US010885368B2

(12) **United States Patent**
Qiao et al.

(10) **Patent No.: US 10,885,368 B2**
(45) **Date of Patent: Jan. 5, 2021**

(54) **SIX-DIMENSIONAL SMART TARGET**

(71) Applicant: **Government of the United States of America, as represented by the Secretary of Commerce**, Gaithersburg, MD (US)

(72) Inventors: **Guixiu Qiao**, Boyds, MD (US); **Craig Schlenoff**, Germantown, MD (US)

(73) Assignee: **GOVERNMENT OF THE UNITED STATES OF AMERICA, AS REPRESENTED BY THE SECRETARY OF COMMERCE**, Gaithersburg, MD (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 61 days.

(21) Appl. No.: **16/409,085**

(22) Filed: **May 10, 2019**

(65) **Prior Publication Data**

US 2019/0354790 A1 Nov. 21, 2019

Related U.S. Application Data

(60) Provisional application No. 62/672,270, filed on May 16, 2018.

(51) **Int. Cl.**

G06T 7/246	(2017.01)
F21K 9/61	(2016.01)
G06T 7/292	(2017.01)
G06K 9/32	(2006.01)
G06K 9/00	(2006.01)
G06T 17/10	(2006.01)

(52) **U.S. Cl.**

CPC ***G06K 9/3241*** (2013.01); ***F21K 9/61*** (2016.08); ***G06K 9/00201*** (2013.01); ***G06T 7/246*** (2017.01); ***G06T 7/292*** (2017.01); ***G06T 17/10*** (2013.01)

(58) **Field of Classification Search**

CPC combination set(s) only.

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,215,391	A *	11/1965	Storm	F16M 11/046 248/396
2006/0182327	A1 *	8/2006	Mundy	G06K 9/00503 382/132
2010/0220390	A1 *	9/2010	Wein	G02B 27/644 359/429

(Continued)

OTHER PUBLICATIONS

Tsumaki , "A Distance-Error Detection and Correction System for Camera-Arm Control", 2014 World Automation Congress (WAC), Oct. 27, 2014, pp. 1-4.*

(Continued)

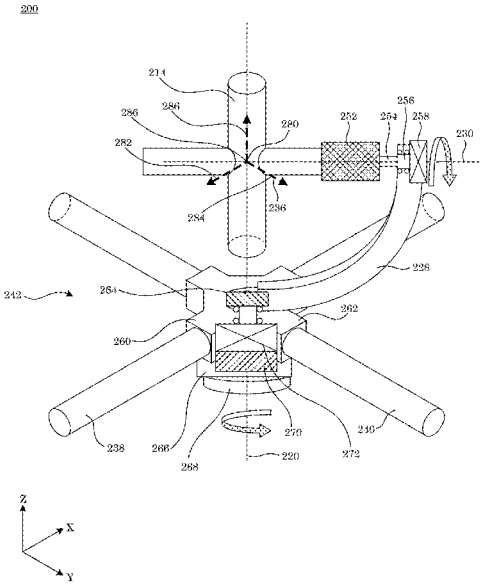
Primary Examiner — Omar S Ismail

(74) *Attorney, Agent, or Firm* — Office of Chief Counsel for National Institute of Standards and Technology

(57) **ABSTRACT**

A six-dimensional smart target determines pose of an object and includes: a gimbal with an azimuthal base and an elevation arm; an elevation member on the elevation arm that has light pipes; and an azimuthal member with light pipes such that the elevation member rotates at a rotary center about an elevation axis and azimuthal axis to consistently maintain the elevation member in a field of view of a measurement instrument.

18 Claims, 15 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

2016/0360096 A1* 12/2016 Holmes F16M 11/205

OTHER PUBLICATIONS

Nguyen ,"A New Full Pose Measurement Method for Robot Calibration", Sensors, www.mdpi.com/journal/sensors, Jul. 16, 2013, pp. 9134-9141.*

Guixiu Qiao,"Quick Positional Health Assessment for Industrial Robot Prognostics and Health Management (PHM)",2017 IEEE International Conference on Robotics and Automation (ICRA),Singapore, May 29-Jun. 3, 2017,pp. 1815-1819.*

Schares,"Improving accuracy of robot-guided 3D laser surface processing by workpiece measurement in a blink",Proc. SPIE 10525, High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VII, 1052508,Feb. 15, 2018,pp. 6-8.*

Tian Wei,"Determination of optimal samples for robot calibration based on error similarity",Chinese Journal of Aeronautics, Published on—Apr. 2, 2015,pp. 949-951.*

Qiao, G., et al., "Quick health assessment for industrial robot health degradation and the supporting advanced sensing development", Journal of Manufacturing Systems, 2018, p. 51-59, vol. 48.

