



(51) International Patent Classification:

G01B 11/26 (2006.01) G01S 17/06 (2006.01)
B25J 13/08 (2006.01) G01S 17/42 (2006.01)
G01B 9/02 (2006.01)

(21) International Application Number:

PCT/AU2018/050873

(22) International Filing Date:

16 August 2018 (16.08.2018)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

2017903310 17 August 2017 (17.08.2017) AU

(71) Applicant: FASTBRICK IP PTY LTD [AU/AU]; 122
Sultana Road West, High Wycombe, Western Australia
6057 (AU).

(72) Inventor: PIVAC, Mark Joseph; 11 Keane Way, Lesmur-
die, Western Australia 6076 (AU).

(74) Agent: DAVIES COLLISON CAVE PTY LTD; Level
10, 301 Coronation Drive, Milton, Queensland 4064 (AU).

(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP,
KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,

(54) Title: LASER TRACKER WITH IMPROVED ROLL ANGLE MEASUREMENT

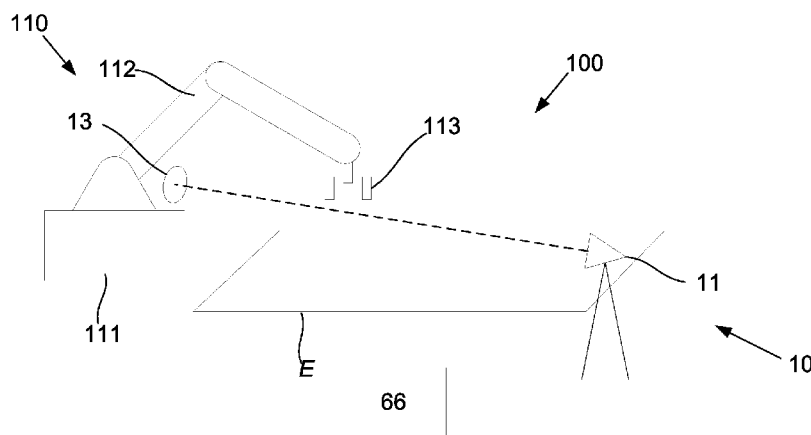


Fig. 1A

(57) Abstract: The present disclosure relates to a tracking system for tracking the position and orientation of an object in an environment, the tracking system including: (a) a tracking base positioned in the environment; (b) a tracking target mountable to the object, wherein in use the tracking base is linked to the tracking target by: (i) a bidirectional light beam transmitted therebetween; and, (ii) a unidirectional light beam transmitted therebetween, said unidirectional light beam parallel to the bidirectional light beam; and, (c) at least one controller configured to determine a roll angle of the tracking target relative to the tracking base, the roll angle determined at least in part by signals received from a sensor housed in at least one of the tracking base and the tracking target that detects the unidirectional light beam.

GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,
TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK,
EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM,
TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW,
KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

LASER TRACKER WITH IMPROVED ROLL ANGLE MEASUREMENT

Priority Documents

[0001] The present application claims priority from Australian Provisional Application No. 2017903310 titled “LASER TRACKER WITH IMPROVED ROLL ANGLE MEASUREMENT” and filed on 17 August 2017, the content of which is hereby incorporated by reference in its entirety.

Background of the Invention

[0002] The present invention relates to a tracking system for measuring the position and orientation of an object in an environment, and in one example to a tracking system including a laser tracker and active target mounted to the object incorporating an improved roll angle measurement.

Description of the Prior Art

[0003] The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that the prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

[0004] In this specification, the position and orientation of a target in space are described as Cartesian coordinates along three axes, x, y, and z, and in addition angular attributes of pitch, yaw, and roll.

[0005] To accurately control the end effector position of industrial robots or large construction robots, it is necessary to measure the position and orientation of the end effector, or a part of the robot close to the end effector. To achieve dynamic stability and accurate control during movement of the robot, it is necessary to measure the position and orientation at a high data rate and in real time. Delays in the feedback loop of a control system lead to

following error and reduced bandwidth and phase margin, all of which are undesirable. Delay can also introduce self-excitation or resonance in servo-controlled systems.

[0006] Large construction robots operating outdoors are subject to dynamic movement due to load, acceleration, and external environmental factors such as wind and temperature which cause unwanted vibration and oscillation. To accurately control an end effector positioned for example at the end of a long boom structure, this dynamic movement must be compensated for in real time so as to perform interactions in an environment. An example of a large construction robot requiring real time dynamic motion compensation and stabilisation is the applicant's automatic brick laying machine as described for example in PCT/AU2007/000001 and PCT/AU2017/050731.

[0007] Laser trackers such as those described in US4714339 (Lau et al) and US 4790651 (Brown et al) are used to measure the position and orientation of a target which is mounted to an object. Lau et al teaches the measurement of the position and orientation of an object in space with three degrees of freedom and preferably five degrees of freedom being position described as Cartesian coordinates along three axes, x, y, and z, and preferably in addition angular attributes of pitch and roll. Kyle in CMSC: Charlotte-Concord, July 21st-25th, 2008, describes a laser tracker polar measurement system for measuring the position and orientation of a target with six degrees of freedom. Kyle discusses the importance of accurate roll angle sensing. While Kyle discusses various means of achieving the roll angle measurement, there are practical difficulties in achieving accurate roll angle measurement with what was proposed by Kyle.

[0008] Manufacturers API (Radian and OT2 with STS (Smart Track Sensor)), Leica (AT960 and Tmac) and Faro provide laser tracker systems, some of which can measure position and orientation of the target. These systems measure position at 300 Hz, or 1kHz or 2 kHz (depending on the equipment). Orientation measurements (for STS and Tmac) rely on respective vision systems using 2D cameras which measure at a current maximum of 100 Hz. Accelerometer data such as from a tilt sensor or INS (Inertial Navigation System) can be used to determine or predict or interpolate orientation measurements at up to 1000 Hz but the

orientation accuracy may only be reduced to 0.01 degree with the known systems (and even this level of accuracy is typically only attainable at 100Hz).

[0009] The Leica Tmac uses frames which each have a field of view of approximately 90 degrees. If a greater field of view is required, multiple Tmac frames must be used and the laser tracker must shift its lock from one to another, which results in a loss of data during the shift. The problem with the loss of data is that during this time, either an alternative data source is required (such as INS measurements), dead reckoning must be used, or the shift needs to be controlled to occur when dynamic motion compensation is not required (for example if the machine is stopped, or moving between tasks needing compensation).

[0010] API have in the past described in US6049377, and manufactured a STS using a roll angle sensor using polarised light. This sensor system can provide data at 300 Hz but the roll angle accuracy is only about 0.1 degrees. The STS has the advantage that it has a heading field of view of 360 degrees, and an altitude field of view of plus minus 45 degrees.

[0011] Some tracking systems use CCD or CMOS sensors to image roll angle targets but these sensors introduce delay and latency because the 2D sensor data from the pixel array has to be transmitted pixel by pixel to a microprocessor which must then use complex vision algorithms to determine the target locations and thus the roll angle. The vision algorithms used typically take some time, usually in excess of 10ms or even 100ms.

[0012] All hitherto described laser trackers suffer from poor data rate and/or latency and/or low accuracy when measuring roll angle. Accordingly, it would be desirable to provide a tracking system with improved roll angle measurement to allow rapid determination of the position and orientation of a tracking target relative to a tracking base in six degrees of freedom (6DOF).

[0013] It is against this background, and the problems and difficulties associated therewith, that the present invention has been developed.

Summary of the Present Invention

[0014] In one broad form, the present invention seeks to provide a tracking system for tracking the position and orientation of an object in an environment, the tracking system including:

- a) a tracking base positioned in the environment;
- b) a tracking target mountable to the object, wherein in use the tracking base is linked to the tracking target by:
 - i) a bidirectional light beam transmitted therebetween; and,
 - ii) a unidirectional light beam transmitted therebetween, said unidirectional light beam parallel to the bidirectional light beam; and,
- c) at least one controller configured to determine a roll angle of the tracking target relative to the tracking base, the roll angle determined at least in part by signals received from a sensor housed in at least one of the tracking base and the tracking target that detects the unidirectional light beam.

[0015] In one embodiment, the sensor measures the displacement of the unidirectional light beam relative to a datum position on a surface thereof.

[0016] In one embodiment, the roll angle is determined from the measured displacement.

[0017] In one embodiment, the unidirectional light beam transits an optical mount mounted on at least one of the tracking base and tracking target for controlled rotation about an axis of rotation that is coaxial with the bidirectional light beam, and wherein the controller is configured to control the rotation of the optical mount in order to maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target and wherein the angle of the controlled rotation is determined by the controller and roll angle data derived therefrom.

[0018] In one embodiment, the sensor is housed in the optical mount, and wherein the sensor provides signals proportional to the location of the unidirectional light beam incident on a surface of the sensor.

[0019] In one embodiment, the controller:

- a) receives the signals from the sensor;
- b) processes the signals to determine the location of the unidirectional light beam on the sensor surface; and,
- c) causes the optical mount to rotate about the axis of rotation in accordance with the processed signals so as to locate the unidirectional light beam on the centre of the sensor surface and maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target.

[0020] In one embodiment, a motor is coupled to the optical mount, and wherein the controller is configured to control the motor to rotate and align the optical mount with the unidirectional light beam.

[0021] In one embodiment, the angle of said controlled rotation is determined by said controller from angle encoders and roll angle data is derived therefrom.

[0022] In one embodiment, the angle of said controlled rotation includes a correction of following error as determined by a measurement signal from the sensor.

[0023] In one embodiment, the angle of said controlled rotation is determined from motor control data.

[0024] In one embodiment, the tracking base is a laser tracker and the tracking target is an active target configured to track the tracking base so as to maintain linkage of the bidirectional light beam transmitted between the laser tracker and active target.

[0025] In one embodiment, the tracking base includes a first head unit mounted to a first base about two axes normal to each other and wherein the tracking target includes a second head unit that is mounted to a second base about two axes normal to each other, and wherein rotation about the two axes in both head units is controlled by a head unit controller to rotate about their respective said two axes to maintain the linkage of said bidirectional light beam.

[0026] In one embodiment, the first head unit is mounted to a first gimbal about a first gimbal axis extending normally to the direction of the bidirectional light beam, the first gimbal being mounted to the first base about a first base axis extending normally to the first

gimbal axis, and the second head unit is mounted to a second gimbal about a second gimbal axis extending normally to the direction of the bidirectional light beam, the second gimbal being mounted to the second base about a second base axis extending normally to said second gimbal axis.

[0027] In one embodiment, a unidirectional light beam source is located in the tracking base to produce said unidirectional light beam, and said optical mount is located on the tracking target, the optical mount further including the sensor to detect the unidirectional light beam.

