preliminary C-axis actuator command, C_prelim.) to generate one or more further-processed rotary actuator commands. For example,