* cited by examiner

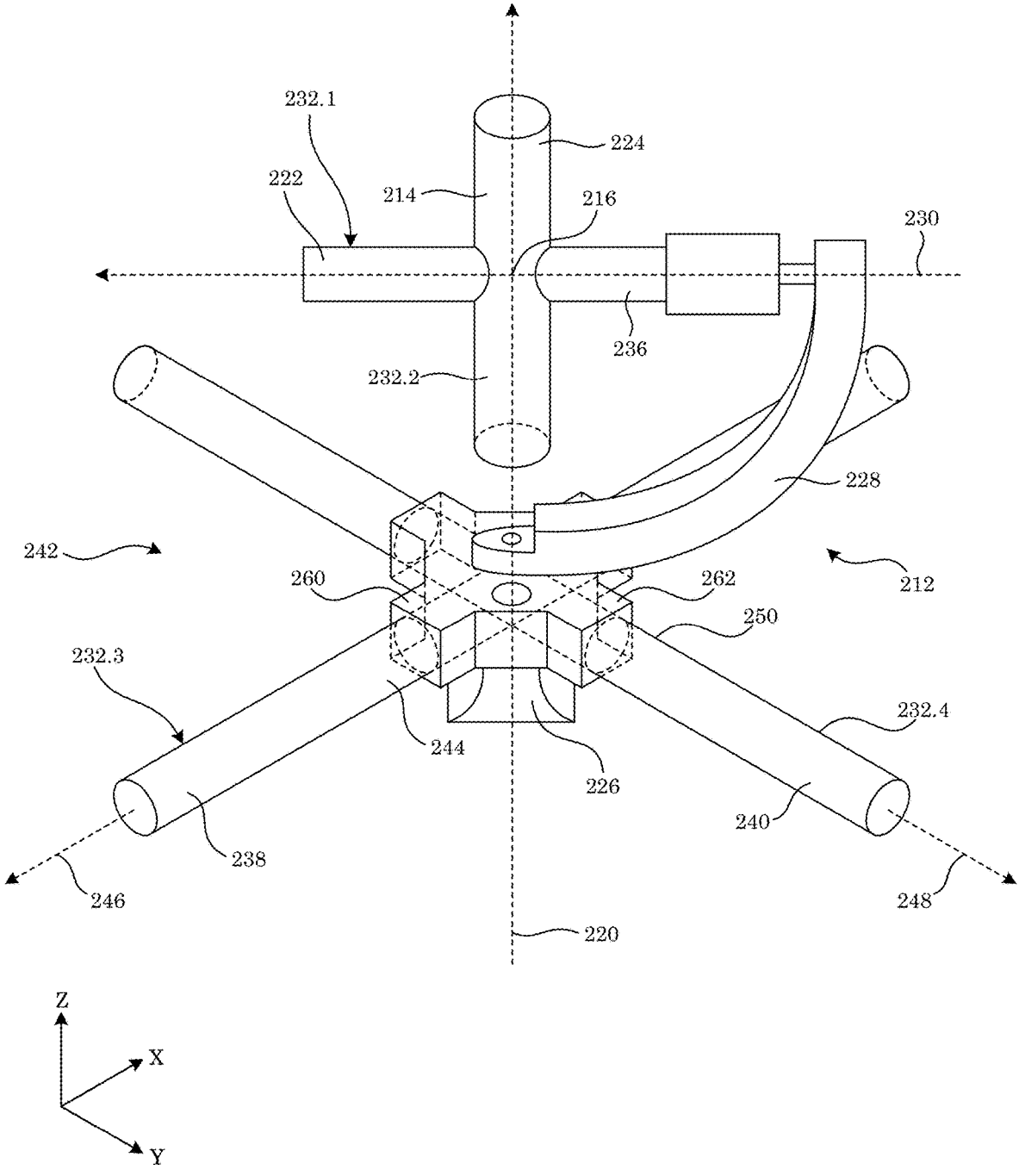

232.1
224
222
214
216
230
236
232.2
228
242
212
260
262
250
232.3
232.4
244
226
240
238
246
248
220
Z
X
Y

Figure. 1

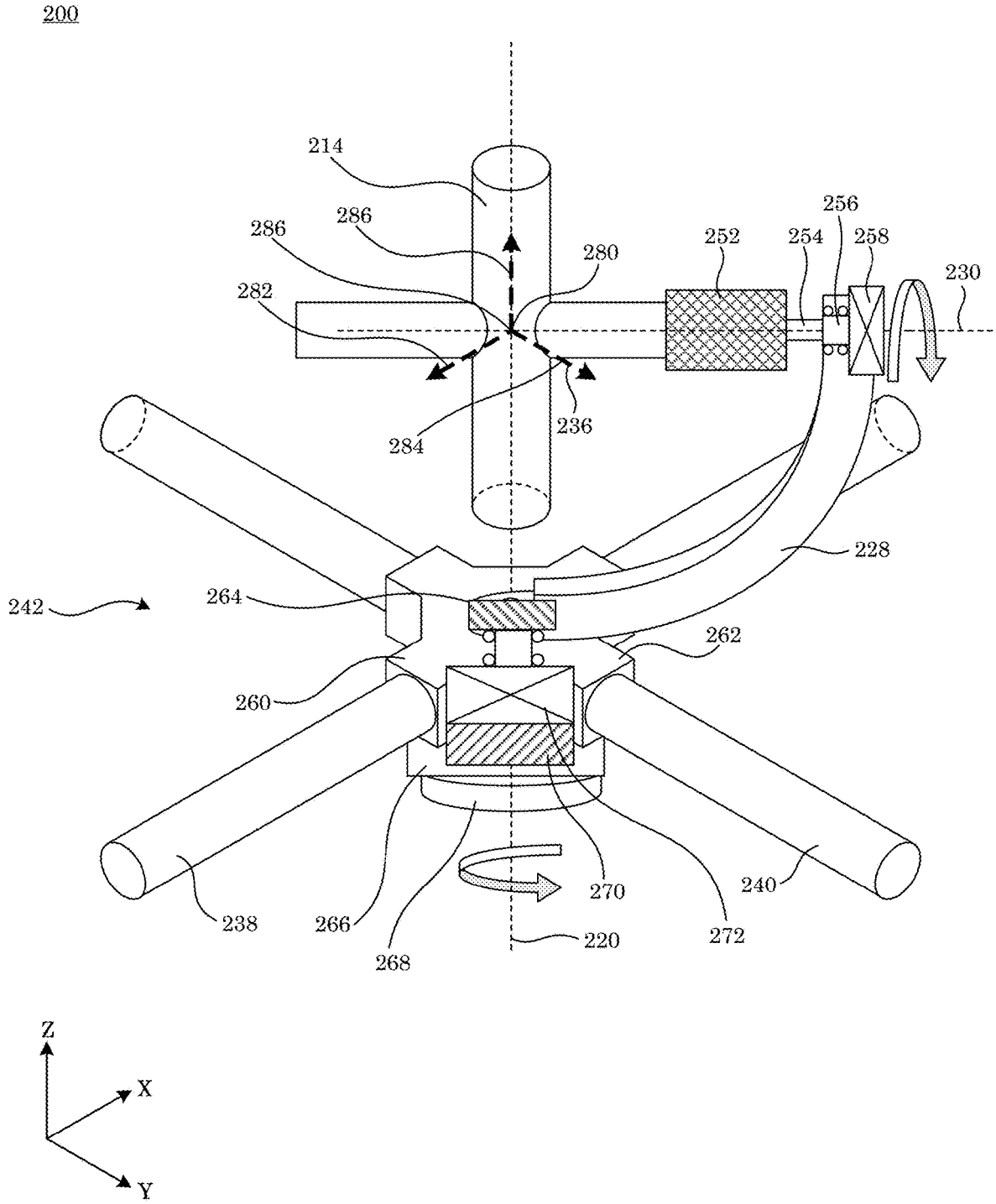

200
214
286
286
280
282
252
254
256
258
230
284
236
228
242
264
262
260
238
266
268
270
272
240
220
Z
X
Y

Figure. 2

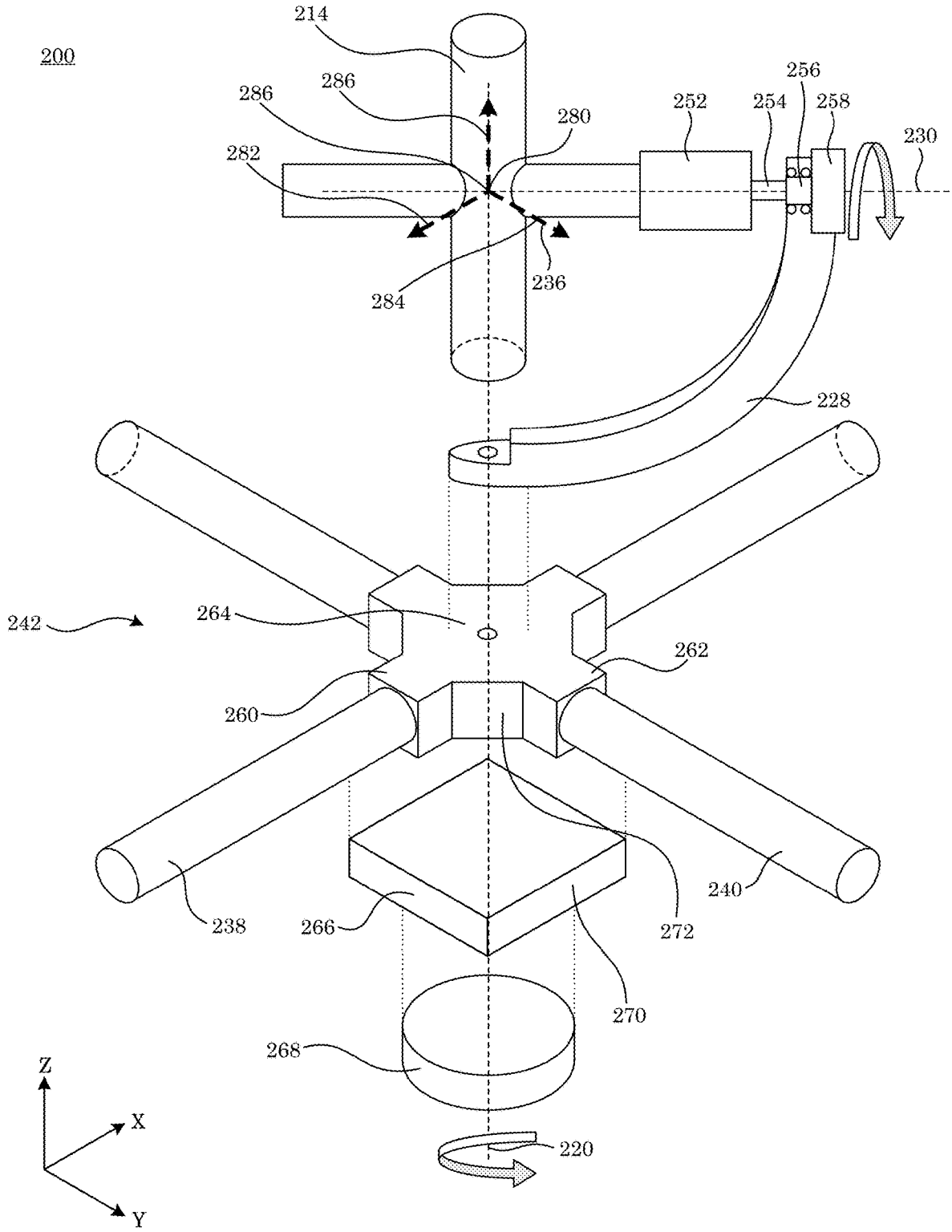

200
214
286
286
280
282
252
254
256
258
230
284
236
228
242
264
262
260
238
266
272
240
270
268
220
Z
X
Y

Figure. 3

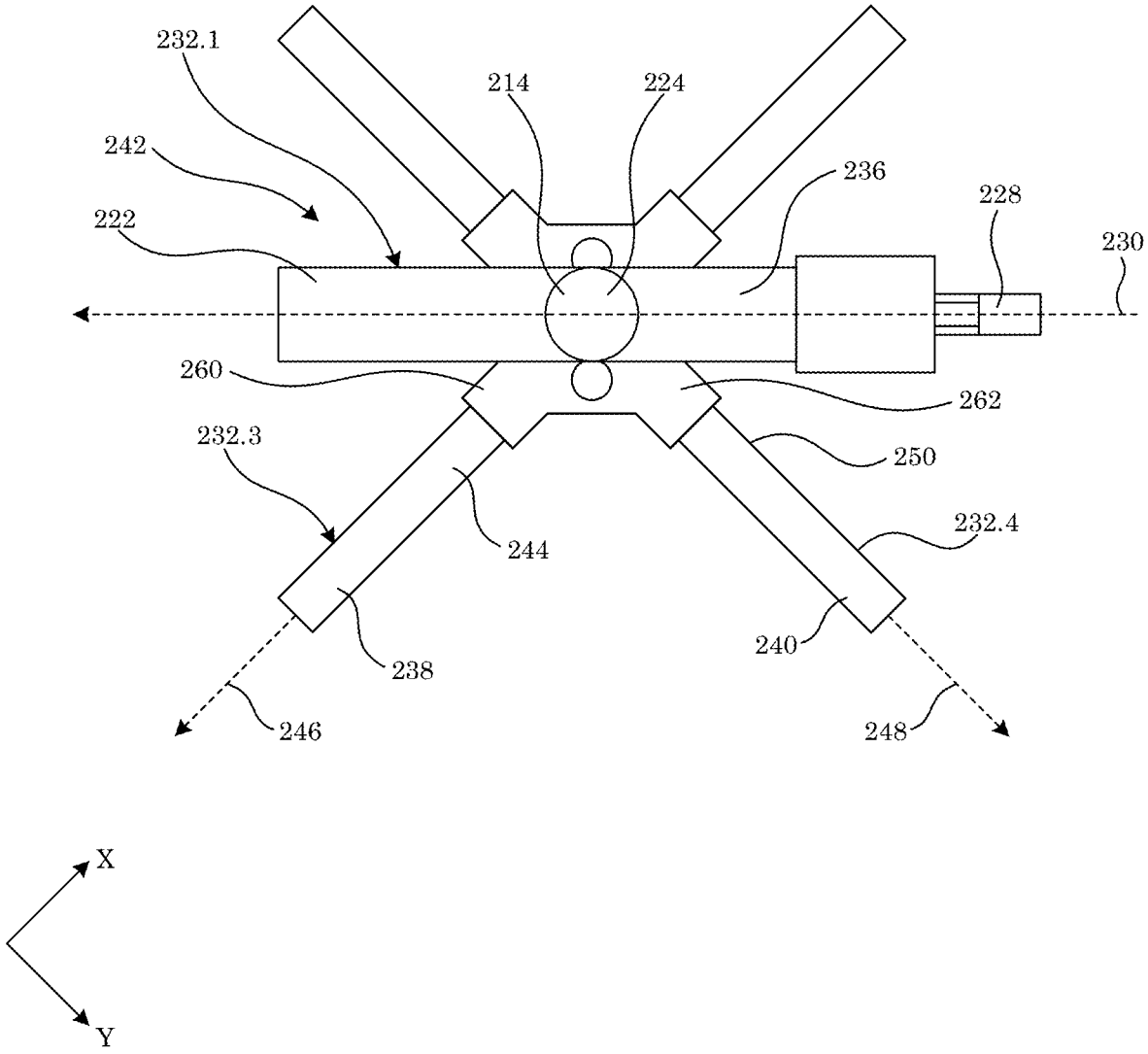

232.1
214
224
242
236
228
222
230
260
262
232.3
250
244
232.4
238
240
246
248
X
Y

Figure. 4

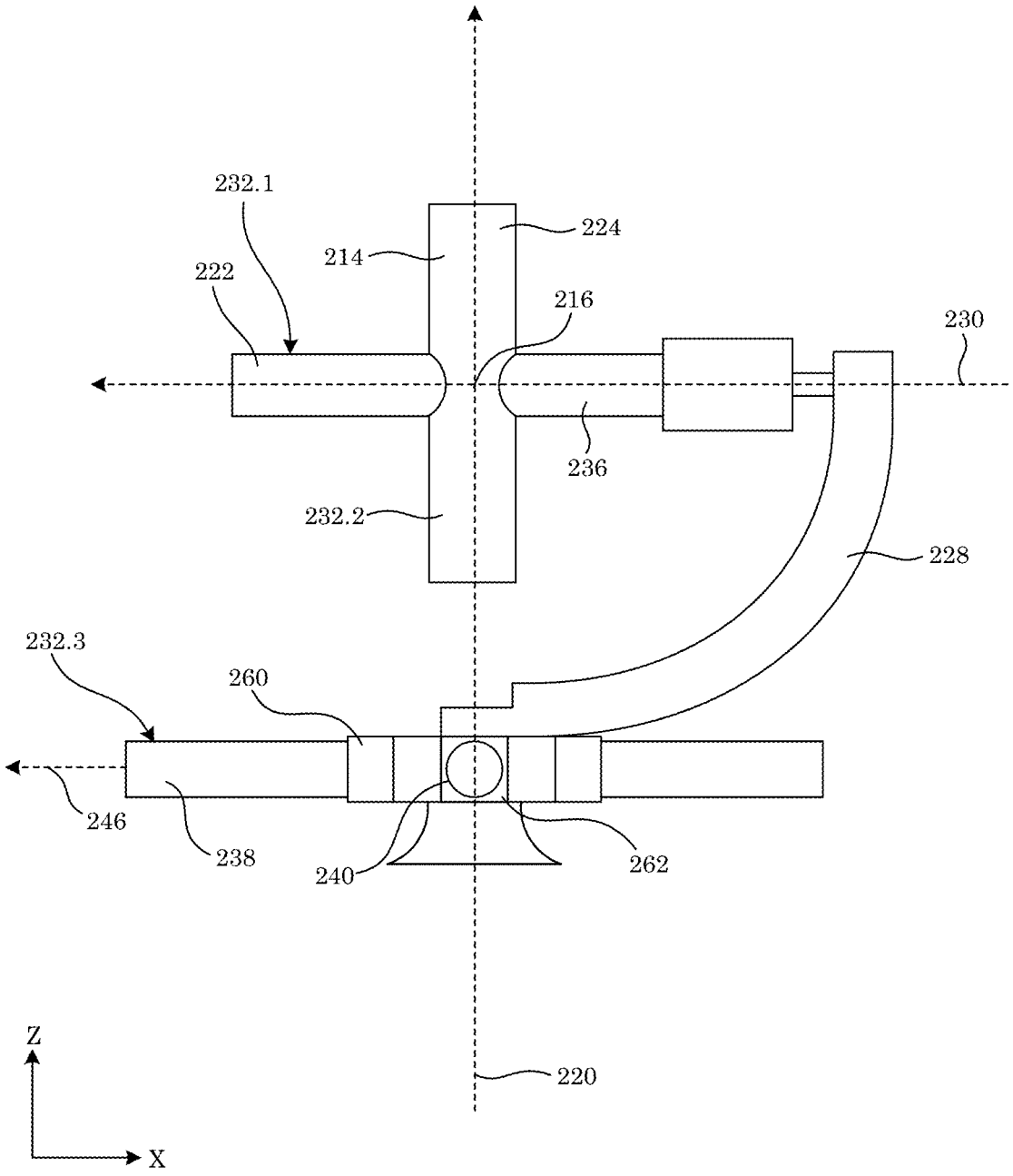

232.1
224
214
222
216
230
236
232.2
228
232.3
260
246
238
240
262
220
Z
X

Figure. 5

214

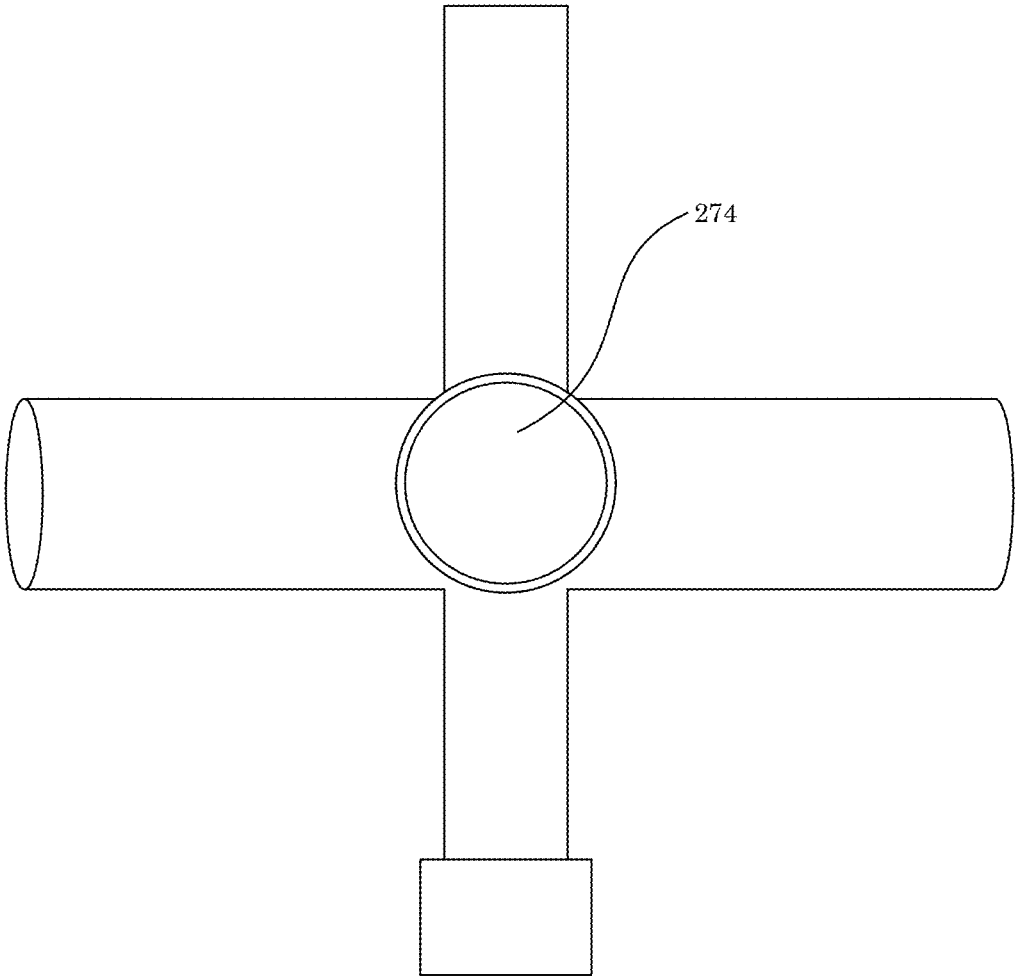


Figure. 6

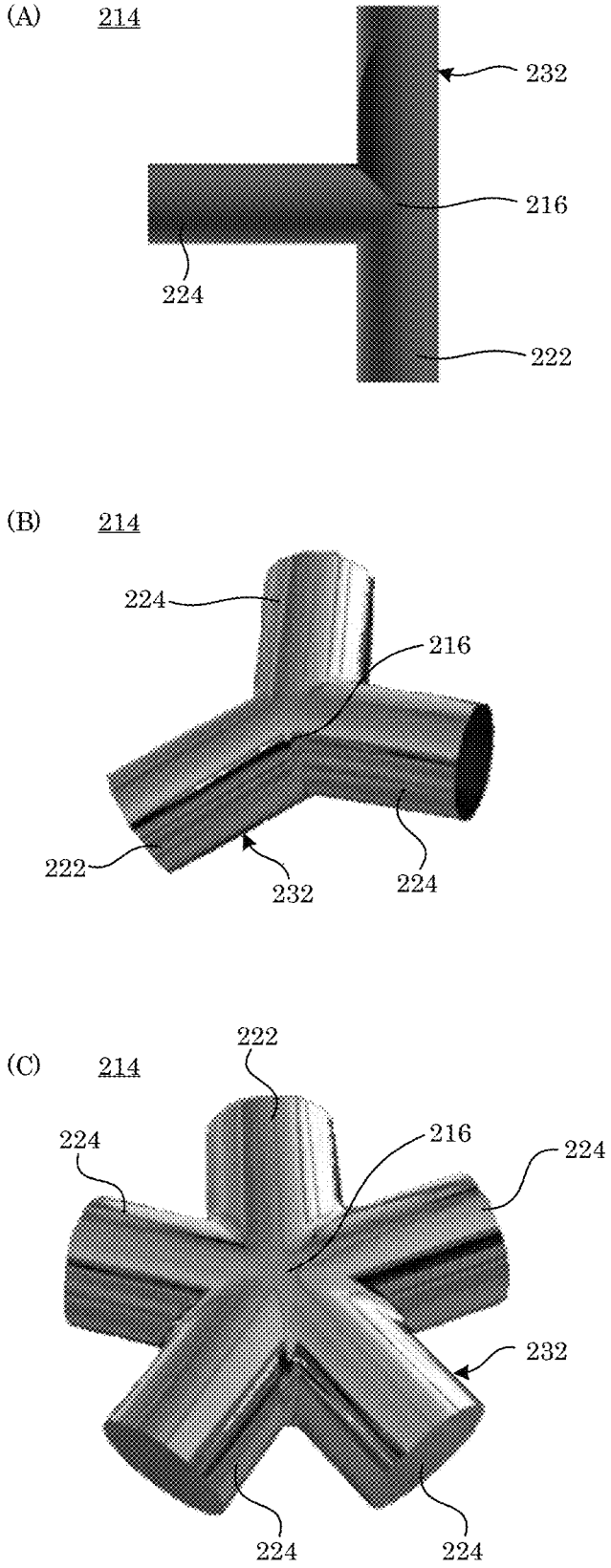

(A) 214
232
216
224
222
(B) 214
224
216
222
232
224
(C) 214
222
224
216
224
232
224
224

Figure. 7

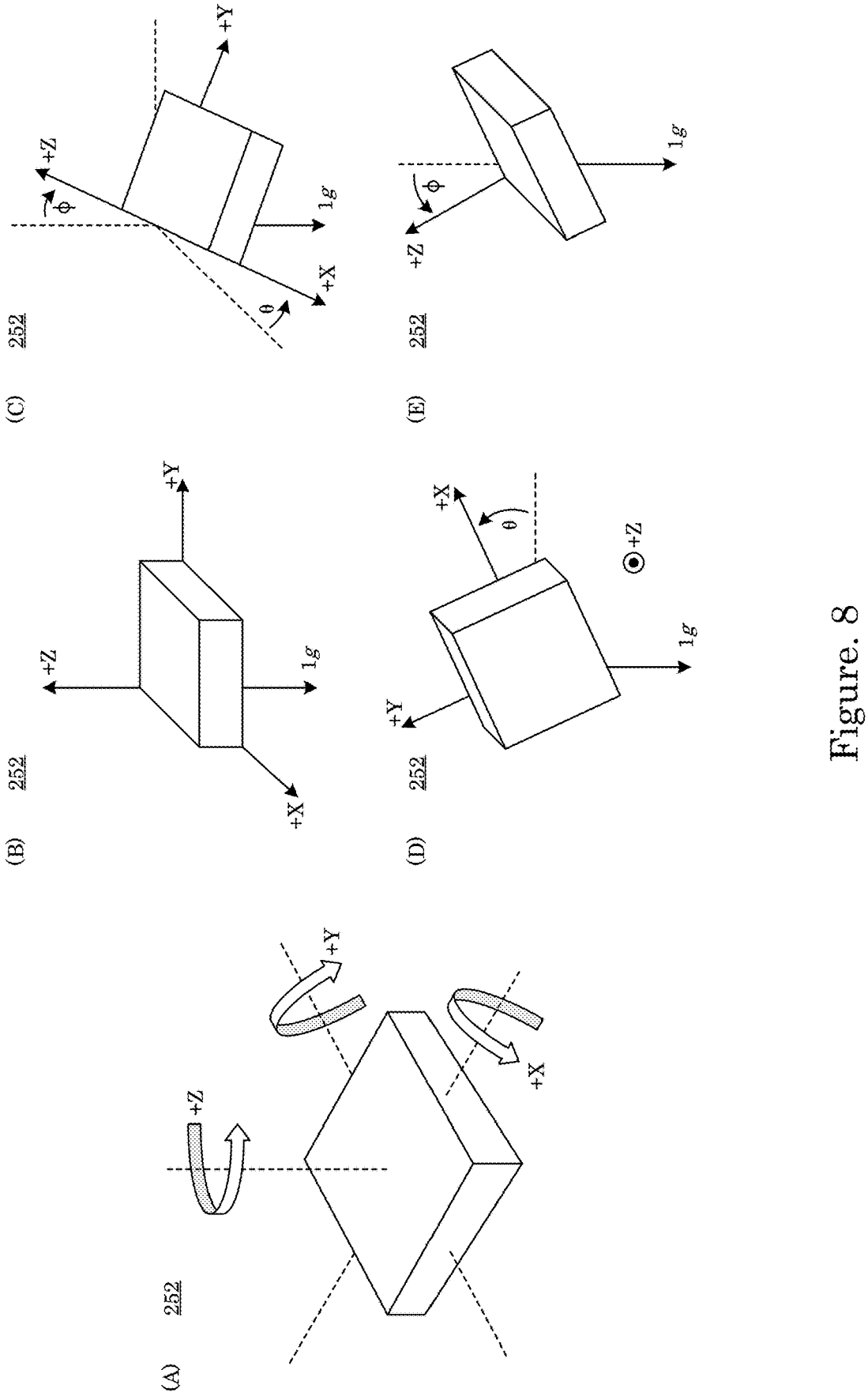


Figure. 8

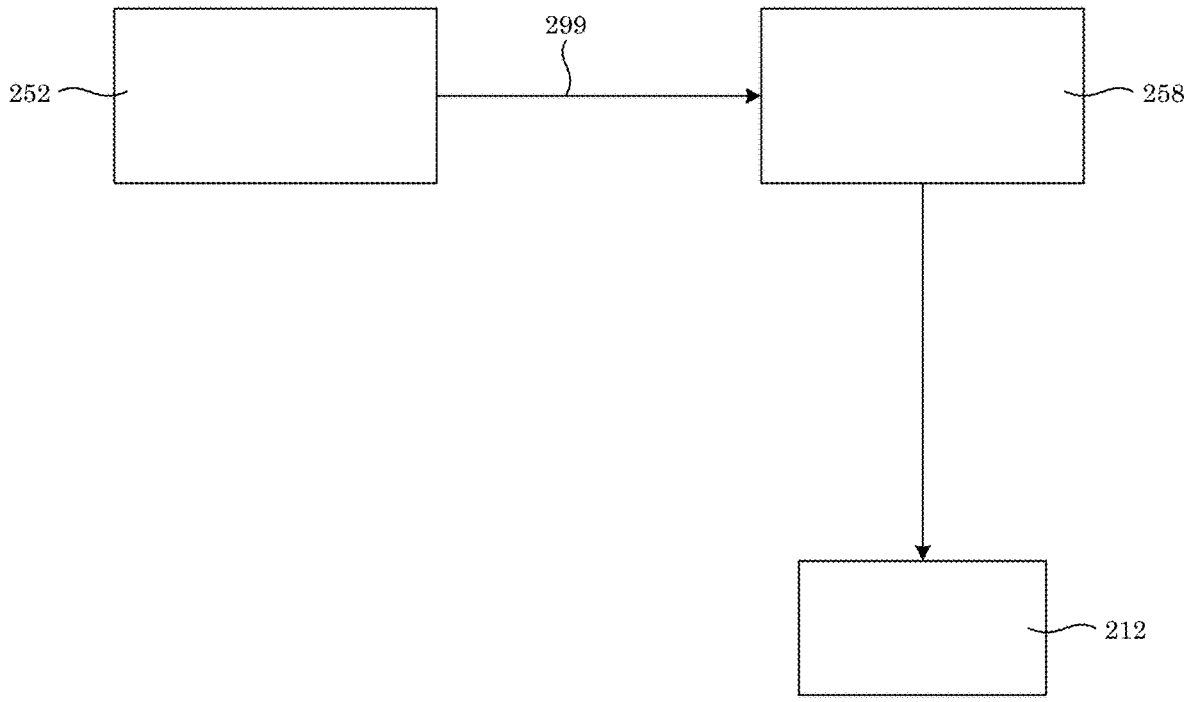


Figure. 9

298

242

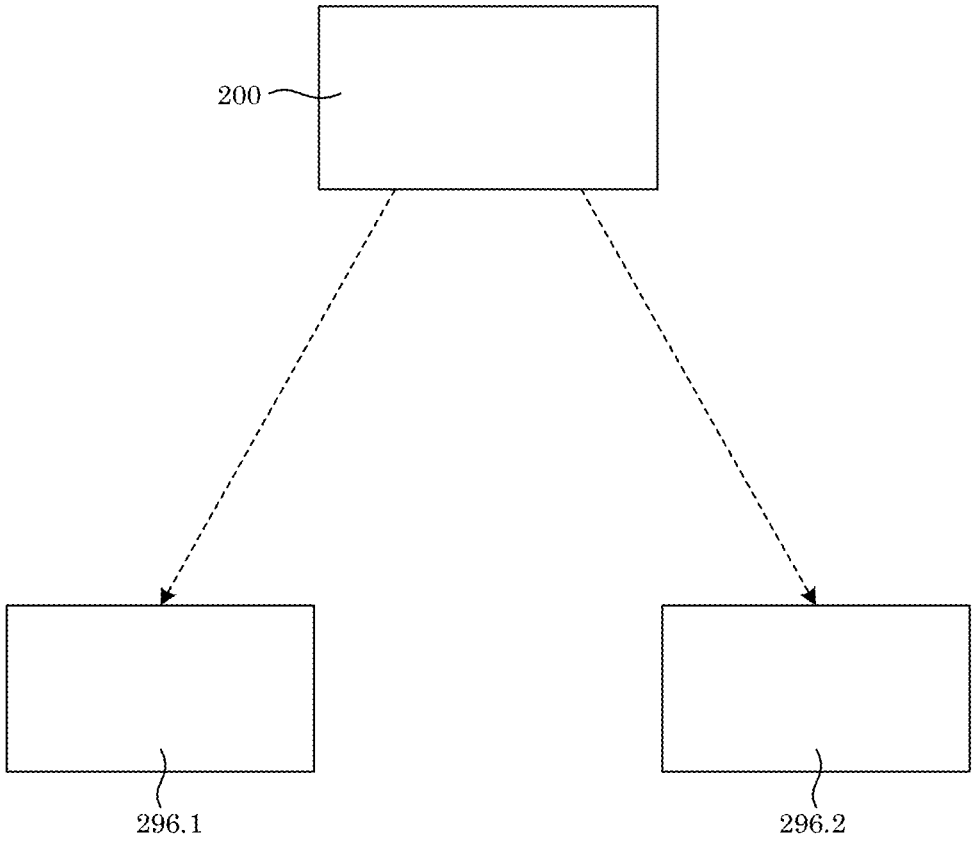


Figure. 10

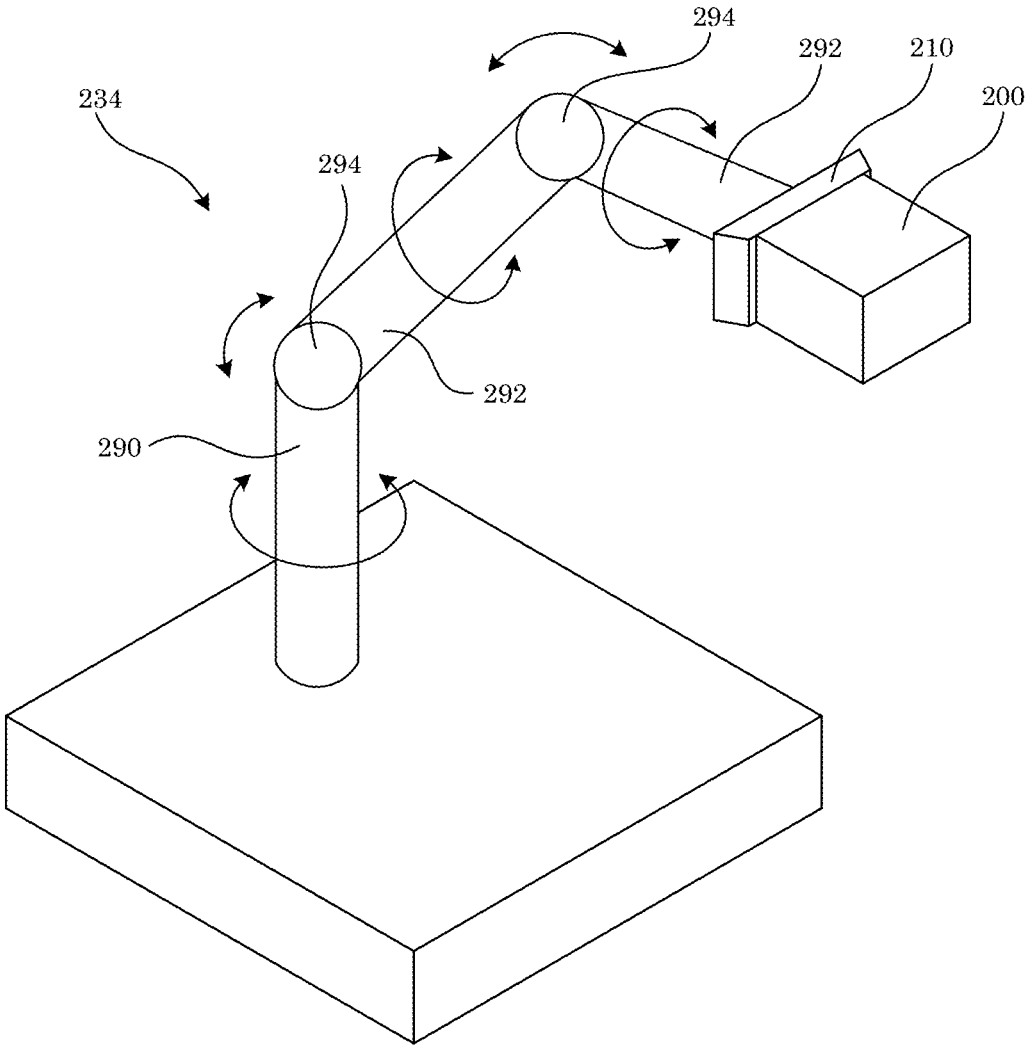


Figure. 11

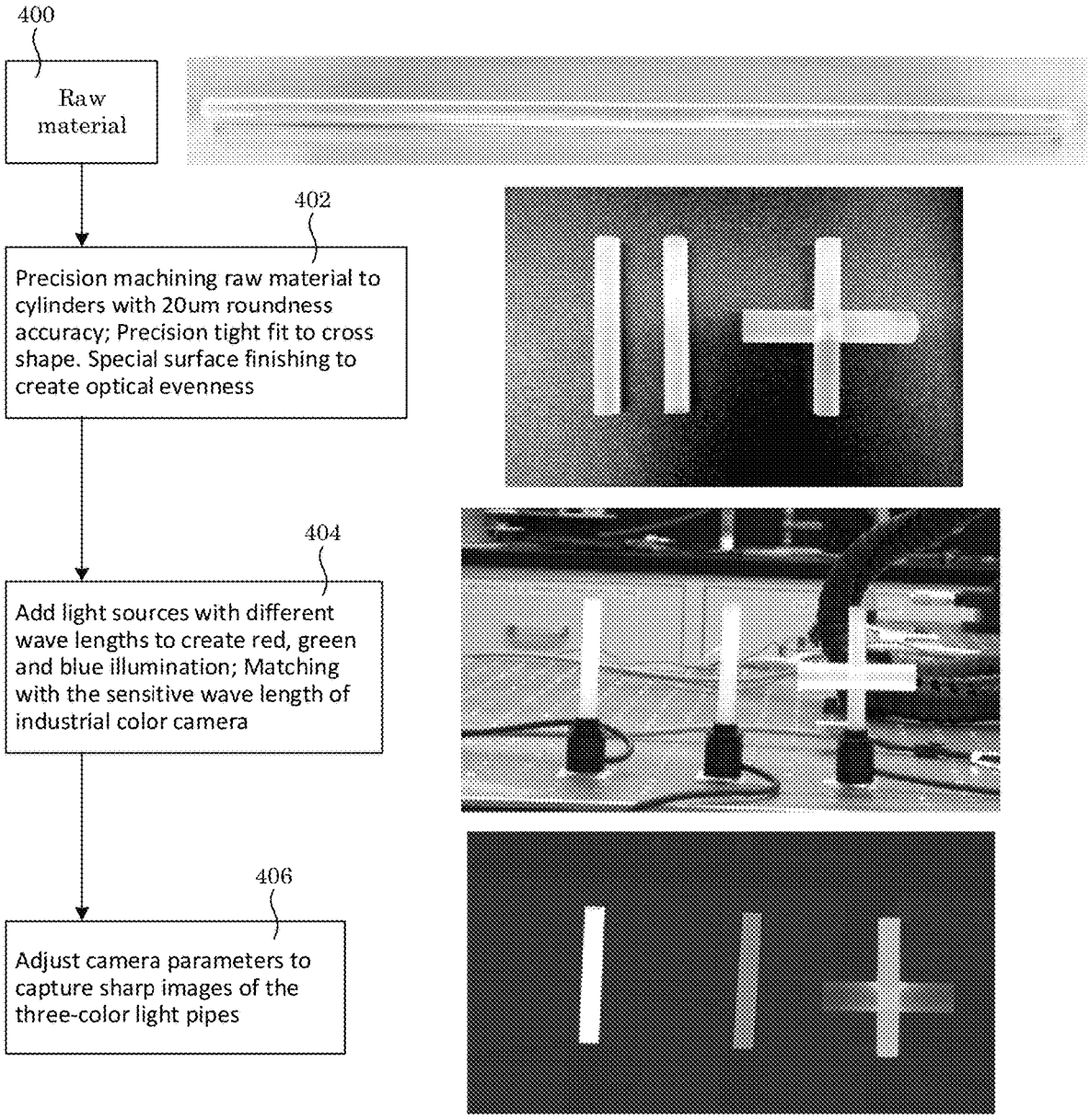

400
Raw material
402
Precision machining raw material to cylinders with 20um roundness accuracy; Precision tight fit to cross shape. Special surface finishing to create optical evenness
404
Add light sources with different wave lengths to create red, green and blue illumination; Matching with the sensitive wave length of industrial color camera