[0028] In one embodiment, a unidirectional light beam source is located in the tracking target to produce the unidirectional light beam, and said optical mount is located on the tracking base, the optical mount further including the sensor to detect the unidirectional light beam.

[0029] In one embodiment, a unidirectional light beam source is located in the optical mount to produce the unidirectional light beam and the optical mount is located on the tracking target, and the tracking base includes the sensor to detect the unidirectional light beam.

[0030] In one embodiment, a unidirectional light beam source is located in the optical mount to produce the unidirectional light beam and the optical mount is located on the tracking base, and the tracking target includes the sensor to detect the unidirectional light beam.

[0031] In one embodiment, the optical mount is located on an annular member arranged for controlled rotation about the axis of rotation (i.e. transmission axis of the bidirectional light beam).

[0032] In one embodiment, the sensor is a position displacement sensor (PDS).

[0033] In another broad form, the present invention seeks to provide a method of tracking the position and orientation of an object in an environment using a tracking system including:

- a) a tracking base positioned in the environment;
- b) a tracking target mountable to the object, wherein in use the tracking base is linked to the tracking target by:
 - i) a bidirectional light beam transmitted therebetween; and,

- ii) a unidirectional light beam transmitted therebetween, said unidirectional light beam parallel to the bidirectional light beam; and, wherein the method includes in at least one controller:
 - (1) receiving signals from a sensor housed in at least one of the tracking base and the tracking target that detects the unidirectional light beam; and,
 - (2) determining a roll angle of the tracking target relative to the tracking base at least in part using the received signals.

[0034] In one embodiment, the method includes in the at least one controller:

- a) determining a displacement of the unidirectional light beam relative to a datum position on a surface of the sensor using the received signals; and,
- b) determining a roll angle using the determined displacement.

[0035] In one embodiment, the tracking system includes an optical mount through which the unidirectional light beam transits, the optical mount mounted on at least one of the tracking base and tracking target, the optical mount housing the sensor and configured for controlled rotation about an axis of rotation that is coaxial with the bidirectional light beam, and wherein the method further includes in the at least one controller:

- a) processing the signals received from the sensor to determine the location of the unidirectional light beam incident on the sensor surface; and,
- b) causing the optical mount to rotate about the axis of rotation in accordance with the processed signal so as to locate the unidirectional light beam on the centre of the sensor surface and maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target.

[0036] This invention provides advantages for the dynamic measurement and control of industrial and construction robots, particularly those with active or dynamic motion compensation and stabilisation. This invention also provides accurate real time roll angle measurement of an active target sensor, overcoming the shortfalls of the above described background art.

[0037] Thus, in one aspect, the invention separately provides an improved laser tracker with an active target. The laser tracker has its known primary laser beam and heading angle and

altitude angle tracking and measuring provisions and is additionally provided with a second laser beam to provide a roll angle reference. The active target uses known means to track the primary laser beam and measure heading angle and altitude angle. In a preferred embodiment, the active target is further provided with a laser position displacement sensor (PDS) mounted to rotate about a controlled roll axis coincident with the primary laser tracker beam so that the roll axis rotates to zero the PDS, thereby providing a roll angle.

[0038] In an alternative embodiment, the active target is further provided with a laser position displacement sensor (PDS) which measures the displacement of the roll beam relative to a datum position, thereby providing a roll angle. This arrangement has the advantage of not requiring the active roll axis but it does require a larger PDS and if the PDS does not extend through 360 degrees it limits the roll angle that can be measured. If a large PDS is used, it reduces the roll angle accuracy. For small roll angles, a smaller and more accurate PDS can be used.

[0039] A PDS (position displacement sensor) is an analogue device which provides a real time signal proportional to the location of the centre of the incident laser beam. Commercially available PDS have good repeatability and analog resolution with low noise and accuracy of better than 0.1% of the size of the sensor. By using a small sensor, the position accuracy is high. The PDS signal in the preferred embodiment is used as feedback to control the roll axis to keep the roll laser beam centred on the PDS. The PDS measurements can be read by the control system via an ADC (analog to digital converter) which can operate at the cyclic control rate of the controller, thereby effectively eliminating latency.

[0040] The laser tracker is connected to and communicates over a network (e.g. a fieldbus network such as Ethercat) and the active target is connected to and communicates over the same network. Preferably the servo drives used to move the axes are connected to and controlled by, and communicate encoder measurements, directly over the network. Preferably all sensors communicate directly over the network. Preferably the control algorithms are implemented as library code executed by a networked master PLC. By this means the laser tracker and active target are tightly integrated so that there is minimal latency

between the measurements and machine axis compensation control based on those measurements.

[0041] To control active dynamic compensation of robot end effector position and orientation on the end of a boom requires fast data with low or preferably no latency (delay). Preferably the measurements can be provided at 1kHz with orientation accuracy of 0.001 degree and an absolute position accuracy of approximately 0.2mm throughout a 40m radius working envelope. Preferably the orientation sensor acts continuously. Preferably the system provides measurement data with low noise so that the motion compensation system is not subjected to vibratory noise. Preferably the measurements have a low latency so that the motion compensation does not have much lag and provides prompt position correction.

[0042] In accordance with one aspect of the invention there is provided position and orientation measurement apparatus having a first head unit and a second head unit, said first head unit and said second head unit being linked in use by a bidirectional light beam transmitted therebetween; wherein said first head unit and said second head unit are linked in use by a unidirectional light beam transmitted therebetween, aligned in parallel with said bidirectional light beam, wherein said unidirectional light beam transmits an optical mount mounted for controlled rotation about an axis, coaxially with said bidirectional light beam on at least one of said first head unit and said second head unit, wherein a controller maintains said controlled rotation in order to maintain linkage of said unidirectional light beam transmitted between said first head unit and said second head unit and the angle of said controlled rotation is determined by said controller and roll angle data is derived therefrom. In this manner, if one of said first head unit and said second head unit rotates about a notional axis of said bidirectional light beam, the controller rotates the optical mount to maintain connection of the unidirectional light beam, and the roll angle can be determined with very little latency.

[0043] In one embodiment, the controller maintains said controlled rotation in order to maintain linkage of said unidirectional light beam transmitted between said first head unit and said second head unit, preferably by controlling a direct drive brushless AC servo motor

to rotate and accurately align the optical mount, and using a sensor, preferably a position displacement sensor, to accurately locate the centre of the unidirectional beam.

[0044] In one embodiment, the angle of said controlled rotation is determined by said controller from angle encoders and roll angle data is derived therefrom.

[0045] In one embodiment, the angle of said controlled rotation includes a correction of following error as determined by a measurement signal from the sensor.

[0046] In one embodiment, preferably the angle of said controlled rotation is determined from stepper motor control data.

[0047] In one embodiment, the bidirectional light beam is a retro reflective arrangement being preferably transmitted from said first head unit and reflected back by said second head unit. The bidirectional light beam and the unidirectional light beam should be non-diverging such as that derived from coherent sources or laser elements such as laser light emitting diodes, for greatest accuracy.

[0048] In one embodiment, the bidirectional light beam is that typically transmitted between a laser tracker sender/receiver unit and an active target utilised in a laser tracker. The first head unit may contain the laser tracker sender/receiver unit, and the second head unit may contain the active target. Position and orientation data is obtained from the laser tracker in known manner, and is supplemented by roll angle data determined by the controller.

[0049] In one embodiment, said first head unit is mounted to a first base about two axes normal to each other said second head unit is mounted to a second base about two axes normal to each other. Rotation about the two axes in both head units is controlled by a head unit controller to rotate about their respective said two axes to maintain the linkage of said first bidirectional beam. There may be a single head unit controller or a separate head unit controller in each head unit. The function of the controller maintaining controlled rotation in order to maintain linkage of the unidirectional beam may be incorporated into one or both head unit controllers.

[0050] In one embodiment, each head unit is typically (though not necessarily – any pivoting mount will work) mounted to a gimbal about a gimbal axis allowing the attitude or altitude of the transmitted beam or reflected beam forming the bidirectional light beam, to be adjusted by said controller. The gimbal is typically mounted to its base (first base or second base as the case may be) about a base axis extending normally to the plane of its base, although this is a relative concept.

[0051] In one embodiment, said first base is mounted with its base axis extending vertically, and the first head unit is mounted to its gimbal about a horizontal axis. The controller may control rotation of the gimbal about the base axis and control rotation of the first head unit about its horizontal axis in order to aim the beam emanating from the first head unit to find a reflector in the second head unit.

[0052] In one embodiment, the second base is mounted with its base axis extending nominally vertically but this axis may deflect from the vertical due to operation of a robotic arm on which the second base is mounted. The second head unit is mounted to its gimbal about a gimbal axis normal to the second base axis. The controller controls rotation of the gimbal about the second base axis and controls rotation of the second head unit about its gimbal axis in order to receive the beam emanating from the first head unit and by controlling all rotation about both base axes and gimbal axes, reflects the beam back to the first head unit and establishes the bidirectional light beam.

[0053] In one embodiment, said first head unit is mounted to a first gimbal about a first gimbal axis extending normally to the direction of said bidirectional light beam, said first gimbal is mounted to said first base about a first base axis extending normally to said first gimbal axis; and said second head unit is mounted to a second gimbal about a second gimbal axis extending normally to the direction of said bidirectional light beam, said second gimbal is mounted to said second base about a first base axis extending normally to said first gimbal axis.

[0054] In one embodiment, a further unidirectional light beam is transmitted preferably from a fixed position in or on the first head unit, transmitted parallel with the bidirectional light beam. This unidirectional light beam is received by a detector located in the optical mount.

In one embodiment, if there is deflection of the second base axis from the vertical, the optical mount may be controllably rotated by the controller so that the detector finds the unidirectional light beam (since it is running parallel to the bidirectional light beam) and the controller can by measuring the rotation of the optical mount, derive roll data for the second head unit, and what it is attached to (e.g. a robotic arm, the base of an end effector, or indeed part of an end effector). In practice once both the bidirectional light beam is established, and the unidirectional light beam is detected, the controller can actuate the optical mount to continually follow the unidirectional light beam as a robotic arm moves, and provide continual roll data.

[0055] The arrangement in the above paragraph may be varied in that the further unidirectional light beam could be transmitted preferably from a fixed position in or on the second head unit, and the optical mount may be mounted for controlled rotation on the first head unit.

[0056] Either arrangement may be varied by having the detector for the unidirectional light beam mounted in a fixed position, and the unidirectional light beam could be mounted within the optical mount.

[0057] In an atypical application the first base may be mounted on a robotic arm, and the first base axis may not necessarily be disposed vertically, however the first gimbal axis will always be disposed normal to the first base axis. The second head unit may be mounted with its second base on the ground, with its second base axis disposed vertically.

[0058] In all cases, light beams, both that used to establish the bidirectional light beam and the unidirectional light beam, are transmitted normally to the gimbal axis of the head unit in which they are mounted.