406
Adjust camera parameters to capture sharp images of the three-color light pipes

Figure. 12

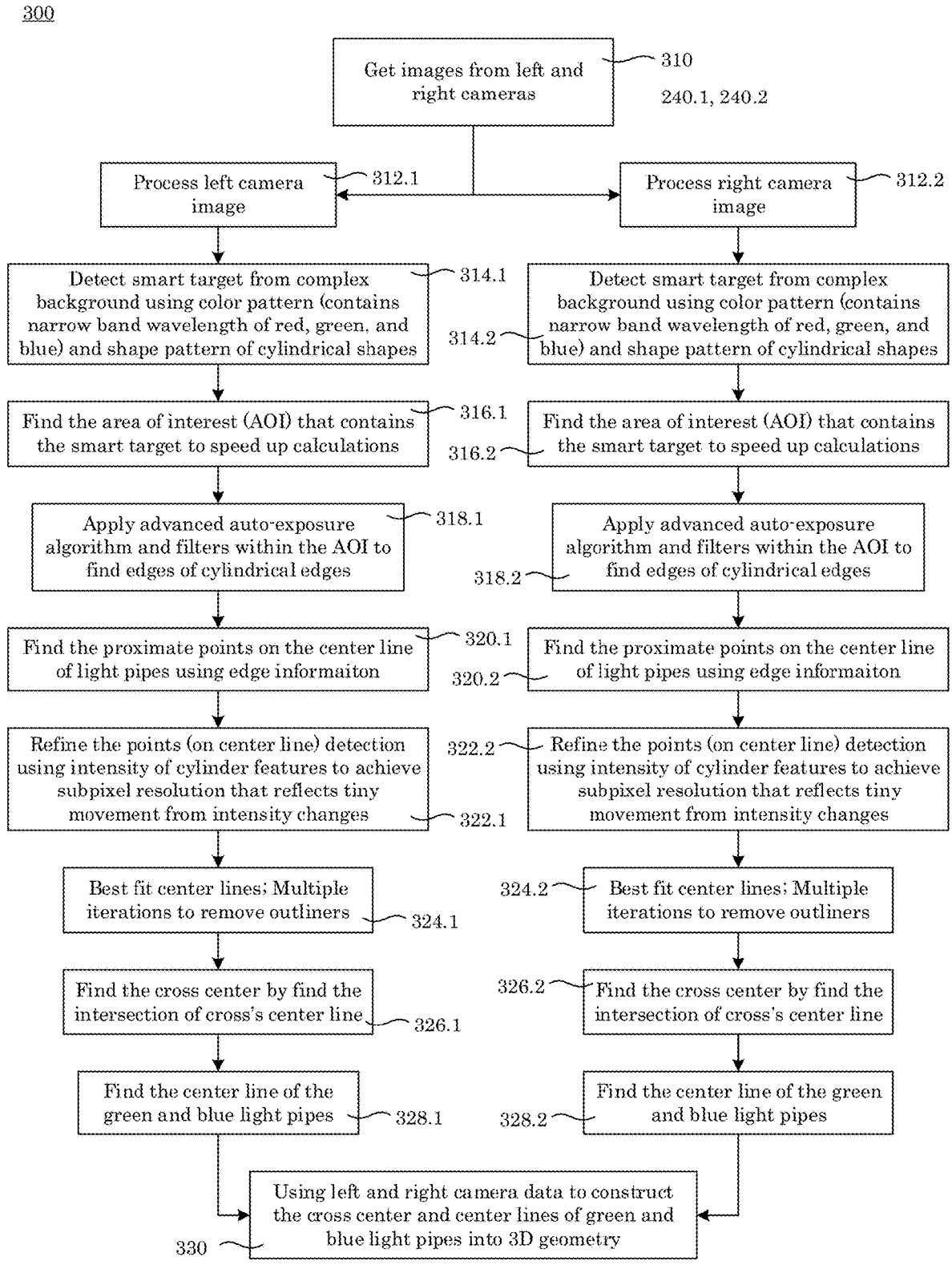

300
Get images from left and right cameras
310
240.1, 240.2
Process left camera image
312.1
Process right camera image
312.2
Detect smart target from complex background using color pattern (contains narrow band wavelength of red, green, and blue) and shape pattern of cylindrical shapes
314.1
Detect smart target from complex background using color pattern (contains narrow band wavelength of red, green, and blue) and shape pattern of cylindrical shapes
314.2
Find the area of interest (AOI) that contains the smart target to speed up calculations
316.1
Find the area of interest (AOI) that contains the smart target to speed up calculations
316.2
Apply advanced auto-exposure algorithm and filters within the AOI to find edges of cylindrical edges
318.1
Apply advanced auto-exposure algorithm and filters within the AOI to find edges of cylindrical edges
318.2
Find the proximate points on the center line of light pipes using edge informaiton
320.1
Find the proximate points on the center line of light pipes using edge informaiton
320.2
Refine the points (on center line) detection using intensity of cylinder features to achieve subpixel resolution that reflects tiny movement from intensity changes
322.1
Refine the points (on center line) detection using intensity of cylinder features to achieve subpixel resolution that reflects tiny movement from intensity changes