[0059] All angle measurements may be made from angle encoders either associated with drive motors controlled to maintain beam linkage between said first head unit and said second head unit, or associated with the axes about which rotating parts connect.

[0060] In one embodiment, a unidirectional light beam source is located in said first head unit to produce said unidirectional light beam, and said optical mount is located on said second head unit and includes a detector to detect said unidirectional light beam.

[0061] In one embodiment, a unidirectional light beam source is located in said second head unit to produce said unidirectional light beam, and said optical mount is located on said first head unit and includes a detector to detect said unidirectional light beam.

[0062] In one embodiment, a unidirectional light beam source to produce said unidirectional light beam is located in said optical mount and said optical mount is located on said second head unit, and said first head unit includes a detector to detect said unidirectional light beam.

[0063] In one embodiment, a unidirectional light beam source to produce said unidirectional light beam is located in said optical mount and said optical mount is located on said first head unit, and said second head unit includes a detector to detect said unidirectional light beam.

[0064] In one embodiment, said optical mount is located on an annular member arranged for controlled rotation coaxially with the extent of travel of said bidirectional light beam.

[0065] In one embodiment, said bidirectional light beam is transmitted along said axis.

[0066] It will be appreciated that the broad forms of the invention and their respective features can be used in conjunction, interchangeably and/or independently, and reference to separate broad forms is not intended to be limiting.

Brief Description of the Drawings

[0067] Examples of the present invention will now be described with reference to the accompanying drawings, in which: -

[0068] Figure 1A is a schematic diagram of a system for performing interactions in an environment having a robot assembly and a position and orientation tracking system;

[0069] Figure 1B is a schematic perspective view of a first example of a position and orientation tracking system having a tracking base and a tracking target;

[0070] Figures 1C to 1D are schematic front views of a tracking target from the position and orientation tracking system of Figure 1B illustrating the target having a roll angle of zero degrees and α degrees respectively;

[0071] Figure 2 is a schematic perspective view of an example of a tracking base for use in a second example of a position and orientation tracking system;

[0072] Figure 3 is a schematic diagram of internal componentry of the tracking base of Figure 2;

[0073] Figure 4 is a schematic perspective view of an example of a tracking target for use in the second example of a position and orientation tracking system;

[0074] Figure 5 is a schematic cross-sectional view showing internal componentry of the tracking target of Figure 4;

[0075] Figure 6 is a schematic perspective view of a third example of a position and orientation tracking system;

[0076] Figure 7 is a schematic diagram showing the internal componentry of the tracking target of Figure 6; and,

[0077] Figure 8 is a flowchart of an example process for tracking the position and orientation of an object in an environment.

Detailed Description of the Preferred Embodiments

[0078] An example of a tracking system 10 for tracking the position and orientation of an object in an environment will now be described with reference to Figures 1A to 1D.

[0079] In this example, it is to be understood that the tracking system 10 usually forms part of a system 100 for performing interactions in the environment. The system 100 may include for example a robot assembly 110 having a robot base 111 which supports a robot arm 112 and end effector 113 programmed to perform interactions within the environment. The robot assembly 110 is positioned relative to an environment E, which in this example is illustrated as a 2D plane, but in practice could be a 3D volume of any configuration. In use, the end effector 113 is used to perform interactions within the environment E, for example to perform bricklaying, object manipulation, or the like. The robot base 111 is typically a moveable robot base that may for example be mounted to a boom structure or the like which may

extend between 3-30m thereby enabling the end effector 113 to work inside a large work volume. The object being tracked may be any component of the robot assembly 110 including for example the robot base 111, the robot arm 112 and the end effector 113.

[0080] For purposes of clarity it is to be understood that typically the tracking system 10 is able to track the robot assembly movement, and in one particular example, movement of the robot base relative to the environment. In one example, the tracking system includes a tracking base 11, which is typically statically positioned relative to the environment E and a tracking target 13, mounted on the robot base 111, allowing a position and orientation of the robot base 111 relative to the environment E to be determined. In other examples, the tracker target 13 may be positioned on another part of the robot assembly 110, including for example on a robot component, such as the robot arm 112 or end effector 113 so that the position and orientation of at least part of the robot is measured.

[0081] The term "interaction" is intended to refer to any physical interaction that occurs within, and including with or on, an environment. Example interactions could include placing material or objects within the environment, removing material or objects from the environment, moving material or objects within the environment, modifying, manipulating, or otherwise engaging with material or objects within the environment, modifying, manipulating, or otherwise engaging with the environment, or the like.

[0082] The term "environment" is used to refer to any location, region, area or volume within which, or on which, interactions are performed. The type and nature of the environment will vary depending on the preferred implementation and the environment could be a discrete physical environment, and/or could be a logical physical environment, delineated from surroundings solely by virtue of this being a volume within which interactions occur. Non-limiting examples of environments include building or construction sites, parts of vehicles, such as decks of ships or loading trays of lorries, factories, loading sites, ground work areas, or the like.

[0083] A robot arm is a programmable mechanical manipulator. In this specification a robot arm includes multi axis jointed arms, parallel kinematic robots (such as Stewart Platform,

Delta robots), spherical geometry robots, Cartesian robots (orthogonal axis robots with linear motion) etc.

[0084] A boom is an elongate support structure such as a slewing boom, with or without stick or dipper, with or without telescopic elements, telescoping booms, telescoping articulated booms. Examples include crane booms, earthmover booms, truck crane booms, all with or without cable supported or cable braced elements. A boom may also include an overhead gantry structure, or cantilevered gantry, or a controlled tensile truss (the boom may not be a boom but a multi cable supported parallel kinematics crane (see PAR systems, Tensile Truss – Chernobyl Crane)), or other moveable arm that may translate position in space.

[0085] An end effector is a device at the end of a robotic arm designed to interact with the environment. An end effector may include a gripper, nozzle, sand blaster, spray gun, wrench, magnet, welding torch, cutting torch, saw, milling cutter, router cutter, hydraulic shears, laser, riveting tool, or the like, and reference to these examples is not intended to be limiting.

[0086] It will be appreciated that in order to control the robot assembly 110 to accurately position the end effector 113 at a desired location in order to perform an interaction within the environment, it is necessary to be able to accurately determine the position and orientation of a reference point on the robot assembly.

[0087] In this example, the tracking system 10 includes a tracking base 11 positioned in the environment and a tracking target 13 mountable to the object. In use, the tracking base 11 is linked to the tracking target 13 by a bidirectional light beam 17 transmitted therebetween, and, a unidirectional light beam 31 transmitted therebetween, said unidirectional 31 light beam parallel to the bidirectional light beam 17. The bidirectional light beam 17 (e.g. a laser beam) is typically transmitted from the tracking base 11 to the tracking target 13. The tracking target 13 is configured to reflect the beam back to the tracking base 11. This enables the distance between the tracking base 11 and tracking target 13 to be determined and along with the pan and tilt of the tracking base 11, the position of the tracking target 13 can be determined. The tracking target 13 typically includes actuators to pitch and yaw so as to mutually track the tracking base 11 and keep locked onto the bidirectional light beam 17.

[0088] The unidirectional light beam 31 (or roll beam) provides a roll angle reference. In this regard, the tracking system 10 also includes at least one controller 66 configured to determine a roll angle of the tracking target 13 relative to the tracking base 11, the roll angle determined at least in part by signals received from a sensor housed in at least one of the tracking base 11 and the tracking target 13 that detects the unidirectional light beam 31. The at least one controller 66 may be a dedicated tracking system controller or alternatively the controller 66 may be a machine controller which also controls moves of a robot or the like to which the target is mounted.

[0089] The at least one controller 66 typically includes an electronic processing device, operating in conjunction with stored instructions, and which operates to receive signals from the tracking base and tracking target, process signals to determine position and orientation data and generate control signals for actuators such as motors and the like to execute beam steering and maintain linkage of the respective light beams between the base and target. The electronic processing device could include any electronic processing device such as a microprocessor, microchip processor, logic gate configuration, firmware optionally associated with implementing logic such as an FPGA (Field Programmable Gate Array), or any other electronic device, system or arrangement.

[0090] Typically, the sensor is a position displacement sensor (PDS) which is an analog device which provides a real time signal proportional to the location of the centre of the incident laser beam on a surface thereof. Commercially available PDS have good repeatability and analog resolution with low noise and accuracy of better than 0.1% of the size of the sensor. By using a small sensor, the position accuracy is high. The PDS measurements can be read by the control system via an ADC (analog to digital converter) which can operate at the cyclic control rate of the controller, thereby effectively eliminating latency.

[0091] The above described tracking system 10 provides an improved roll angle measurement which provides a number of advantages. Firstly, orientation measurement accuracy for roll is increased enabling accuracy in the order of 0.001 degree or better to be achieved depending on the sensor size. This in turn can enable an absolute position accuracy

of approximately 0.2mm throughout a 40m radius working envelope. This is significantly better than the 0.1 or 0.01 degree that the currently available laser tracking systems are able to achieve. This is important as the further the end effector is from the position where a tracking target is mounted, the greater the end effector positional error due to orientation measurement error.

[0092] Furthermore, measurements of this degree of accuracy can be provided at at least 1kHz as the roll measurements can be read at the cyclic rate of the controller which may have a 1ms clock cycle for example. Very accurate and continuous roll measurements with minimal latency are therefore achievable which enables real time dynamic motion compensation to be implemented. To control dynamic motion compensation of the robot end effector position and orientation on the end of a moveable boom requires fast data with low or preferably no latency (or delay). By reducing latency, the motion compensation does not have much lag and provides prompt position and orientation correction. Finally, the tracking system is also able to provide measurement data with low noise so that the motion compensation system is not subjected to vibratory noise.

[0093] A number of further features will now be described.

[0094] In one example, the sensor measures the displacement of the unidirectional light beam relative to a datum position on a surface thereof. The roll angle is then determined from the measured displacement. If only a small roll angle needs to be measured (e.g. a few degrees) then a small enough sensor (e.g. PDS) can be used to provide highly accurate measurements in order of 0.001 degree or better. However, in systems where the target may experience a significant amount of roll, a larger PDS would be required and if the PDS does not extend through 360 degrees it limits the roll angle that can be measured. If a large PDS is used, it also reduces the roll angle accuracy. However, for systems where roll is minimal, this implementation is straightforward as it does not require any moving parts that other arrangements require as will be described below.

[0095] In the example shown in Figures 1B to 1D, the unidirectional light beam 31 transmits an optical mount 37 mounted on at least one of the tracking base 11 and tracking target 13 (in this case the tracking target 13) for controlled rotation about an axis of rotation that is coaxial

with the bidirectional light beam 17, and wherein the controller is configured to control the rotation of the optical mount 37 in order to maintain linkage of the unidirectional light beam 31 transmitted between the tracking base 11 and the tracking target 13 and wherein the angle of the controlled rotation is determined by the controller and roll angle data derived therefrom.

[0096] Typically, the sensor is housed in the optical mount and wherein the sensor provides signals proportional to the location of the unidirectional light beam incident on a surface of the sensor. In Figure 1C, the tracking target 13 is shown in a nominally upright position in which the optical mount 37 is disposed centrally with respect to curved surface 39 of a tracking head unit 57 about which the optical mount 37 rotates. This position is indicative of zero roll angle. In Figure 1D, the tracking target 13 is shown having a roll angle α . It can be seen that as the tracking target 13 rolls (e.g. due to the object it is mounted on undergoing roll) the optical mount 37 rotates in the opposing direction about a roll axis coincident with the bidirectional light beam 17. The optical mount 37 rotates to ensure that the unidirectional light beam 37 always remains centred on the sensor which zeros the PDS.

[0097] Typically, the controller receives the signals from the sensor, processes the signals to determine the location of the unidirectional light beam incident on the sensor surface; and, causes the optical mount to rotate about the axis of rotation in accordance with the processed signals so as to locate the unidirectional light beam on the centre of the sensor surface and maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target.

[0098] In this regard, a motor may be coupled to the optical mount and wherein the controller is configured to control the motor to rotate and align the optical mount with the unidirectional light beam.

[0099] The angle of the controlled rotation which is indicative of the roll angle may be determined in at least two ways. In one example, the angle of said controlled rotation is determined by said controller from angle encoders and roll angle data is derived therefrom. Alternatively, the angle of said controlled rotation is determined from motor control data.

Furthermore, the angle of said controlled rotation may include a correction of following error as determined by a measurement signal from the sensor.

[0100] It will be appreciated that preferably the tracking base is a laser tracker and the tracking target is an active target configured to track the tracking base so as to maintain linkage of the bidirectional light beam transmitted between the laser tracker and active target.

[0101] Typically, the tracking base includes a first head unit mounted to a first base about two axes normal to each other and wherein the tracking target includes a second head unit that is mounted to a second base about two axes normal to each other, wherein rotation about the two axes in both head units is controlled by a head unit controller to rotate about their respective said two axes to maintain the linkage of said bidirectional light beam. The ability for the second head unit to rotate about its axes to follow the first head unit enables for example the active target to determine its own yaw and pitch.

[0102] In one example, the first head unit is mounted to a first gimbal about a first gimbal axis extending normally to the direction of the bidirectional light beam, the first gimbal being mounted to the first base about a first base axis extending normally to the first gimbal axis; and the second head unit is mounted to a second gimbal about a second gimbal axis extending normally to the direction of the bidirectional light beam, the second gimbal being mounted to the second base about a second base axis extending normally to said second gimbal axis. Whilst a gimbal system may be used, in practice any suitable pivoting mount may be used to mount the respective head units of the tracking base and tracking target.

[0103] A number of different permutations of the tracking system are envisaged.

[0104] In one arrangement, a unidirectional light beam source is located in the tracking base to produce said unidirectional light beam, and said optical mount is located on the tracking target, the optical mount further including the sensor to detect the unidirectional light beam.

[0105] In another arrangement, a unidirectional light beam source is located in the tracking target to produce the unidirectional light beam, and said optical mount is located on the

tracking base, the optical mount further including the sensor to detect the unidirectional light beam.

[0106] In a further arrangement, a unidirectional light beam source is located in the optical mount to produce the unidirectional light beam and the optical mount is located on the tracking target, and the tracking base includes the sensor to detect the unidirectional light beam.

[0107] In yet a further arrangement, a unidirectional light beam source is located in the optical mount to produce the unidirectional light beam and the optical mount is located on the tracking base, and the tracking target includes the sensor to detect the unidirectional light beam. From the above, it will be appreciated therefore the unidirectional light beam source (i.e. roll beam laser) may be located in either the tracking base or tracking target and likewise for the optical mount and sensor.

[0108] The optical mount may be arranged in a number of ways as well. It may be housing configured to rotate about a curved surface of one of the head units or alternatively the optical mount may be located on an annular member arranged for controlled rotation about a transmission axis of the bidirectional light beam.

[0109] In another broad form, the present invention provides a method of tracking the position and orientation of an object in an environment using a tracking system including: a tracking base positioned in the environment; a tracking target mountable to the object, wherein in use the tracking base is linked to the tracking target by: a bidirectional light beam transmitted therebetween; and, a unidirectional light beam transmitted therebetween, said unidirectional light beam parallel to the bidirectional light beam; and, wherein the method includes in at least one controller: receiving signals from a sensor housed in at least one of the tracking base and the tracking target that detects the unidirectional light beam; and, determining a roll angle of the tracking target relative to the tracking base at least in part using the received signals.

[0110] In one example, the method further includes in the at least one controller: determining a displacement of the unidirectional light beam relative to a datum position on a surface of

the sensor using the received signals; and, determining a roll angle using the determined displacement.

[0111] In another example, the tracking system includes an optical mount through which the unidirectional light beam transits, the optical mount mounted on at least one of the tracking base and tracking target, the optical mount housing the sensor and configured for controlled rotation about an axis of rotation that is coaxial with the bidirectional light beam, and wherein the method further includes in the at least one controller: processing the signals received from the sensor to determine the location of the unidirectional light beam incident on the sensor surface; and, causing the optical mount to rotate about the axis of rotation in accordance with the processed signal so as to locate the unidirectional light beam on the centre of the sensor surface and maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target.

[0112] Preferred embodiments of the invention will now be described in further detail. All of the embodiments are improved position and orientation measurement apparatus having a first head unit in the form of a laser tracker 11 and a second head unit in the form of an active target sensor 13, incorporating improved roll angle measuring. The laser tracker 11 has a primary laser 15 which generates a primary laser beam 17 which is reflected back by the active target sensor 13, forming the bidirectional laser beam. Referring to Figure 3, the laser tracker 11 includes a single beam interferometer 19 and mirror 21 reflecting part of the primary laser beam 17 to a fringe counter 23, from which range data is acquired. A 50% beam splitter 25 sends part of the primary laser beam 17 to a dual axis lateral effect photodiode or dual axis position displacement sensor 27 to derive data for “steering” the laser tracker primary laser beam 17, in order to accurately aim at the active target sensor 13.

[0113] The laser tracker 11 also has a second laser 29 arranged to send a unidirectional second laser beam 31 in parallel with the primary laser beam 17, to a roll position displacement sensor 33 located on the active target sensor 13. In the first embodiment, the roll position displacement sensor 33 comprises a position displacement sensor 35 located within a housing 37 mounted on a curved surface 39 for rotation so that the position displacement sensor 35 rotates with the primary laser beam 17. The housing 37 mounted on

a curved surface 39 rotates about the same axis as the line of travel of the primary laser beam 17 (i.e. transmission or roll axis), when correctly aligned to be reflected back by the active target sensor 13. The curved surface denotes a surface about which rotation of the housing 37 through 120 degrees occurs, about the transmission axis, making this embodiment suitable for use in applications where roll sensing is limited to plus or minus 60 degrees from the central position of the housing 37. An angle encoder produces a signal to indicate the angle at which the housing 37 is disposed, thus providing roll angle measurement of the active target sensor 13.

[0114] The laser tracker 11 is supported on a yoke 41 that rotates on a support 43 about a substantially vertical heading axis 45. The yoke 41 rotatably supports a head 47 that rotates about a horizontal altitude axis 49. The head 47 contains the primary laser 15, the single beam interferometer 19 and mirror 21, the fringe counter 23, the 50% beam splitter 25, and the sensor 27, and supports the second laser 29.

[0115] The laser tracker primary beam optics include the primary laser 15, and the single beam interferometer 19 and fringe counter 23, but as an alternative to the single beam interferometer 19 and fringe counter 23, may include a time of flight ADM (automated distance measurer), or a combination of both. The laser tracker primary beam optics also include the 50% beam splitter 25 and the sensor 27, which as discussed above can be selected from a dual axis PDS (position displacement sensor) or a dual axis lateral effect photo diode, but as a further alternative may utilise a CCD or CMOS sensor array with associated circuitry. Data derived from the sensor is processed and used to control brushless AC servo motors 50 to move the yoke 41 relative to the support 43, and to move the head 47 relative to the yoke 41. Angle encoders associated with the servo motors 50 measure the angle of rotation and this data is used to provide attitude and heading data, additional to the distance data determined from analysis of the fringe counter 23 data which then enables the position of the target to be determined. While brushless AC servo motors 50 are most preferred, alternative embodiments may utilise DC servo motors or stepper motors or other suitable drive motors.

[0116] An alternative embodiment of laser tracker 11 is illustrated in Figure 2. This differs from the laser tracker shown in Figure 1B only in the more compact shape and configuration of the yoke 41 and head 47.

[0117] In both arrangements of laser tracker 11, the roll laser 29 is provided with calibration means to align its beam 31 to be parallel to the primary laser beam 17, which would be a setting that is adjusted during manufacture, but would not be expected to be adjusted in field.

[0118] Referring back to Figure 1B, the active target sensor 13 has a base 51 that is mounted to the target object which is to be tracked (e.g. robot base 111 shown in Figure 1A). The base 51 rotatably supports a yoke 53 that rotates about a first axis 55. The yoke 53 has a clevis that supports a head 57 for rotation about a second axis 59, normal to the first axis 55. The head 57 has the curved surface 39 located on the top thereof.

[0119] The head 57 supports internal equipment to sense the primary laser beam 17. Details of two different embodiments of this are shown in Figures 5 and 7. Referring to Figure 5, in one arrangement, typically this can include a mirror 61 with a pin hole 63, behind which is located a dual axis position displacement sensor 65. The mirror 61 can reflect most of the primary laser beam 17 back to the laser tracker 11, while some of the primary laser beam 17 passes through the pin hole 63 to reach the dual axis position displacement sensor 65. Signals from the position displacement sensor 65 are fed to a controller 66 which controls brushless AC servo motors controlling the positioning of the yoke 53 and the positioning of the head 57 so that the mirror 61 is aligned to reflect the primary laser beam 17 back to the laser tracker 11.