322.2
Best fit center lines; Multiple iterations to remove outliners
324.1
Best fit center lines; Multiple iterations to remove outliners
324.2
Find the cross center by find the intersection of cross's center line
326.1
Find the cross center by find the intersection of cross's center line
326.2
Find the center line of the green and blue light pipes
328.1
Find the center line of the green and blue light pipes
328.2
Using left and right camera data to construct the cross center and center lines of green and blue light pipes into 3D geometry
330

Figure. 13

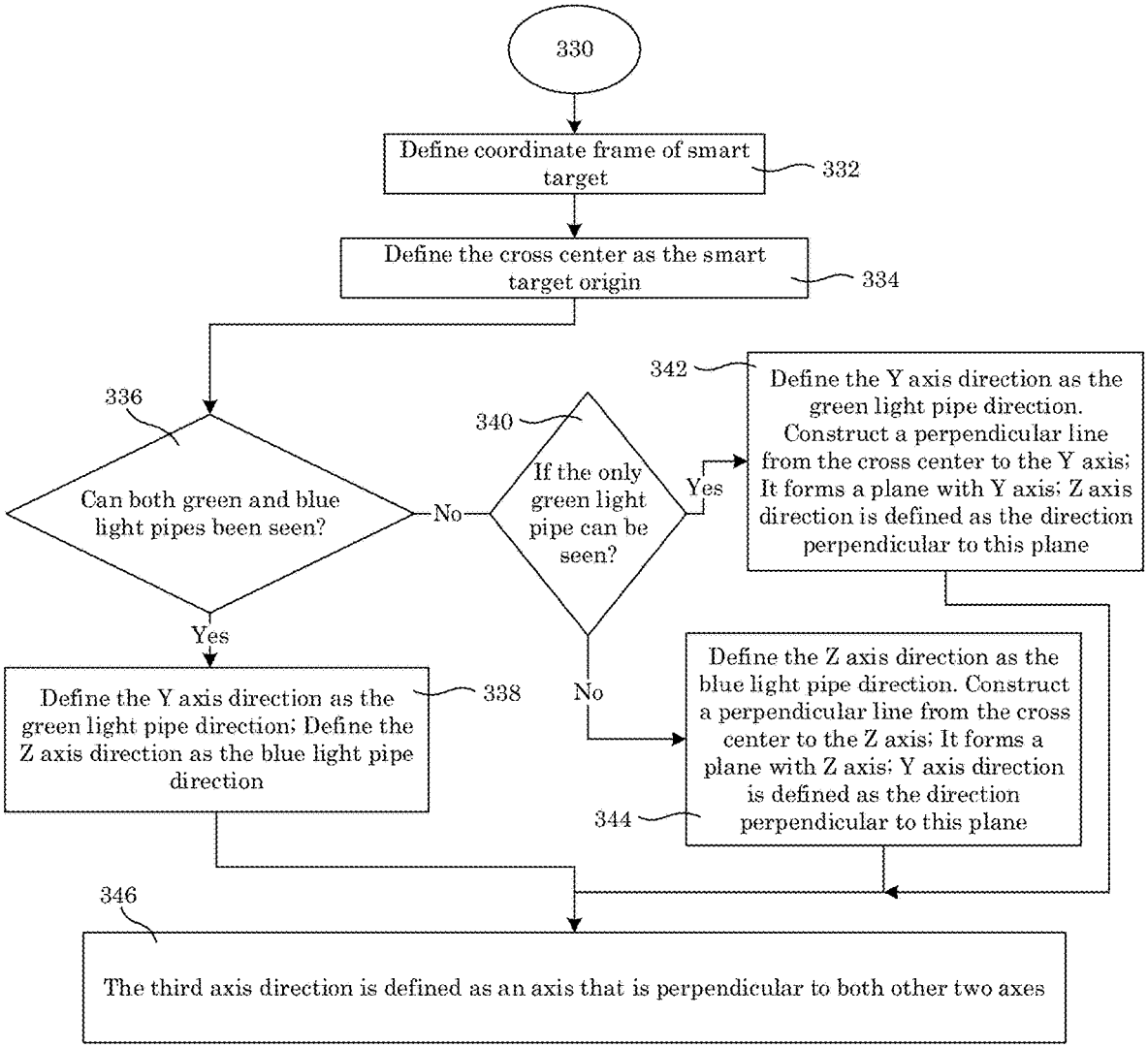

330
Define coordinate frame of smart target
332
Define the cross center as the smart target origin
334
336
Can both green and blue light pipes been seen?
No
340
If the only green light pipe can be seen?
Yes
342
Define the Y axis direction as the green light pipe direction. Construct a perpendicular line from the cross center to the Y axis; It forms a plane with Y axis; Z axis direction is defined as the direction perpendicular to this plane
Yes
Define the Y axis direction as the green light pipe direction; Define the Z axis direction as the blue light pipe direction
338
No
Define the Z axis direction as the blue light pipe direction. Construct a perpendicular line from the cross center to the Z axis; It forms a plane with Z axis; Y axis direction is defined as the direction perpendicular to this plane
344
346
The third axis direction is defined as an axis that is perpendicular to both other two axes