[0120] An embodiment of the active target sensor 13 is shown in Figures 4 and 5. The active target sensor 13 has base 51 that is mounted to the target object which is to be tracked (not shown). The base 51 rotatably supports yoke 53 that rotates about first axis 55. The yoke 53 has a clevis that supports the head 57 for rotation about second axis 59, normal to the first axis 55. The primary laser beam 17 passes through a window 71 to reach the internal equipment to sense and reflect it, comprising the mirror 61 with pin hole 63, behind which is located a dual axis position displacement sensor 65, shown in figure 5. The window 71 is mounted on the exposed end of a cylindrical housing 73 about which is mounted for

controlled rotation an annular housing 75 with a window 77 for the unidirectional second laser beam 31 to pass to reach the position displacement sensor 35. An annular servo motor 79 rolls the annular housing 75 about the cylindrical housing 73 under feedback control of the position displacement sensor 35 accurately locating the unidirectional second laser beam 31. The annular servo motor is of a brushless outrunner configuration (a well known configuration used in CD drive motors and in brushless electric motors used in model cars and model aircraft amongst other applications) and comprises an even number of permanent magnets 81 arranged in alternating pole fashion (i.e. starting with a magnet arranged with N pole to the inner and S pole to the outer, then the adjacent magnet S to the inner and N to the outer and so on) attached to and extending around the inside of the annular housing 75 (which is preferably ferro magnetic and constructed from steel), and a plurality (in multiples of three) of electromagnet coils 83 shown schematically as coils 85 wound around soft iron or silicon steel laminations 87. A typical annular servo motor in this application might have 18 permanent magnets and nine electromagnet coils arranged as three groups of three coils. An angle encoder 89 comprising an encoder ring 91 mounted on the back of the annular housing 75 and an encoder read head 93 mounted on a support 95, provides accurate roll angle data back to the controller 66.

[0121] The controller 66 uses the signal from the position displacement sensor 35 as a feedback signal to control movement of the servo motor 79 to roll the annular housing 75 about its roll axis, to zero the signal from the position displacement sensor 35. The angle encoder 89 associated with the annular housing 75 provides the roll angle measurement back to the controller 66. In its simplest form the roll axis speed is proportional to the position displacement sensor 35 signal so that as the value from the position displacement sensor 35 increases, the speed of the roll axis is increased in proportion to a proportional gain applied to the feedback so as to move the roll axis and the position displacement sensor 35 toward its zero position. In more sophisticated forms of the feedback control, differential gains and integral gains may be applied within the control loop in order to minimise following error.

[0122] The roll angle measurement may be made more accurate by adding to the angle encoder angle a following error correction based on the measurement from the position displacement sensor 35. The position displacement sensor 35 may be calibrated by rotating

the position displacement sensor 35 about the roll axis and relating the position displacement sensor 35 signal to the encoder angle. Calibration is normally carried out during manufacture or in a lab and not in field conditions.

[0123] The arrangements of the active target sensor 13 shown in Figures 1, 4 and 5 can be difficult to implement in practice because it is necessary to simultaneously align both the laser tracker 11 and the active target sensor 13. The laser tracker 11 must point the bidirectional beam 17 at the mirror 61 which must be aligned to reflect the bidirectional beam 17 back to the laser tracker 11. This makes set up difficult. Optional video cameras (not shown) may be fitted to the laser tracker 11 or active target sensor 13 to assist with set up alignment. These video cameras may be connected to computer vision processors to automatically recognise and align the laser tracker 17 to the active target sensor 13 and vice versa. An alternative which is easier to set up entails replacing the mirror 61 with a retro reflector as shown in the embodiment illustrated in Figures 6 and 7.

[0124] Referring to Figure 6, another embodiment of the position and orientation tracking system is shown. The position and orientation tracking system has a first head unit in the form of laser tracker 11 and a second head unit in the form of active target sensor 13. This embodiment differs from the previous embodiments in that the roll angle measurement is incorporated in the laser tracker 11.

[0125] The laser tracker 11 has a primary laser 15 which generates a primary laser beam 17 which is reflected back by the active target sensor 13, forming the bidirectional laser beam. The internal arrangements for the primary laser beam 17 are the same as in the first and second embodiments, as illustrated in Figure 3. However, the second laser 29 arranged to send a unidirectional second laser beam 31 in parallel with the primary laser beam 17, is mounted in an annular housing 97 which is mounted for rotation by a brushless AC servo motor. The annular housing 97 has an associated angle encoder 89 to send roll angle data to the controller 66. The second laser beam 31 is transmitted to the roll position displacement sensor 33 located in the active target sensor 13. The annular housing 97 must be rotated to the correct angle for the roll position displacement sensor 33 to detect the second laser beam

31, once the primary laser beam 17 is locked by the laser tracker 11 and the active target sensor 13.

[0126] The angle encoder 89 associated with the annular housing 97 produces a signal to indicate the angle at which the annular housing 81 is disposed, thus providing roll angle measurement of the active target sensor 13.

[0127] The laser tracker 11 is supported on a yoke 41 that rotates on a support 43 about a substantially vertical heading axis 45. The yoke 41 rotatably supports a head 47 that rotates about a horizontal altitude axis 49. The head 47 contains the primary laser 15, the single beam interferometer 19 and mirror 21, the fringe counter 23, the 50% beam splitter 25, and the sensor 27, and supports the second laser 29 in the annular housing 97.

[0128] The active target sensor 13 has an alternative arrangement for sensing the primary laser beam 17 which includes a pin hole retro reflector 99 with a dual axis position displacement sensor 101 located behind. In an alternative embodiment, the pin hole retro reflector 99 may be replaced with a pentaprism.

[0129] Signals from the position displacement sensor 101 are fed to the controller 66 which controls stepper motors controlling the positioning of the yoke 53 and the positioning of the head 57 so that the retro reflector 99 is aligned to reflect the primary laser beam 17 back to the laser tracker 11. Data derived from the sensor 27 is processed by the controller 66 and used to control brushless AC servo motors 50 or DC servo motors or stepper motors or other suitable drive motors to move the yoke 41 relative to the support 43, and to move the head 47 relative to the yoke 41. Angle encoders associated with the servo motors 50 measure the angle of rotation and this data is used to provide attitude and heading data, additional to the distance data determined from analysis of the fringe counter 23 data. The positioning of the yoke 53 and the positioning of the head 57 is orientated to point back to the laser tracker 11 by zeroing the beam 17 on the position displacement sensor 101, and data from angle encoders provide pitch and yaw data for the head 57 back to the controller 66. The alignment of the pointing direction, relative to the alignment of the position displacement sensor 101 and the pin hole in the retro reflector 87 is calibrated during manufacture and is not normally field adjusted. The bidirectional laser beam 17 is reflected by the retro reflector 99 back to

the laser tracker 11. This alternative arrangement shown in Figure 7 has the advantage that the laser tracker 11 can be easily aligned to track the retro reflector 99 before the head 57 is oriented to point precisely back to the laser tracker 11. The angle of the head 57 relative to the beams 17 and 31 shown in Figure 7, is shown in position once the primary laser beam 17 has found the position displacement sensor 101, and prior to the head 57 being aligned by the stepper motors controlling the positioning of the yoke 53 and the positioning of the head 57 so that the retro reflector 99 is exactly aligned to reflect the primary laser beam 17 back to the laser tracker 11, with the primary laser beam 17 incident on the position displacement sensor 89 at exact right angles and at its exact central position.

[0130] Optional video cameras (not shown) may be fitted to the laser tracker 11 or active target sensor 13 to assist with the initial set up alignment. These cameras may be connected to computer vision processors to automatically recognise and align the laser tracker 17 to the active target sensor 13 and vice versa.

[0131] Laser position displacement sensors are commercially available (e.g. from Hamar), or as discrete optical components and silicon chips (e.g. from On-Trak Photonics). The position displacement sensors 33, 35 are provided with means to adjust their detection radius from the primary beam axis to exactly match the distance (or radius) R of the roll axis laser from the primary beam laser.

[0132] Referring now to Figure 8, a method of tracking the position and orientation of an object in an environment shall now be described.

[0133] In this example, at step 200 the method includes transmitting a bidirectional light beam between a tracking base and a tracking target. Typically, the tracking base includes the bidirectional light beam source which emits the light beam towards the target, which reflects the beam back towards the tracking base. Both the tracking base and tracking target include actuators to steer the beam and typically a mirror located in the target to maintain bidirectional light beam linkage between the base and target.

[0134] A step 210, the method includes transmitting a unidirectional light beam between the tracking base and target. Typically, the tracking base includes the unidirectional light beam

source which emits the unidirectional light beam towards the target, ensuring that the unidirectional light beam is parallel to the bidirectional light beam. The unidirectional light beam is incident upon a sensor (e.g. a position displacement sensor) housed in the target (or base if the unidirectional beam source is located in the target).

[0135] At step 220, at least one controller receives signals from the sensor that detects the unidirectional light beam. The sensor provides a signal proportional to the location of the unidirectional light beam incident on a surface of the sensor. When the light beam is incident on the centre of the sensor, the PDS will be zeroed.

[0136] Finally, at step 230 the at least one controller determines the roll angle at least in part using the received signals. In this regard, the signals may be directly indicative of the roll angle, such as the case when the sensor measures the displacement of the unidirectional light beam relative to a datum position on a surface thereof and the roll angle is determined from the measured displacement. In another example, the signals are used as feedback to controllably rotate an optical housing in which the sensor is disposed which rotates in order to zero the PDS as the target rolls. The roll angle is then determined from the amount of controlled rotation of the optical mount.

[0137] Accordingly, in at least one of the above described examples a tracking system that provides advantages for the dynamic measurement and control of industrial and construction robots, particularly those with active or dynamic motion compensation and stabilisation is provided. The tracking system provides accurate real time roll angle measurement of an active target sensor, overcoming the shortfalls of the prior art and enabling roll angle to be measured with an accuracy of at least 0.001 degrees at 1kHz which assists in achieving an absolute position accuracy of a robotic end effector of at least 0.2mm throughout a 40m radius working envelope. Roll angle measurement can be provided continuously and with minimal latency therefore making the tracking system suitable for robotic systems where dynamic motion compensation is required.

[0138] Further details of the applicants technology are described in patent publications and co-pending applications US8166727, PCT/AU2008/001274, PCT/AU2008/001275, PCT/AU2017/050731, PCT/AU2017/050730, PCT/AU2017/050728, PCT/AU2017/050739,

PCT/AU2017/050738, PCT/AU2018/050698, AU2017902625, AU2017903310, AU2017903312, AU2017904002, AU2017904110, PCT/AU2018/050698, AU2018902566, AU2018902557, PCT/AU2018/050733, PCT/AU2018/050734, PCT/AU2018/050740, PCT/AU2018/050737 and PCT/AU2018/050739, the contents of which are incorporated herein by cross reference.

[0139] Throughout this specification and claims which follow, unless the context requires otherwise, the word “comprise”, and variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated integer or group of integers or steps but not the exclusion of any other integer or group of integers.

[0140] Persons skilled in the art will appreciate that numerous variations and modifications will become apparent. All such variations and modifications which become apparent to persons skilled in the art, should be considered to fall within the spirit and scope that the invention broadly appearing before described.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

- 1) A tracking system for tracking the position and orientation of an object in an environment, the tracking system including:
 - a) a tracking base positioned in the environment;
 - b) a tracking target mountable to the object, wherein in use the tracking base is linked to the tracking target by:
 - i) a bidirectional light beam transmitted therebetween; and,
 - ii) a unidirectional light beam transmitted therebetween, said unidirectional light beam parallel to the bidirectional light beam; and,
 - c) at least one controller configured to determine a roll angle of the tracking target relative to the tracking base, the roll angle determined at least in part by signals received from a sensor housed in at least one of the tracking base and the tracking target that detects the unidirectional light beam.
- 2) A tracking system according to claim 1, wherein the sensor measures the displacement of the unidirectional light beam relative to a datum position on a surface thereof.
- 3) A tracking system according to claim 2, wherein the roll angle is determined from the measured displacement.
- 4) A tracking system according to claim 1, wherein the unidirectional light beam transits an optical mount mounted on at least one of the tracking base and tracking target for controlled rotation about an axis of rotation that is coaxial with the bidirectional light beam, and wherein the controller is configured to control the rotation of the optical mount in order to maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target, and wherein the angle of the controlled rotation is determined by the controller and roll angle data derived therefrom.
- 5) A tracking system according to claim 4, wherein the sensor is housed in the optical mount, and wherein the sensor provides signals proportional to the location of the unidirectional light beam incident on a surface of the sensor.
- 6) A tracking system according to claim 5, wherein the controller:
 - a) receives the signals from the sensor;

- b) processes the signals to determine the location of the unidirectional light beam on the sensor surface; and,
 - c) causes the optical mount to rotate about the axis of rotation in accordance with the processed signals so as to locate the unidirectional light beam on the centre of the sensor surface and maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target.
- 7) A tracking system according to claim 6, wherein a motor is coupled to the optical mount, and wherein the controller is configured to control the motor to rotate and align the optical mount with the unidirectional light beam.
- 8) A tracking system according to any one of claims 4 to 7, wherein the angle of said controlled rotation is determined by said controller from angle encoders and roll angle data is derived therefrom.
- 9) A tracking system according to claim 8, wherein the angle of said controlled rotation includes a correction of following error as determined by a measurement signal from the sensor.
- 10) A tracking system according to claim 7, wherein the angle of said controlled rotation is determined from motor control data.
- 11) A tracking system according to any one of claims 4 to 10, wherein the optical mount is located on an annular member arranged for controlled rotation about the axis of rotation.
- 12) A tracking system according to any one of claims 4 to 11, wherein a unidirectional light beam source is located in the tracking base to produce said unidirectional light beam, and said optical mount is located on the tracking target, the optical mount further including the sensor to detect the unidirectional light beam.
- 13) A tracking system according to any one of claims 4 to 11, wherein a unidirectional light beam source is located in the tracking target to produce the unidirectional light beam, and said optical mount is located on the tracking base, the optical mount further including the sensor to detect the unidirectional light beam.
- 14) A tracking system according to any one of claims 4 to 11, wherein a unidirectional light beam source is located in the optical mount to produce the unidirectional light beam and the optical mount is located on the tracking target, and the tracking base includes the sensor to detect the unidirectional light beam.

- 15) A tracking system according to any one of claims 4 to 11, wherein a unidirectional light beam source is located in the optical mount to produce the unidirectional light beam and the optical mount is located on the tracking base, and the tracking target includes the sensor to detect the unidirectional light beam.
- 16) A tracking system according to any one of the preceding claims, wherein the tracking base is a laser tracker and the tracking target is an active target configured to track the tracking base so as to maintain linkage of the bidirectional light beam transmitted between the laser tracker and active target.
- 17) A tracking system according to any one of the preceding claims, wherein the tracking base includes a first head unit mounted to a first base about two axes normal to each other, and wherein the tracking target includes a second head unit that is mounted to a second base about two axes normal to each other, and wherein rotation about the two axes in both head units is controlled by a head unit controller to rotate about their respective said two axes to maintain the linkage of said bidirectional light beam.
- 18) A tracking system according to claim 17, wherein the first head unit is mounted to a first gimbal about a first gimbal axis extending normally to the direction of the bidirectional light beam, the first gimbal being mounted to the first base about a first base axis extending normally to the first gimbal axis, and the second head unit is mounted to a second gimbal about a second gimbal axis extending normally to the direction of the bidirectional light beam, the second gimbal being mounted to the second base about a second base axis extending normally to said second gimbal axis.
- 19) A tracking system according to any one of the preceding claims, wherein the sensor is a position displacement sensor (PDS).
- 20) A method of tracking the position and orientation of an object in an environment using a tracking system including:
 - a) a tracking base positioned in the environment;
 - b) a tracking target mountable to the object, wherein in use the tracking base is linked to the tracking target by:
 - i) a bidirectional light beam transmitted therebetween; and,

- ii) a unidirectional light beam transmitted therebetween, said unidirectional light beam parallel to the bidirectional light beam; and, wherein the method includes in at least one controller:
 - (1) receiving signals from a sensor housed in at least one of the tracking base and the tracking target that detects the unidirectional light beam; and,
 - (2) determining a roll angle of the tracking target relative to the tracking base at least in part using the received signals.
- 21) A method according to claim 20, wherein the method includes in the at least one controller:
 - a) determining a displacement of the unidirectional light beam relative to a datum position on a surface of the sensor using the received signals; and,
 - b) determining a roll angle using the determined displacement.
- 22) A method according to claim 20, wherein the tracking system includes an optical mount through which the unidirectional light beam transits, the optical mount mounted on at least one of the tracking base and tracking target, the optical mount housing the sensor and configured for controlled rotation about an axis of rotation that is coaxial with the bidirectional light beam, and wherein the method further includes in the at least one controller:
 - a) processing the signals received from the sensor to determine the location of the unidirectional light beam incident on the sensor surface; and,
 - b) causing the optical mount to rotate about the axis of rotation in accordance with the processed signal so as to locate the unidirectional light beam on the centre of the sensor surface and maintain linkage of the unidirectional light beam transmitted between the tracking base and the tracking target.