Figure. 14

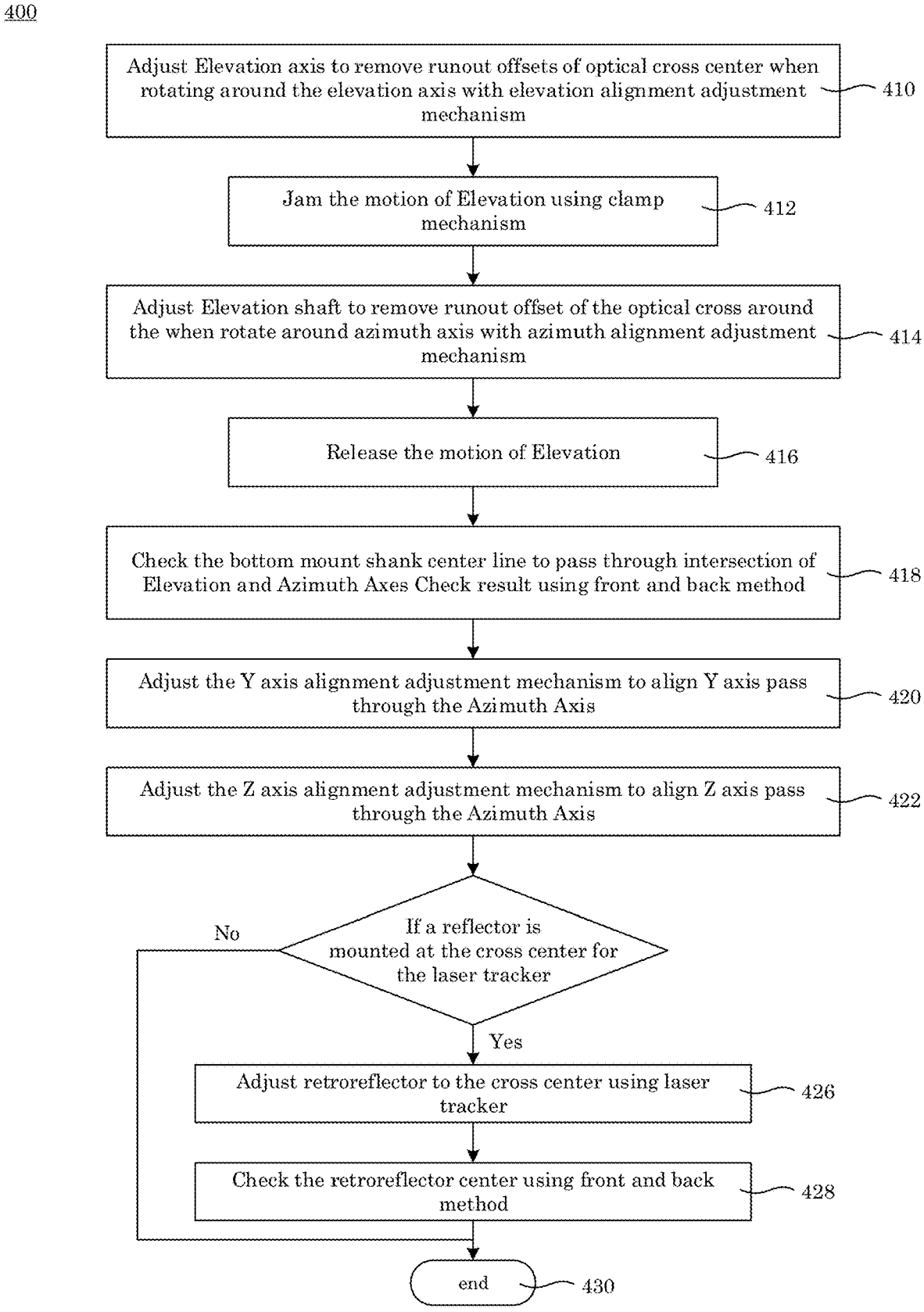

400
Adjust Elevation axis to remove runout offsets of optical cross center when rotating around the elevation axis with elevation alignment adjustment mechanism
410
Jam the motion of Elevation using clamp mechanism
412
Adjust Elevation shaft to remove runout offset of the optical cross around the when rotate around azimuth axis with azimuth alignment adjustment mechanism
414
Release the motion of Elevation
416
Check the bottom mount shank center line to pass through intersection of Elevation and Azimuth Axes Check result using front and back method
418
Adjust the Y axis alignment adjustment mechanism to align Y axis pass through the Azimuth Axis
420
Adjust the Z axis alignment adjustment mechanism to align Z axis pass through the Azimuth Axis
422
If a reflector is mounted at the cross center for the laser tracker
No
Yes
Adjust retroreflector to the cross center using laser tracker
426
Check the retroreflector center using front and back method
428
end
430

Figure. 15

SIX-DIMENSIONAL SMART TARGET

CROSS REFERENCE TO RELATED APPLICATIONS

The application claims priority to U.S. Provisional Patent Application Ser. No. 62/672,270 filed May 16, 2018, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

This invention was made with United States Government support from the National Institute of Standards and Technology (NIST), an agency of the United States Department of Commerce. The Government has certain rights in the invention. Licensing inquiries may be directed to the Technology Partnerships Office, NIST, Gaithersburg, Md., 20899; voice (301) 301-975-2573; email tpo@nist.gov.

BRIEF DESCRIPTION

Disclosed is a six-dimensional smart target for dynamically determining pose of an object, the six-dimensional smart target comprising: a gimbal comprising: an azimuthal base that provides an azimuthal axis; an elevation arm disposed on and in rotary communication with the azimuthal base and that: extends from the azimuthal base, rotates about the azimuthal axis, and provides an elevation axis; and a rotary center provided by an intersection of the azimuthal axis and the elevation axis; an elevation member disposed on the elevation arm of the gimbal at the rotary center of the gimbal and in rotary communication with the elevation arm, the elevation member comprising: a first light pipe comprising an elongated body disposed axially along the elevation axis with a first end connected to the elevation arm and that: receives first light and uniformly distributes the first light along the first light pipe to illuminate peripheral edges of the first light pipe; and a second light pipe disposed on the first light pipe and arranged with the second light pipe intersecting the first light pipe at the rotary center such that the second light pipe receives the first light from the first light pipe and uniformly distributes the first light along the second light pipe to illuminate peripheral edges of the second light pipe, the second light pipe comprising an elongated body disposed axially at an oblique angle to the first light pipe and the elevation axis; an azimuthal member comprising: the azimuthal base; a y-axis light pipe disposed on the azimuthal base and comprising an elongated body disposed axially along a y-direction that is perpendicular to the azimuthal axis with a second end connected to the azimuthal base and that: receives a second light and uniformly distributes the second light along the y-axis light pipe to illuminate peripheral edges of the y-axis light pipe; and a z-axis light pipe disposed on the azimuthal base and comprising an elongated body disposed axially along a z-direction that is perpendicular to the azimuthal axis and the y-direction, with a third end connected to the azimuthal base such that the z-axis light pipe: receives a third light and uniformly distributes the third light along the z-axis light pipe to illuminate peripheral edges of the z-axis light pipe, wherein the elevation member rotates at the rotary center about the elevation axis and the azimuthal axis to consistently maintain the first light pipe and the second light pipe in a field of view of a measurement instrument that views the six-dimensional smart target.

Disclosed is a process for determining a pose of an object with the six-dimensional smart target, the process comprising: disposing the six-dimensional smart target on object so that six-dimensional smart target moves synchronously with object; receiving a first image of the six-dimensional smart target from a first camera; detecting the six-dimensional smart target from a background environment in which the is disposed; determining an area of interest of the six-dimensional smart target; determining peripheral edges of the first light pipe; determining peripheral edges of the second light pipe; determining peripheral edges of the y-axis light pipe; determining peripheral edges of the z-axis light pipe; determining, from the peripheral edges of the first light pipe, a first center line.1 of first light pipe; determining, from the peripheral edges of the second light pipe, a second center line.2 of second light pipe; determining, from the peripheral edges of the y-axis light pipe, a third center line.3 of y-axis light pipe; determining, from the peripheral edges of the z-axis light pipe, a fourth center line.4 of z-axis light pipe; determining an elevation intersection of the first center line.1 and the second center line.2; determining, from the elevation intersection, the rotary center; determining, from the rotary center, the third center line.3, and the fourth center line.4, a three-dimensional coordinate frame for the six-dimensional smart target to determine the pose of the object, the three-dimensional coordinate frame comprising: an origin that is disposed at the rotary center; a principal y-axis parallel to the y-direction and arranged to intersect the origin; a principal z-axis parallel to the z-direction and arranged to intersect the origin; and a principal x-axis parallel to the azimuthal axis and arranged to intersect the origin.

BRIEF DESCRIPTION OF THE DRAWINGS

The following description should not be considered limiting in any way. With reference to the accompanying drawings, like elements are numbered alike.

FIG. **1** shows a perspective view of a six-dimensional smart target;

FIG. **2** shows a cut-away view of the six-dimensional smart target shown in FIG. **1**;

FIG. **3** shows an exploded view of the six-dimensional smart target shown in FIG. **1**;

FIG. **4** shows an plan view of the six-dimensional smart target shown in FIG. **1**;

FIG. **5** shows a side view of the six-dimensional smart target shown in FIG. **1**;

FIG. **6** shows a reflector disposed on an elevation member for a six-dimensional smart target;

FIG. **7** shows, in panel A, an elevation member with a first light pipe and second light pipe; shows elevation members, in panel B and panel C, with a first light pipe and a plurality of second light pipes;

FIG. **8** shows, in panel A, an orientation sensor; shows, in panel B, the sensor has no angle output; shows, in panel C, sensor has angle ouput about x-axis and z-axis; shows, in panel D, sensor has angle output about z-axis; and shows, in panel E, sensor has angle output about x-axis;

FIG. **9** shows communication between an orientation sensor, elevation motor, and gimbal;

FIG. **10** shows a vision system that includes a six-dimensional smart target;

FIG. **11** shows a six-dimensional smart target disposed on a robot **234**;

FIG. **12** shows a process for making a six-dimensional smart target;

FIG. **13** shows a process for dynamically determining a pose of an object;

FIG. **14** shows a process for dynamically determining a pose of an object; and

FIG. **15** shows a process for adjusting elements of a six-dimensional smart target.

DETAILED DESCRIPTION

A detailed description of one or more embodiments is presented herein by way of exemplification and not limitation.

It has been discovered that a six-dimensional smart target herein provides six-dimensional (6-D) information of a moving object (x, y, z, pitch, yaw, and roll) with high accuracy and can be used, e.g., in a vision agnostic system to acquire the six-dimensional (6-D) information of the moving object (x, y, z, pitch, yaw, and roll) with high accuracy. The six-dimensional smart target is motorized to maintain an elevation member of the six-dimensional smart target in a field of view a measurement instrument that views the six-dimensional smart target, wherein the six-dimensional smart target rotates toward the measurement instrument for a non-blocking dynamic measurement. Advantageously, the six-dimensional smart target in a vision agnostic system provides precise 6-D information of an object with precision localization, including registering multiple objects, adaptively locating objects for unplanned adaptive control, precisely tracking a pose of an object used by robot operations, and applications in machine and robot visions. Measured 6-D information also can be used as feedback control for motion, relative position or orientation monitoring of objects, data registration for in-process inspection, and the like.

Six-dimensional smart target **200** dynamically determines a pose of object **210**. In an embodiment, with reference to FIG. **1**, FIG. **2**, FIG. **3**, FIG. **4**, and FIG. **5**, six-dimensional smart target **200** includes gimbal **212**. Gimbal **212** includes azimuthal base **226** that provides azimuthal axis **220**. Elevation arm **228** is disposed on and is in rotary communication with azimuthal base **226**, wherein elevation arm **228** extends from azimuthal base **226**, rotates about azimuthal axis **220**, and provides an elevation axis **230**. Rotary center **216** is provided by an intersection of azimuthal axis **220** and elevation axis **230**, Elevation member **214** is disposed on elevation arm **228** of gimbal **212** at rotary center **216** of gimbal **212**. Elevation member **214** is in rotary communication with elevation arm **228** and includes first light pipe **222**. First light pipe **222** has an elongated body disposed axially along elevation axis **230** with first end **236** connected to elevation arm **228**, wherein first light pipe **222** receives a first light and uniformly distributes the first light along first light pipe **222** to illuminate peripheral edges **232.1** of first light pipe **222**. Second light pipe **224** is disposed on first light pipe **222** and arranged with second light pipe **224** intersecting first light pipe **222** at rotary center **216** such that second light pipe **224** receives the first light from first light pipe **222** and uniformly distributes the first light along second light pipe **224** to illuminate peripheral edges **232.2** of second light pipe **224**. Second light pipe **224** includes an elongated body disposed axially at an oblique angle to first light pipe **222** and elevation axis **230**. Six-dimensional smart target **200** also includes azimuthal member **242** that includes azimuthal base **226**; y-axis light pipe **238** disposed on azimuthal base **226**. Y-axis light pipe **238** includes an elongated body disposed axially along y-direction **246** that is perpendicular to azimuthal axis **220** with second end **244** connected to azimuthal base **226**, wherein y-axis light pipe **238** receives a second light and uniformly distributes the second light along y-axis light pipe **238** to illuminate peripheral edges **232.3** of y-axis light pipe **238**. Z-axis light pipe **240** is disposed on azimuthal base **226** and includes an elongated body disposed axially along z-direction **248** that is perpendicular to azimuthal axis **220** and y-direction **246**, with third end **250** connected to azimuthal base **226**. Z-axis light pipe **240** receives a third light and uniformly distributes the third light along z-axis light pipe **240** to illuminate peripheral edges **232** of z-axis light pipe **240**. In this manner, elevation member **214** rotates at rotary center **216** about elevation axis **218** and azimuthal axis **220** to consistently maintain first light pipe **222** and second light pipe **224** in a field of view of a measurement instrument that views six-dimensional smart target **200**.