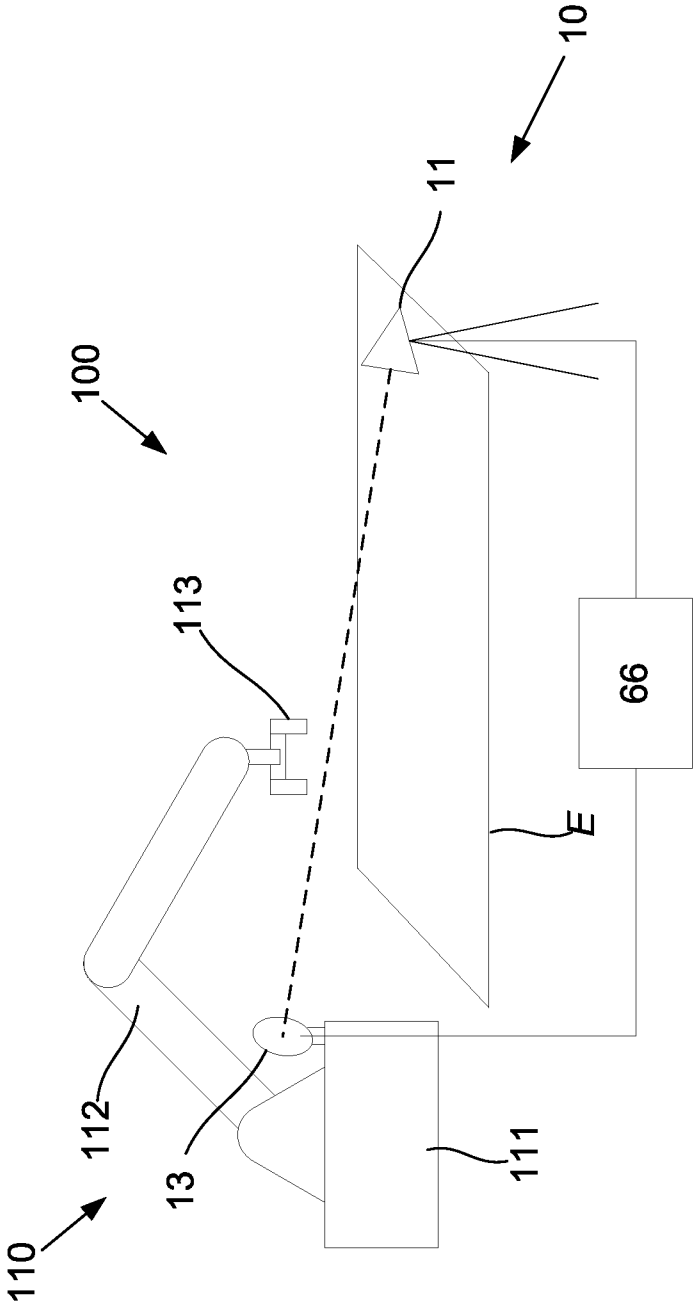


Fig. 1A

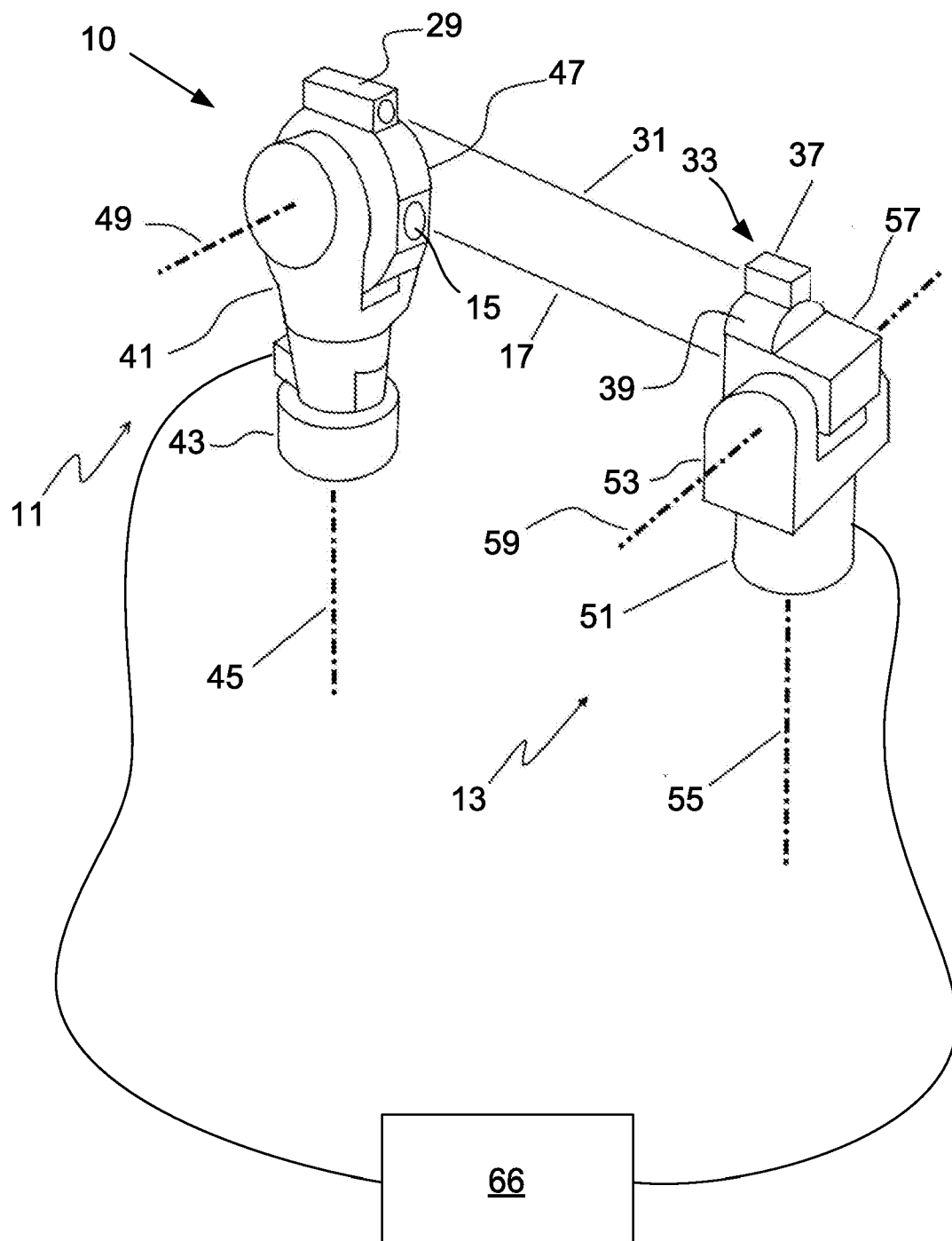


FIG. 1B

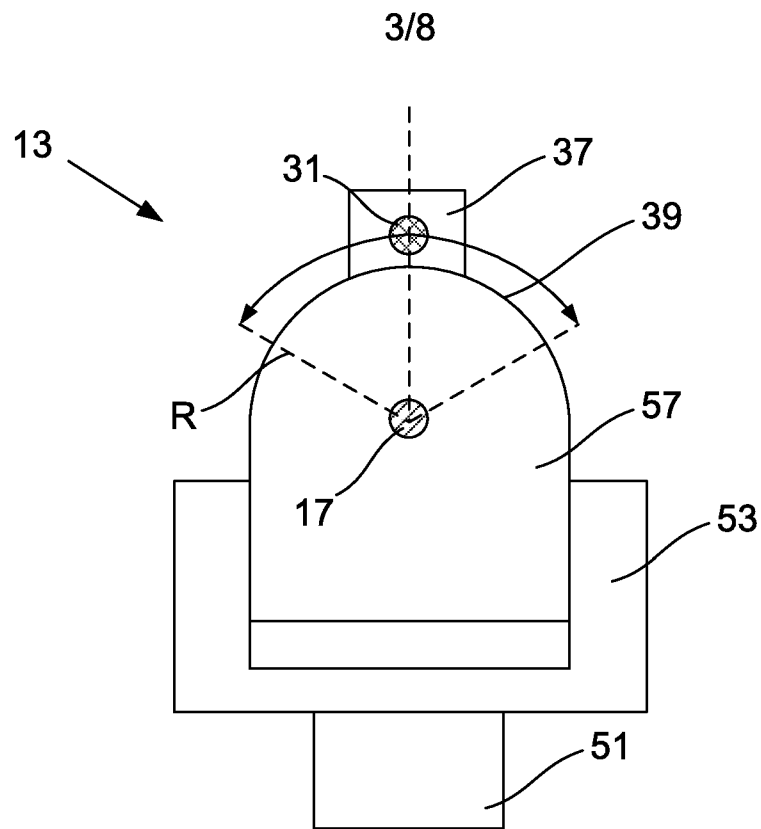


FIG. 1C

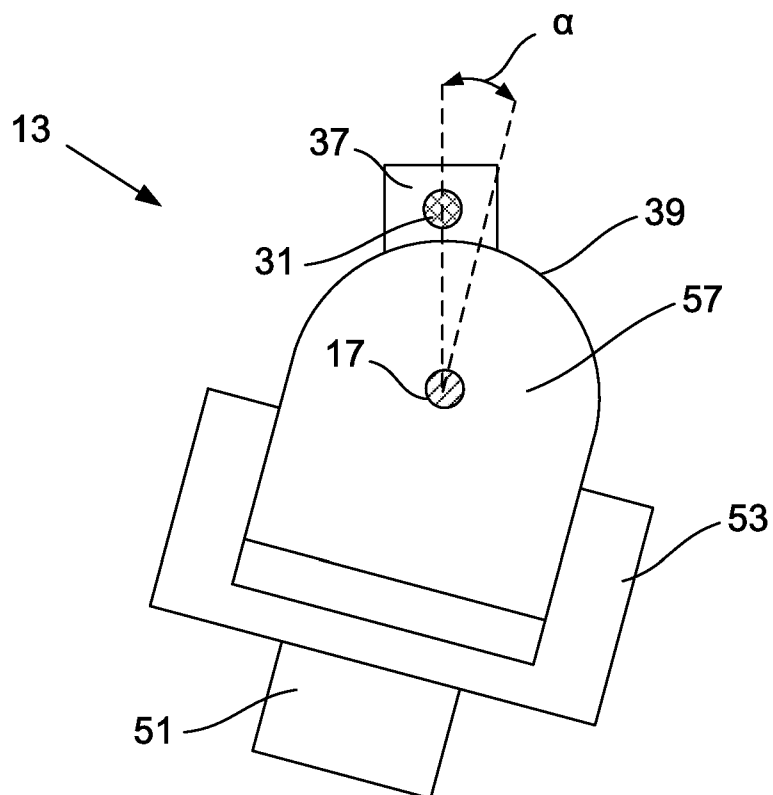


FIG. 1D

4/8

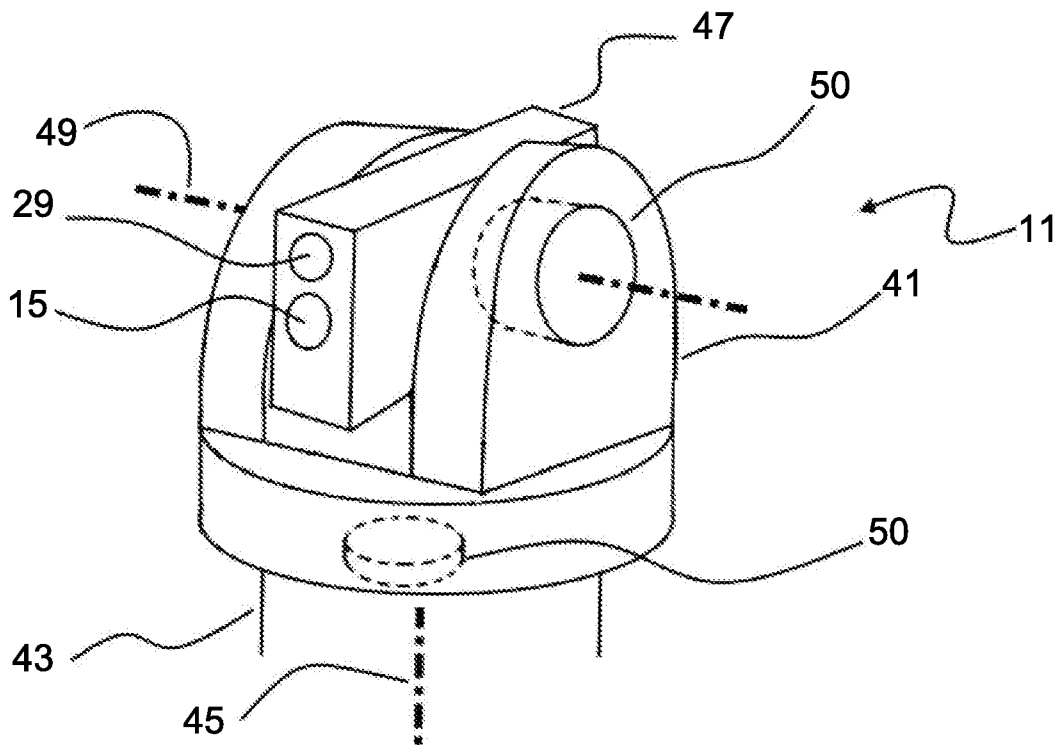


FIG. 2