Six-dimensional smart target **200** can include orientation sensor **252** interposed between elevation member **214** and elevation arm **228**, and elevation adjuster **254** interposed between elevation member **214** and elevation arm **228**. For rotary manipulation of elevation member **214**, six-dimensional smart target **200** includes bearing **256** interposed between elevation member **214** and elevation arm **228**; and elevation motor **258** interposed between elevation member **214** and elevation arm **228**. Y-direction adjuster **260** can be interposed between azimuthal base **226** and y-axis light pipe **238**, and z-direction adjuster **262** can be interposed between azimuthal base **226** and z-axis light pipe **240**. Moreover, azimuthal adjuster **264** can be interposed between azimuthal base **226** and elevation arm **228** with bearing **266** interposed between azimuthal base **226** and elevation arm **228**. Azimuthal flange **268** is disposed on azimuthal base **226** to connect azimuthal base **226** to object **210**, e.g., robot **234** as shown in FIG. **11**. Controller **270** can be disposed on azimuthal base **226** with azimuthal motor **272** disposed on azimuthal base **226**.

In an embodiment, with reference to FIG. **6**, six-dimensional smart target **200** includes reflector **274** disposed on elevation member **214** proximate to and centered on rotary center **216**.

Six-dimensional smart target **200** dynamically determines a pose of object **210**. Object **210** can include objects used within robot or machine operations to locate parts during mobile operations and can reach to certain positions with designed orientations. Moreover, the accuracy of the object's pose is to be controlled to prevent operation failures. In an embodiment, with reference to FIG. **11**, object **210** is an end effector of robot **234**. Exemplary robots **234** include base, arm articulations, kinematic links, and the like. Robot **234** can include armpiece **290** disposed on a base and in communication with articulated arm **292** via arm articulation **294**. At a terminal articulated arm **292**, object **210** can be disposed and receive six-dimensional smart target **200**. It should be appreciated that the pose of object **210** can be determined by six dimensions that include x, y, z, pitch, yaw, and roll. Accordingly, six-dimensional smart target **200** provides determination of the six dimensions by principal y-axis **282**, principal z-axis **284**, principal x-axis **286**, and orientation sensor **252**.

In six-dimensional smart target **200**, gimbal **212** includes elevation arm **228** in rotary communication with azimuthal base **226**. Elevation arm **228** can include elevation motor, and bearing to support the elevation member rotate about elevation axis. Moreover, elevation arm can rotate about azimuthal axis. A size of elevation arm **228** can be any selected size, e.g., from 30 mm to 500 mm or even larger, specifically from 60 mm to 200 mm, and more specifically

from 100 mm to 150 mm. Elevation arm **228** can rotate about azimuthal axis **220** in an angular range from 0 radians to **27***c* radians. In an embodiment, elevation arm **228** is supported by bearing **266** so elevation arm **228** rotates about azimuthal axis **220** and through 360°. Azimuthal adjuster **264** connects to an inner shaft of bearing **266**. A runout offset of rotary center **216** of elevation member **214** about azimuthal axis **220** is removed by azimuthal adjuster **264**. Azimuthal motor **272** is in rotary communication with elevation arm **228** and is fixed with respect to a bottom housing and drives elevation arm **228** and elevation member **214** to rotate about azimuthal axis **220**.

Slip rings disposed on elevation adjuster **254** and azimuthal adjuster **264** dynamically provide electrical connection and unlimited 360° rotation in elevation and azimuth.

Six-dimensional smart target **200** includes a plurality of light pipes (**222**, **224**, **238**, **240**). Light pipes (**222**, **224**, **238**, **240**) independently can include, e.g., peripheral edges **232**, uniformly lighted surface, and three LED colors to enable center line detection to construct a coordinate frame that represents six-dimensional information. Light pipes (**222**, **224**, **238**, **240**) independently can have a shape such as a cylinder, cone, blunted cone, symmetrical 3D shape created by rotating about a center line, and the like. A length of light pipes (**222**, **224**, **238**, **240**) independently can be from 20 mm to 300 mm or even larger, specifically from 50 mm to 150 mm, and more specifically from 60 mm to 120 mm. A cross-sectional diameter of pipes (**222**, **224**, **238**, **240**) independently can be from 4 mm to 50 mm or even larger (but not limited to 50 mm), specifically from 5 mm to 30 mm, and more specifically from 8 mm to 15 mm.

First light pipe **222** and second light pipe **224** in combination provide elevation member **214**. Elevation member **214** can include peripheral edges **232**, uniformly lighted surface, and three LED colors to enable center line detection. Moreover, intersection of the center lines can create a point to represent the origin of a coordinate frame. Elevation member **214** can include an arbitrary number of light pipes that intersect in an arbitrary angle, e.g., as shown in FIG. **7**.

In an embodiment, with reference to FIG. **6**, reflector **274** is disposed on elevation member **214**. Reflector **274** can include a retroreflector, spherically mounted retroreflector, or corner cube to enable the use by laser trackers directly measuring the center (x, y, z). In an embodiment, reflector **274** is a retro-reflector that is disposed proximate to rotary center **216** of elevation member **214** an in communication with, e.g., a laser-vision based measurement instrument. A laser in the laser-vision based measurement instrument can measure 3-D positions of reflector **274**. The vision part of the laser-vision based measurement instrument can obtain orientation information for 6-D measurement. Alignment of the laser-vision based measurement instrument provides disposal of reflector **274** at rotary center **216** of elevation member **214**.

First light pipe **222** receives first light that illuminates first light pipe **222** and second light pipe **224**. Accordingly, peripheral edges **232** of first light pipe **222** and second light pipe **224** are distinguished from a background environment in which six-dimensional smart target **200** is disposed by a contrast in a selected color or intensity of emission. In that respect, first light can have a selected wavelength, e.g., from 600 nm to 650 nm, specifically from 642 nm to 648 nm, and more specifically from 644 nm to 646 nm, although not limited recited wavelength or intensity. The wavelength or intensity can distinguish a background environment. It is contemplated that the first light can be continuous or modulated at a selected frequency, e.g., for phase sensitive detection of the first light and enhancement of visual recognition of peripheral edges **232** of elevation member **214** over the background environment.

Y-axis light pipe **238** and z-axis light pipe **240** are disposed on azimuthal base **226** to provide respectively y-direction **246** and z-axis light pipe **240**. Y-axis light pipe **238** receives the second light, and z-axis light pipe **240** receives the third light. The second light and third light respectively illuminate y-axis light pipe **238** and z-axis light pipe **240**. Accordingly, peripheral edges **232** of first light pipe **222** and second light pipe **224** are distinguished from each, peripheral edges **232** of elevation member **214**, and the background environment in which six-dimensional smart target **200** is disposed by a contrast in selected colors or intensity of emission of the second light and the third light. In that respect, the second light and third light independently can have a selected wavelength, e.g., the second light has from 500 nm to 550 nm, specifically from 517 nm to 523 nm, and more specifically from 519 nm to 521 nm; the third light has from 440 nm to 470 nm, specifically from 462 nm to 468 nm, and more specifically from 464 nm to 466 nm without limitation to recited wavelength or intensity because they are used to distinguish from a background environment. It is contemplated that the second light and third light independently can be continuous or modulated at a selected frequency, e.g., for phase sensitive detection of the first light and enhancement of visual recognition of peripheral edges **232** of y-axis light pipe **238** and z-axis light pipe **240** over the background environment.

It is contemplated that the first light, second light, and third light independently can be produced by a red, green, blue, and the like. In an embodiment, the first light is red; the second light is green, and the third light is blue. Three different colors of LEDs can be used. A wavelength of the first light, second light, and third light interpedently can be selected to match a narrow band filter of cameras of the measurement instrument to reduce ambient light effects. The bottom panel of FIG. **12** shows an image of elevation member **214**, y-axis light pipe **238**, and z-axis light pipe **240** with even lighting and sharply resolved peripheral edges **232**. Quality and accuracy of elevation member **214**, y-axis light pipe **238**, and z-axis light pipe **240** provide accurate line features and image definition of six-dimensional smart target **200**.

Additionally, to provide redundancy of direction measurement from different views of six-dimensional smart target **200**, a plurality of y-axis light pipes **238** or z-axis light pipes **240** can be disposed in parallel on azimuthal base **226**.

Azimuthal base **226** can include bearing, azimuthal motor, azimuthal flange and controller to support the elevation arm rotating about azimuthal axis.

Orientation sensor **252** is interposed between elevation member **214** and elevation arm **228** to determine an orientation of elevation member **214** relative to azimuthal base **226**. The orientation of elevation member **214** provided by orientation sensor **252** includes pitch (rotation about principal x-axis **286**), yaw (rotation about principal y-axis **282**), and roll (rotation about principal z-axis **284**) directions in three-dimensional coordinate frame **278** as shown in FIG. **2**. Orientation sensor **252** can include sensor board and cables to detect the pose changes and can be, e.g., a level sensor, tilt sensor, gyro, inclinometer, accelerometer, and the like. With reference to FIG. **8**, orientation sensor **252** can output angles to reflect pose changes in pitch, yaw, and roll. An initial pose of elevation member **214** is taught facing a measurement instrument such as vision system **298**. To maintain elevation member **214** constantly facing to the measurement instru-

ment, elevation member **214** maintains the initial pose or a taught pose. Electronic signals produced by orientation sensor **252** control motors (e.g., **258**) to maintain the pose of elevation member **214**.

Elevation adjuster **254** can be interposed between elevation member **214** and elevation arm **228** to perform adjustment and remove runout offsets of the rotary center about the elevation axis.

Bearing **256** can be interposed between elevation member **214** and elevation arm **228** to support the elevation member rotating about the elevation axis.

Elevation motor **258** can be interposed between elevation member **214** and elevation arm **228** to rotate the elevation member rotating about the elevation axis. Moreover, elevation motor can contain encoder to improve drive precision. In an embodiment, with reference to FIG. **9**, orientation sensor **252** is in communication with elevation motor **258** and send orientation signal **299** to elevation motor **258**, also, orientation sensor **252** is in communication with azimuthal motor and communicates an orientation signal to azimuthal motor, to drive the elevation member maintaining the initial pose. In this manner, elevation member **214** can be rotated to maintain elevation member **214** constant orientation and in a field of view, e.g., a vision system **298** as shown in FIG. **10**. Vision system **298** can include a plurality of cameras **296** that image six-dimensional smart target **200**. Vision system **298** can be a motion tracker **288**.

Y-direction adjuster **260**, z-direction adjuster **262**, and azimuthal adjuster **264** can be interposed respectively between light pipes (**238**, **240**) and elevation arm **228** and azimuthal base **226** to perform adjustment and remove offsets from design during assembly. Y-direction adjuster **260** aligns y-axis light pipe **238** so that y-direction **246** intersects azimuthal axis **220**. Z-direction adjuster **262** aligns z-axis light pipe **240** so that z-direction **248** intersects azimuthal axis **220** and so that z-axis light pipe **240** is perpendicular to y-axis light pipe **238**. After alignment, y-direction adjuster **260** and z-direction adjuster **262** are locked by tightening fasteners to prevent change in y-direction adjuster **260** and z-direction adjuster **262**.

Bearing **266** can be interposed between azimuthal base **226** and elevation arm **228** to support the elevation arm rotating about the azimuthal axis.

Azimuthal motor **272** can be disposed on azimuthal base **226** to rotate the elevation arm rotating about the azimuthal axis. Moreover, azimuthal motor can contain encoder to improve drive precision.

Azimuthal flange **268** can be disposed on azimuthal base **226** to connect with different adaptors designed for different end effector tools. In this manner, azimuthal flange **268** provides rigid attachment to object **210** for synchronous communication of motion of object **210** to azimuthal base **226**.

Controller **270** can be disposed on azimuthal base **226** to provide electronic control of the rotation sensor, motors, and power. In an embodiment, controller **270** includes electrical circuity to communicate with orientation sensor **252**, elevation motor **258**, and azimuthal motor **272**. Orientation sensor **252** detects a change in pose of elevation member **214**. Electrical signals are generated to drive elevation motor **258** and azimuthal motor **272** that can rotate clockwise or counter-clockwise respective about elevation axis **230** and azimuthal axis **220**. Controller **270** controls activation of both elevation motor **258** and azimuthal motor **272** to maintain elevation member **214** facing to the measurement instrument at all times during operation. Controller **270** also can include a power source, e.g., a portable power source such as a battery, to provide power to orientation sensor **252**, elevation member **214**, light pipes (**238**, **240**), elevation motor **258**, and azimuthal motor **272**. The battery can be rechargeable. Such power source can be self-contained within six-dimensional smart target **200** to avoid interference with the mobility of the target.

Six-dimensional smart target **200** can be made in various ways. In an embodiment, with reference to FIG. **12**, a process for making six-dimensional smart target **200** includes machining an optical material (e.g., glass, a polymer such as poly(methyl methacrylate) (PMMA) and the like, and the like) to provide cylindrical light pipes (**222**, **224**, **238**, **240**); making an aperture in second light pipe **224** to receive first light pipe **222**; disposing second light pipe **224** in the aperture so that first light pipe **222** receives second light pipe **224**, wherein first light pipe **222** and second light pipe **224** are in mechanical and optical communication to form elevation member **214**; finishing a surface of elevation member **214** to create a surface for peripheral edges **232** to be uniformly illuminated by first light; disposing light sources in optical communication with light pipes (**222**, **224**, **238**, **240**); disposing elevation arm **228** on azimuthal base **226**; disposing elevation member **214** on elevation arm **228**; disposing y-axis light pipe **238** on azimuthal base **226**; and disposing z-axis light pipe **240** on azimuthal base **226**.

The optical material for light pipes (**222**, **224**, **238**, **240**) provides optical functionality that includes high light guidance and distribution to provide a uniformly bright and sharp edge illumination for peripheral edges **232**. Precision machining can be performed on raw rod material to create precision cylinders, e.g., with 20-μm roundness accuracy. Surface finishing can be applied light pipes (**222**, **224**, **238**, **240**) to provide a matte surface thereto. Ends of light pipes can be optically ground so that an end is connected, e.g., to a light source such as an LED. The other end can be capped with a mirror to retro-reflect the light. In an embodiment, to make elevation member **214**, two cylindrical light pipes are joined, wherein a cross-sectional diameter of second light pipe **224** can be, e.g., 5 mm larger than a cross-sectional diameter of first light pipe **222**. A hole is drilled through the larger diameter light pipe, and first light pipe **222** is tight-fit into second light pipe **224** to connect first light pipe **222** and second light pipe **224** to form elevation member **214**. Surface finishing is performed over the surface of elevation member **214**. For first light pipe **222**, a central portion of first light pipe **222** is not matte finished. Instead, the central portion can be ground to pass light out of first light pipe **222**. The LEI) light source is added to first end **236** of first light pipe **222**. After disposing first light pipe **222** into second light pipe **224** by tight-fit, the central portion of first light pipe **222** communicates the first light to second light pipe **224** to illuminate second light pipe **224**, wherein elevation member **214** is illuminated by the first light received by first light pipe **222**.

The process for making molecular scrivener **200** also can include the assembly of elevation arm on azimuthal base to form gimbal. The elevation arm can be assembled on the azimuthal base. A rotary center provided by an intersection of the azimuthal axis and the elevation axis coincides with the intersection center of the first and second light pipes of the elevation member. The elevation adjuster removes runout offsets of the first and second light pipes intersection center about elevation axis. A runout offset of rotary center **216** of elevation member **214** about azimuthal axis **220** is removed by adjusting azimuthal adjuster **264**.

The process for making molecular scrivener **200** also can include mounting orientation sensor on the elevation element. The orientation sensor x-axis is aligned with the first light pipe center line. The elevation adjuster is assembled at the end of the elevation element, connecting to elevation motor shaft. The bearing supports elevation motor shaft on the elevation arm. The elevation motor is mounted on the elevation arm. The azimuthal adjuster is assembled at the end of the elevation arm, connecting to azimuthal motor shaft. The bearing supports the azimuthal motor shaft on the azimuthal base. The azimuthal motor is mounted on the azimuthal base. Y-direction adjuster, z-direction adjuster, and controller are mounted on azimuthal base.

FIG. **12** shows material for first light pipe **222**, second light pipe **224**, y-axis light pipe **238**, and z-axis light pipe **240** for six-dimensional smart target **200**. Six-dimensional smart target **200** uses line features of light pipe (**222**, **224**, **238**, **240**) to define three-dimensional coordinate frame **278** that determines 6-D information about pose of object **210**. Three-dimensional coordinate frame **278** includes origin **280**, principal x-axis **286**, principal y-axis **282**, and principal z-axis **284**, wherein principal x-axis **286**, principal y-axis **282**, and principal z-axis **284** are vector elements that include a position and a direction.

Center lines first light pipe **222**, second light pipe **224**, y-axis light pipe **238**, and z-axis light pipe **240** to define vector for principal x-axis **286**, principal y-axis **282**, and principal z-axis **284** instead of two points per vector. Compared with conventional methods, six-dimensional smart target **200** involves high accuracy line detection by using more points and supporting information. The information of peripheral edges **232** of light pipes (**222**, **224**, **238**, **240**), parallelism of peripheral edges **232**, points for peripheral edges **232** and origin **280**, and internal intensity distribution of light are used for centerline detection of light pipes (**222**, **224**, **238**, **240**). Also, origin **280** is determined from an intersection of two line features (e.g., each 75 mm long) and achieves higher accuracy compared with the conventional methods that use a spherical center to define an origin. Under operation of six-dimensional smart target **200**, elevation member **214** can constantly rotate toward the measurement instrument to provide a non-blocking measurement of six-dimensional smart target **200**, even when six-dimensional smart target **200** is moving as when six-dimensional smart target **200** is disposed on robot **234**, and articulated arm **292** moves. Moreover, a measurement uncertainty provided by six-dimensional smart target **200** remains the same when six-dimensional smart target **200** rotates at different angles, rotation rates, and the like.

Six-dimensional smart target **200** has numerous advantageous and unexpected benefits and uses. In an embodiment, a process for dynamically determining a pose of object **210** with six-dimensional smart target **200** includes: disposing six-dimensional smart target **200** on object **210** so that six-dimensional smart target **200** moves synchronously with object **210**; receiving a first image of six-dimensional smart target **200** from first camera **296.1** as shown in FIG. **10**; detecting six-dimensional smart target **200** from a background environment in which the six-dimensional smart target **200** is disposed; determining an area of interest of six-dimensional smart target **200**; determining peripheral edges **232** of first light pipe **222**; determining peripheral edges **232** of second light pipe **224**; determining peripheral edges **232** of y-axis light pipe **238**; determining peripheral edges **232** of z-axis light pipe **240**; determining, from peripheral edges **232** of first light pipe **222**, first center line **276.1** of first light pipe **222**; determining, from peripheral edges **232** of second light pipe **224**, second center line **276.2** of second light pipe **224**; determining, from peripheral edges **232** of y-axis light pipe **238**, third center line **276.3** of y-axis light pipe **238**; determining, from peripheral edges **232** of z-axis light pipe **240**, fourth center line **276.4** of z-axis light pipe **240**; determining an elevation intersection of first center line **276.1** and second center line **276.2**; determining, from the elevation intersection, rotary center **216**; determining, from rotary center **216**, third center line **276.3**, and fourth center line **276.4**, three-dimensional coordinate frame **278** for six-dimensional smart target **200** to determine the pose of object **210**, three-dimensional coordinate frame **278** including: origin **280** that is disposed at rotary center **216**; principal y-axis **282** parallel to y-direction **246** and arranged to intersect origin **280**; principal z-axis **284** parallel to z-direction **248** and arranged to intersect origin **280**; and principal x-axis **286** parallel to azimuthal axis **220** and arranged to intersect origin **280**.

The process for determining pose further can include removing an elevation runoff offset of elevation member **214** for rotation about elevation axis **230** by adjusting elevation adjuster **254** interposed between elevation member **214** and elevation arm **228**; and jamming a motion of elevation member **214**.

The process for determining pose further can include removing an azimuthal runoff offset of elevation member **214** for rotation about azimuthal axis **220** by adjusting azimuthal adjuster **264** interposed between azimuthal base **226** and elevation arm **228**; and releasing a motion of elevation member **214**.

The process for determining pose further can include aligning y-axis light pipe **238** by adjusting y-direction adjuster **260** so that y-direction **246** intersects azimuthal axis **220**.

The process for determining pose further can include adjusting a position of reflector **274** disposed on elevation member **214** to be disposed coincident rotary center **216** as viewed from motion tracker **288**.

In the process, disposing six-dimensional smart target **200** on object **210** so that six-dimensional smart target **200** moves synchronously with object **210** can include using rotation sensor signals to drive elevation motor and azimuthal motor to keep the elevation element maintaining the initial pose or a taught pose.

In the process, receiving a first image of six-dimensional smart target **200** from first camera **296.1** can include initializing the camera connection, performing auto-exposure, capturing image, and storing image in software image buffer.

In the process, detecting six-dimensional smart target **200** from a background environment can include adjusting camera exposure, applying color filters in algorithm to identify light pipes, and using the pattern of three light pipe colors to detect smart target.

In the process, determining an area of interest of six-dimensional smart target **200** can include detecting smart target from a background environment, finding a bounding box of the smart target in image, generating an area of interest using the bounding box, and applying the area of interest for image capturing to increase the camera frame rate.

In the process, determining peripheral edges **232** can include applying noise removal algorithm for image processing, implementing edge detection filter in algorithm to detect edges, and using sub-pixel interpretation for edge representation.

In the process, determining, from peripheral edges **232** center line **276** can include constructing an edge represen-

tation to edge line features, calculating a middle line using the edge lines, using intensity information to fine-tune the location of center line points along the direction perpendicular to middle line, best-fit the center line points to a center line.

In the process, determining an elevation intersection of first center line **276.1** and second center line **276.2** can include constructing center lines from the first light pipe and the second light pipe, and calculating the intersection of the two center lines to get a point, which is the origin of the coordinate frame.

In the process, determining three-dimensional coordinate frame **278** can include calculating coordinate frame origin from the intersection of two light pipes in elevation element, then from the origin, creating a vector to represent the y-axis of the coordinate frame. The direction of the y-axis vector is defined by constructing center line from y-axis light pipe, z-axis vector is defined by constructing center line from z-axis light pipe. A coordinate frame is constructed by having an origin and two directions of axes.

In the process, determine the pose of object **210** from coordinate frame can include extracting position information (x, y, z) from the origin of the coordinate frame, and orientation information (pitch, yaw, roll) from the direction of coordinate x-axis, y-axis, and z-axis.

In the process, removing runoff offset can include rotating elevation member about the elevation axis, measuring runoff of the intersection center of the first and second light pipes on elevation element, removing the runoff by adjusting elevation adjuster, then jamming a motion of elevation member about the elevation axis, rotating elevation arm about azimuthal axis, measuring runoff of the intersection center of the first and second light pipes on elevation element, and removing the runoff by adjusting azimuthal adjuster.

In the process, jamming a motion of elevation member **214** can include using a fixture to clamp elevation motor shaft to stop elevation motor from rotating.

In the process, releasing a motion of elevation member **214** can include removing the clamping fixture to resume the rotation of elevation motor.

In the process, aligning y-axis light pipe **238** can include measuring the center line of the y-axis light pipe and z-axis light pipe and adjusting the direction of the y-axis light pipe using y-direction adjuster to align y-axis direction perpendicular to z-axis direction.

In the process, adjusting a position of reflector **274** disposed on elevation member **214** can include adjusting the location of the reflector to make it coincide with the origin or the coordinate frame.

With reference to FIG. **13** and FIG. **14**, a process for recognizing elevation member **214**, y-axis light pipe **238**, and z-axis light pipe **240** and also establishing three-dimensional coordinate frame **278** includes measuring, e.g., with a vision-based measurement instrument, six-dimensional smart target **200** with cameras **296** to obtain features; performing stereo triangulations to convert features in 2-D images to 3-D points or features; and processing images for first camera **296.1** and second camera **296.2** as shown in FIG. **10**.

A first image from first camera **296.1** is processed (step **312.1**), wherein the first image includes a background and six-dimensional smart target **200**. A color pattern of six-dimensional smart target **200** includes a narrowband wavelength of red, green, and blue colors. The color pattern is used to create a color pattern filter. Together with a shape pattern of light pipes (**222**, **224**, **238**, **240**), six-dimensional smart target **200** is identified from the background (step **314.1**). Centered by the identified six-dimensional smart target **200**, an area of interest (AOI) is created (step **316.1**). Advanced algorithms are performed on AOI to speed up calculation because fewer calculations are performed on the smaller area of AOI as compared with processing the whole image (step **318.1**). An advanced auto-exposure algorithm and filters are applied to AOI to find peripheral edges **232** of light pipes (**222**, **224**, **238**, **240**). Here, camera parameters, including shutter speed and gain, are adjusted to achieve the intensity partition of the selected wavelength to background. For elevation member **214**, peripheral edges **232** are identified for the intersection of first light pipe **222** and second light pipe **224**. Using information for peripheral edges **232**, points on the center line of first light pipe **222** and second light pipe **224** are determined (step **320.1**). It is contemplated that a movement of object **210** can be less than a representation that a resolution of a camera pixel might have, but such motion can be reflected by an intensity change. Intensity information is used to refine center line detection to achieve a sub-pixel accuracy of the center line (step **322.1**). Here, edge line features are constructed. A middle line is created using the edge lines. Intensity information of the light pipe image is used to fine-tune the location of center line points along the direction perpendicular to middle line with sub-pixel accuracy. Best-fit is performed to fit the center line points to a center line. Refined center points are used to best-fit the center line of light pipes (**222**, **224**, **238**, **240**) (step **324.1**). Multiple iterations and an optimization algorithm remove outliers and points that have high uncertainty. Rotary center **216** of elevation member **214** is origin **280** for three-dimensional coordinate frame **278** of six-dimensional smart target **200** (step **326.1**), wherein rotary center **216** is determined from the intersection of the center lines of first light pipe **222** and second light pipe **224**. Center lines of y-axis light pipe **238** and z-axis light pipe **240** are used as y-direction **246** and z-direction **248** (step **328.1**).

A second image from second camera **296.2** is processed according to the process for processing the first image from first camera **296.1** (steps **312.2**-**328.2**). Triangulation is performed with the first image and the second image to construct, from detected features, a 3-D point and lines (steps **330**, **332**). Rotary center **216** from elevation member **214** is defined as origin **280** of six-dimensional smart target **200** (step **334**). Coordinate axes are identified by, if y-axis light pipe **238** and z-axis light pipe **240** can be viewed by camera **296**, making y-direction **246** as the direction of the center line of y-axis light pipe **238** and making the z-direction **248** as the direction of the center line of z-axis light pipe **240** and projecting y-direction **246** and z-direction **248** into a plane parallel to y-direction **246** and z-direction **248** and including origin **280** to make principal y-axis **282** and principal z-axis **284**.

If only y-axis light pipe **238** is viewable by camera **296**, y-direction **246** is defined as the direction of the center line of y-axis light pipe **238**, and principal x-y plane **284** is made by projecting y-direction **246** onto a plane parallel to y-direction **246** and including origin **280**. Principal z-axis is defined as a vector passing through the origin, and perpendicular to the principle x-y plane.

If only z-axis light pipe **240** is viewable by camera **296**, z-direction **248** is define as the direction of the center line of z-axis light pipe **240**, and principal x-z plane **284** is made by projecting z-direction **246** onto a plane parallel to z-direction

246 and including origin 280. Principal y-axis is defined as a vector passing through the origin, and perpendicular to the principle x-z plane.

After origin 280, principal y-axis 282, and principal z-axis 284 are defined, principal x-axis 286 is defined to be perpendicular to principal y-axis 282, and principal z-axis 284.

Y-axis light pipe 238 can be larger in diameter than other light pipes (222, 224, 240) and defines y-direction 246, a positive direction of the Y-axis. The positive Y axis direction point from base azimuth rotation center points to a distal terminus of y-axis light pipe 238. A positive X axis direction is in a direction from base azimuth rotation center pointing to rotary center 216 of elevation member 214.

With origin 280 and direction of axes defined, three-dimensional coordinate frame 278 of six-dimensional smart target 200 is as follows. Origin 280 is at rotary center 216 of elevation member 214. Principal y-axis 282 passes through origin 280, and points in a positive direction defined by y-axis light pipe 238. Principal z-axis 284 passes through origin 280 and points in a direction defined by z-axis light pipe 240. Principal x-axis 286 is perpendicular to principal z-axis 284 and principal y-axis 282. The positive direction is defined as pointing from the rotary center of azimuthal base 226 to elevation member 214.

FIG. 15 shows a process for adjusting elements of six-dimensional smart target 200. Alignment of elevation member 214 causes elevation member 214 to stay at the intersection of elevation axis 230 and azimuthal axis 220. When elevation member 214 rotates solely about elevation axis 230 azimuthal axis 220, rotary center 216 of elevation member 214 stays at the same position under rotation. Otherwise, offset errors from alignment occur as the pose of object 210 changes. Y-axis light pipe 238 and z-axis light pipe 240 are aligned to be perpendicular to each other and are the primary definition of directions for two axes. Alignment of y-axis light pipe 238 and z-axis light pipe 240 to pass through azimuthal axis 220 provides advantages of using rotary center 216 of elevation member 214 and information about an axis to define three-dimensional coordinate frame 278 according to the process shown in FIG. 13 and FIG. 14.

Adjustment starts from elevation axis 230. Elevation adjuster 254 removes a runout offset of rotary center 216 of elevation member 214 when rotating about elevation axis 230 after which motion of elevation is jammed with a clamp to immobilize elevation member 214 with elevation arm 228. Azimuthal adjuster 264 removes the runout offset of rotary center 216 of elevation member 214 when rotating about azimuthal axis 220. Thereafter, motion of elevation is released by removing the clamping fixture to resume the rotation of elevation motor. Verification that elevation member 214 passes through the intersection of azimuthal axis 220 and elevation axis 230 is performed by measuring a current position of rotary center with a subsequent rotation of about azimuthal axis by 180° followed by rotating 180° about elevation axis 230. If there is an offset in any direction, the front and back method will double the errors so that problem of the alignment is highlighted and corrected accordingly through adjustment, referred to as a front and back method. The front and back method measures a current position of rotary center 216 with a subsequent rotation about azimuthal axis 220 by 180° followed by rotating 180° about elevation axis 230. If there is an offset in any direction, the front and back method will double the errors so that problem of the alignment is highlighted and corrected accordingly through adjustment.

Alignment of y-axis light pipe 238 so that y-direction 246 intersects azimuthal axis 220 is performed by y-direction adjuster 260. Similarly, alignment of z-axis light pipe 240 so that z-direction 248 intersects azimuthal axis 220 is performed by z-direction adjuster 262. Adjusting y-direction adjuster 260 or z-direction adjuster 262 occurs by adjusting the direction of the y-axis light pipe using y-direction adjuster to align y-axis direction perpendicular to z-axis direction or adjusting the direction of the z-axis light pipe using z-direction adjuster to align z-axis direction perpendicular to y-axis direction. When present, reflector 274 can be aligned by adjusting reflector 274 to be interposed between rotary center 216 and a laser tracker, wherein alignment reflector 274 can be verified using the front and back method with respect to reflector 274 as viewed by the laser tracker.

Six-dimensional smart target 200 and processes disclosed herein have numerous beneficial uses, including the high accuracy that comes from the design herein, non-blocking measurement by rotating the target constantly toward the measurement instrument, the capability to measure both static and dynamic TCP data, the consistent and unique definition of a coordinate frame of reference to remove measurement uncertainty, and a hybrid target for the cross-platform measurement system, including vision-base measurement systems and laser-vision hybrid measurement systems. Advantageously, six-dimensional smart target 200 overcomes limitations of technical deficiencies of conventional articles such as uncertainty in high accuracy orientation measurement, blocking issue for dynamic measurement, and lack of a unique definition of a coordinate frame of reference. Further, ambient light has a high influence on accuracy when using traditional infrared (IR) technology to distinguish target from background environment. Images using IR technology only contains markers that cannot distinguish the target from reflective lights. The active lighted three-color smart target allows the frame of reference to stand out from background environment, enabling more accurate measurements. Redundant information from color images are used to remove ambient lights influences and ensure the clear delineation of the frame of reference, ensuring more accurate measurements. The rotating nature of the target ensures that there is a clear vision of the target, allowing for the measurement at multiple orientation and positions without the risk of occlusion.

Six-dimensional smart target 200 overcomes shortcomings of conventional devices by using line features of light pipes to define three-dimensional coordinate frame 278. In conventional devices, a frame is constructed by defining an origin and two of the axes. A third axis is defined as being perpendicular to the other two axes, and an origin of the frame of the conventional device is a point feature. Conventionally, a coordinate frame is a made by a three-point method in which three or more sphere artifacts are structured together, and centers of the sphere artifacts are used in the three-point method for coordinate frame definition. The three points are used as the origin, the point defining an axis (e.g., X-axis), and the point in a plane (e.g., XY plane). Because the axis vector is only defined by two points at close distance, the uncertainty of the point center detection can cause large uncertainty in the axis direction definition. As a result, the conventional device can have a tremendous uncertainty in orientation measurement. Moreover, blocking or overlapping can occur in the conventional device from different views of the conventional device, or when the conventional device rotates with an object of interest. Different spheres are selected to redefine the origin and axes in

the conventional device, and the process is inconsistent with additional errors of frame position and orientation definition. Six-dimensional smart target **200** overcomes these technical limitations.

Moreover, six-dimensional smart target **200** and processes herein have numerous advantageous properties. In an aspect, six-dimensional smart target offers unique advantages in supporting a vision system's ability to capture precise 6-D information of an object that requires precision localization. Capturing both the accurate position and the orientation of an object is involved in a variety of applications, including registering multiple machines, tools, or objects, adaptively locating objects during mobile applications, or precisely tracking the pose of an object, including objects used within robot or machine operations. In many of these applications, even a very small error in position and pose can result in significant cost in the production process, due to rework and product failures.

Six-dimensional smart target **200** and processes herein unexpectedly provide high accuracy, non-blocking dynamic measurement, and a low-cost solution to acquire 6-D information that is involved in many applications that involve measuring and monitoring the pose of an object or using precision 6-D information to merge measurement data. Conventional processes may not adequately account for occlusions and blocking. The tracked object can be in positions or orientations that do not provide tracking. At these locations, the user of conventional processes cannot be confident that the object is at the expected position or pose, creating an uncertainty in the measurement process. Moreover, six-dimensional smart target **200** can be a general target for vision agnostic systems, providing wide capabilities of monitor the performance degradation or tracking the pose of objects.

While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation. Embodiments herein can be used independently or can be combined.

All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. The ranges are continuous and thus contain every value and subset thereof in the range. Unless otherwise stated or contextually inapplicable, all percentages, when expressing a quantity, are weight percentages. The suffix "(s)" as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including at least one of that term (e.g., the colorant(s) includes at least one colorants). "Optional" or "optionally" means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event occurs and instances where it does not. As used herein, "combination" is inclusive of blends, mixtures, alloys, reaction products, and the like.

As used herein, "a combination thereof" refers to a combination comprising at least one of the named constituents, components, compounds, or elements, optionally together with one or more of the same class of constituents, components, compounds, or elements.

All references are incorporated herein by reference.

The use of the terms "a" and "an" and "the" and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. "Or" means "and/or." It should further be noted that the terms "first," "second," "primary," "secondary," and the like herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. The modifier "about" used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity). The conjunction "or" is used to link objects of a list or alternatives and is not disjunctive; rather the elements can be used separately or can be combined together under appropriate circumstances.

What is claimed is:

1. A six-dimensional smart target for dynamically determining pose of an object, the six-dimensional smart target comprising:

a gimbal comprising:

an azimuthal base that provides an azimuthal axis;

an elevation arm disposed on and in rotary communication with the azimuthal base and that:

extends from the azimuthal base,

rotates about the azimuthal axis, and

provides an elevation axis; and

a rotary center provided by an intersection of the azimuthal axis and the elevation axis;

an elevation member disposed on the elevation arm of the gimbal at the rotary center of the gimbal and in rotary communication with the elevation arm, the elevation member comprising:

a first light pipe comprising an elongated body disposed axially along the elevation axis with a first end connected to the elevation arm and that:

receives first light and uniformly distributes the first light along the first light pipe to illuminate peripheral edges of the first light pipe; and

a second light pipe disposed on the first light pipe and arranged with the second light pipe intersecting the first light pipe at the rotary center such that the second light pipe receives the first light from the first light pipe and uniformly distributes the first light along the second light pipe to illuminate peripheral edges of the second light pipe, the second light pipe comprising an elongated body disposed axially at an oblique angle to the first light pipe and the elevation axis;

an azimuthal member comprising:

the azimuthal base;

a y-axis light pipe disposed on the azimuthal base and comprising an elongated body disposed axially along a y-direction that is perpendicular to the azimuthal axis with a second end connected to the azimuthal base and that:

receives a second light and uniformly distributes the second light along the y-axis light pipe to illuminate peripheral edges of the y-axis light pipe; and

a z-axis light pipe disposed on the azimuthal base and comprising an elongated body disposed axially along a z-direction that is perpendicular to the azimuthal axis and the y-direction, with a third end connected to the azimuthal base such that the z-axis light pipe:

receives a third light and uniformly distributes the third light along the z-axis light pipe to illuminate peripheral edges of the z-axis light pipe,

wherein the elevation member rotates at the rotary center about the elevation axis and the azimuthal axis

to consistently maintain the first light pipe and the second light pipe in a field of view of a measurement instrument that views the six-dimensional smart target.

2. The six-dimensional smart target of claim **1**, further comprising an orientation sensor interposed between the elevation member and the elevation arm.

3. The six-dimensional smart target of claim **1**, further comprising an elevation adjuster interposed between the elevation member and the elevation arm.

4. The six-dimensional smart target of claim **1**, further comprising a bearing interposed between the elevation member and the elevation arm.

5. The six-dimensional smart target of claim **1**, further comprising an elevation motor interposed between the elevation member and the elevation arm.

6. The six-dimensional smart target of claim **1**, further comprising a y-direction adjuster interposed between the azimuthal base and the y-axis light pipe.

7. The six-dimensional smart target of claim **1**, further comprising a z-direction adjuster interposed between the azimuthal base and the z-axis light pipe.

8. The six-dimensional smart target of claim **1**, further comprising an azimuthal adjuster interposed between the azimuthal base and the elevation arm.

9. The six-dimensional smart target of claim **1**, further comprising a bearing interposed between the azimuthal base and the elevation arm.

10. The six-dimensional smart target of claim **1**, further comprising an azimuthal flange disposed on the azimuthal base that connects the azimuthal base to the object.

11. The six-dimensional smart target of claim **1**, further comprising a controller disposed on the azimuthal base.

12. The six-dimensional smart target of claim **1**, further comprising an azimuthal motor disposed on the azimuthal base.

13. The six-dimensional smart target of claim **1**, further comprising a reflector disposed on the elevation member proximate to and centered on rotary center.

14. A process for dynamically determining a pose of an object with the six-dimensional smart target of claim **1**, the process comprising:

disposing the six-dimensional smart target on object so that six-dimensional smart target moves synchronously with object;

receiving a first image of the six-dimensional smart target from a first camera;

detecting the six-dimensional smart target from a background environment in which the is disposed;

determining an area of interest of the six-dimensional smart target;

determining peripheral edges of the first light pipe;

determining peripheral edges of the second light pipe;

determining peripheral edges of the y-axis light pipe;

determining peripheral edges of the z-axis light pipe;

determining, from the peripheral edges of the first light pipe, a first center line.1 of first light pipe;

determining, from the peripheral edges of the second light pipe, a second center line.2 of second light pipe;

determining, from the peripheral edges of the y-axis light pipe, a third center line.3 of y-axis light pipe;

determining, from the peripheral edges of the z-axis light pipe, a fourth center line.4 of z-axis light pipe;

determining an elevation intersection of the first center line.1 and the second center line.2;

determining, from the elevation intersection, the rotary center;

determining, from the rotary center, the third center line.3, and the fourth center line.4, a three-dimensional coordinate frame for the six-dimensional smart target to determine the pose of the object, the three-dimensional coordinate frame comprising:

an origin that is disposed at the rotary center;

a principal y-axis parallel to the y-direction and arranged to intersect the origin;

a principal z-axis parallel to the z-direction and arranged to intersect the origin; and

a principal x-axis parallel to the azimuthal axis and arranged to intersect the origin.

15. The process for determining pose of claim **14**, further comprising:

removing an elevation runoff offset of the elevation member for rotation about the elevation axis by adjusting an elevation adjuster interposed between the elevation member and the elevation arm; and

jamming a motion of the elevation member.

16. The process for determining pose of claim **15**, further comprising:

removing an azimuthal runoff offset of the elevation member for rotation about the azimuthal axis by adjusting an azimuthal adjuster interposed between the azimuthal base and the elevation arm; and

releasing a motion of the elevation member.

17. The process for determining pose of claim **16**, further comprising:

aligning y-axis light pipe by adjusting y-direction adjuster so that y-direction intersects the azimuthal axis.

18. The process for determining pose of claim **15**, further comprising:

adjusting a position of a reflector disposed on the elevation member to be disposed coincident with rotary center as viewed from a motion tracker.

* * * * *