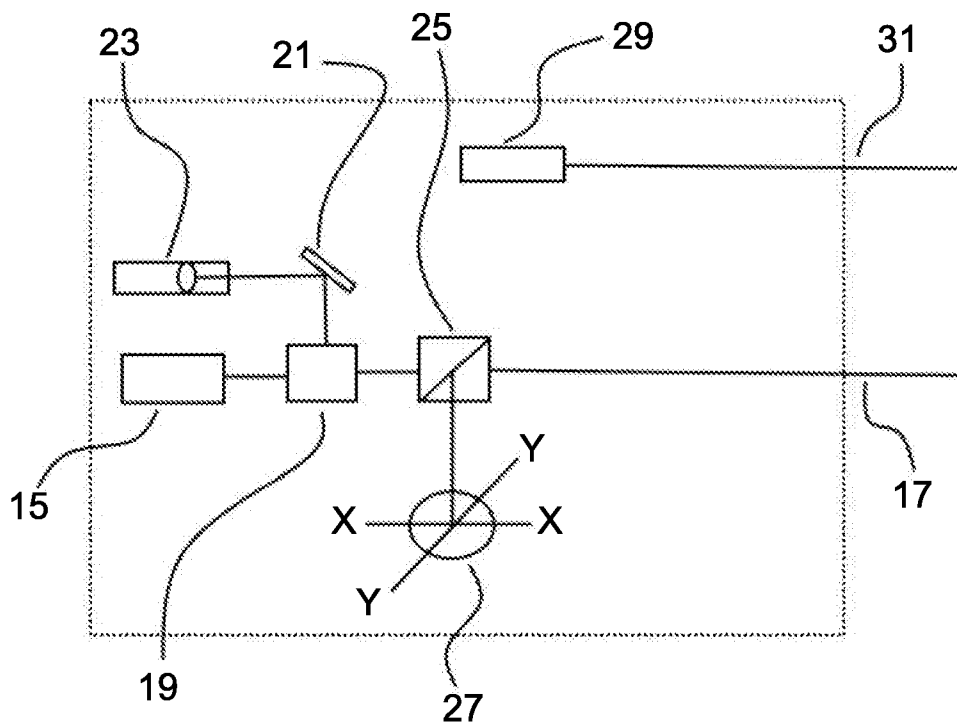


FIG. 3

5/8

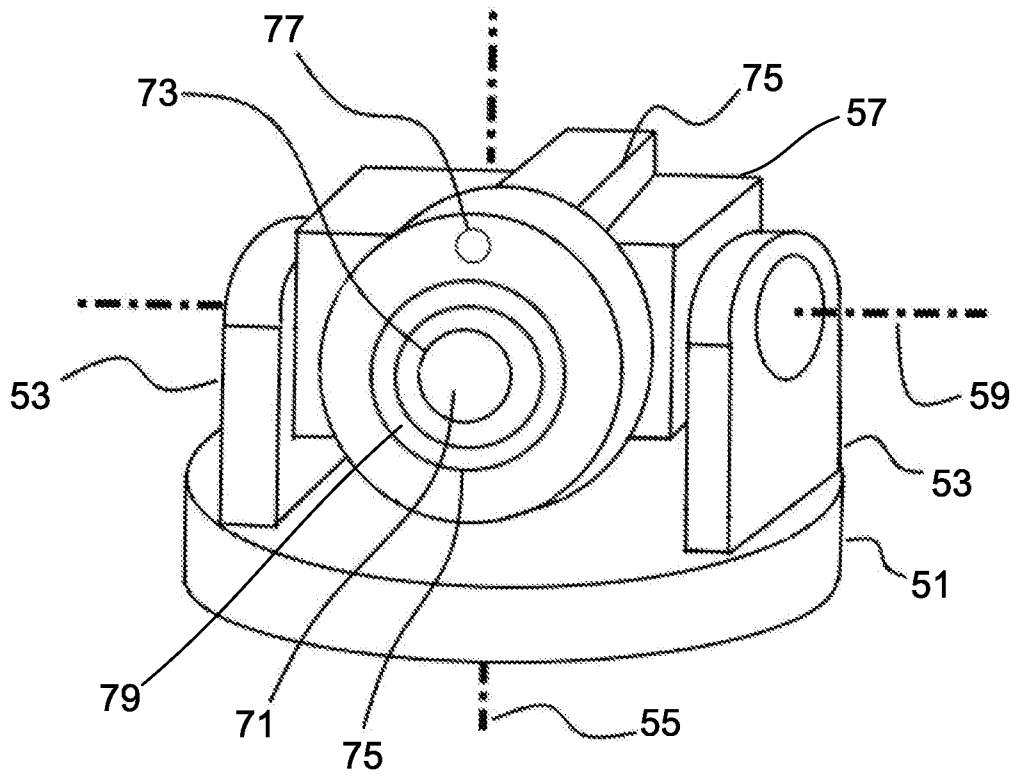


FIG. 4

6/8

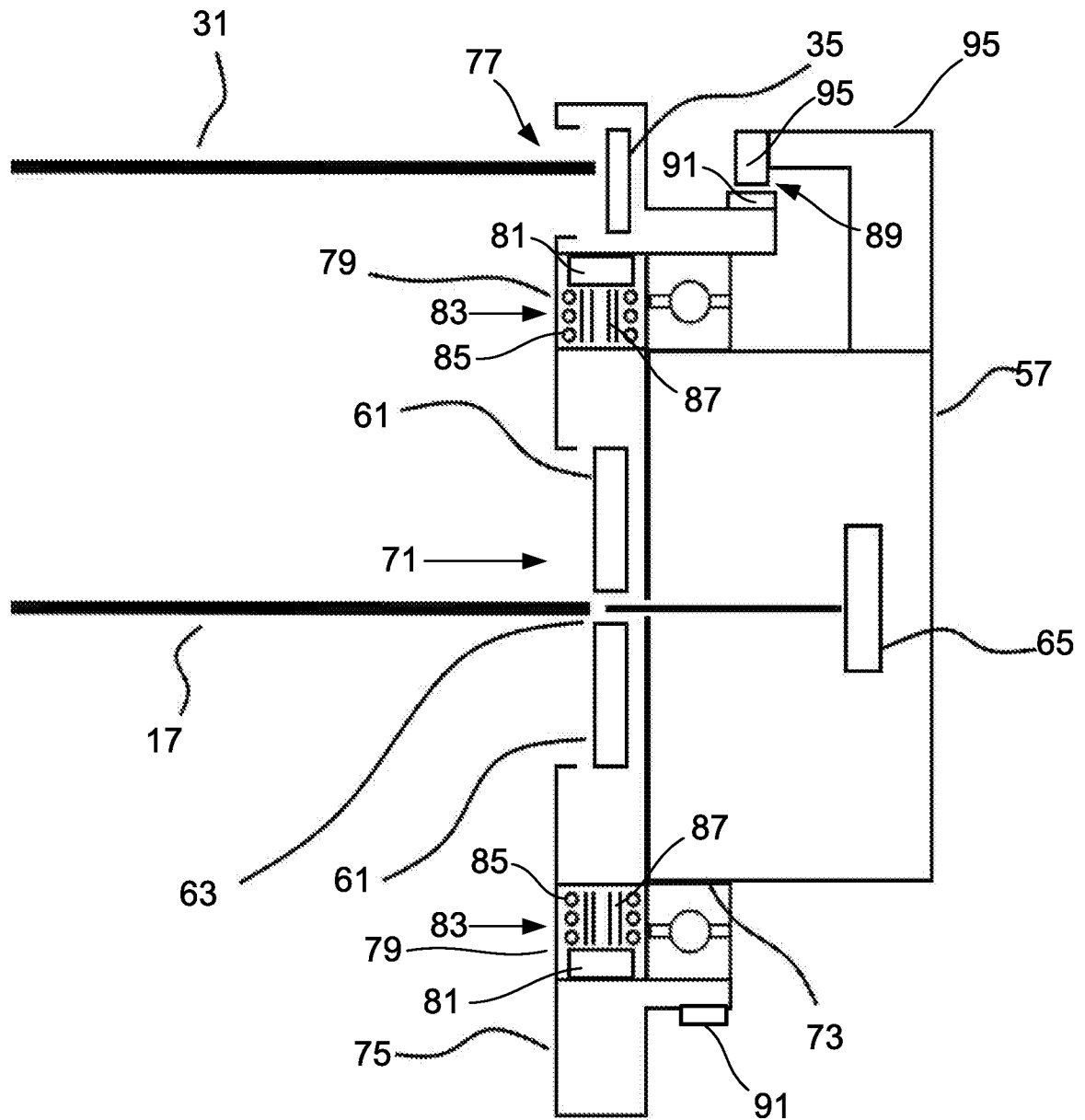


FIG. 5

7/8

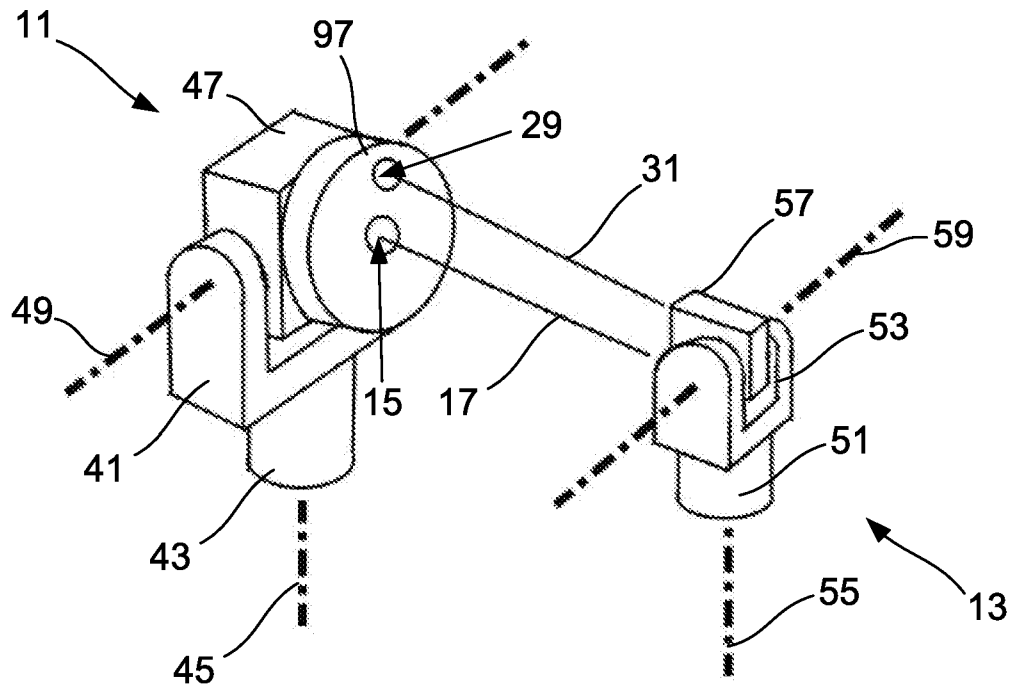


FIG. 6

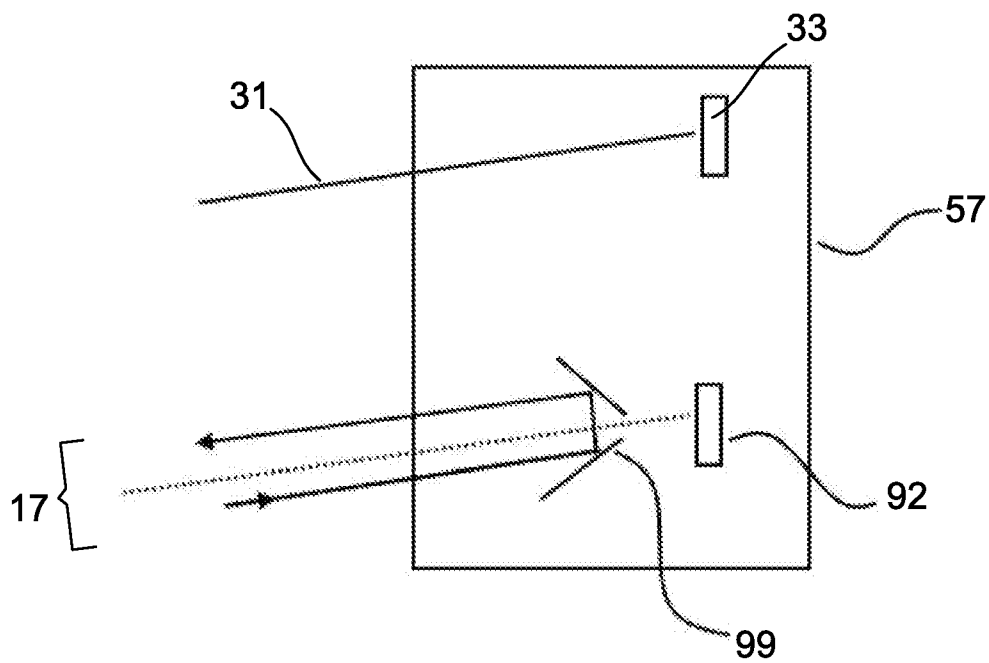
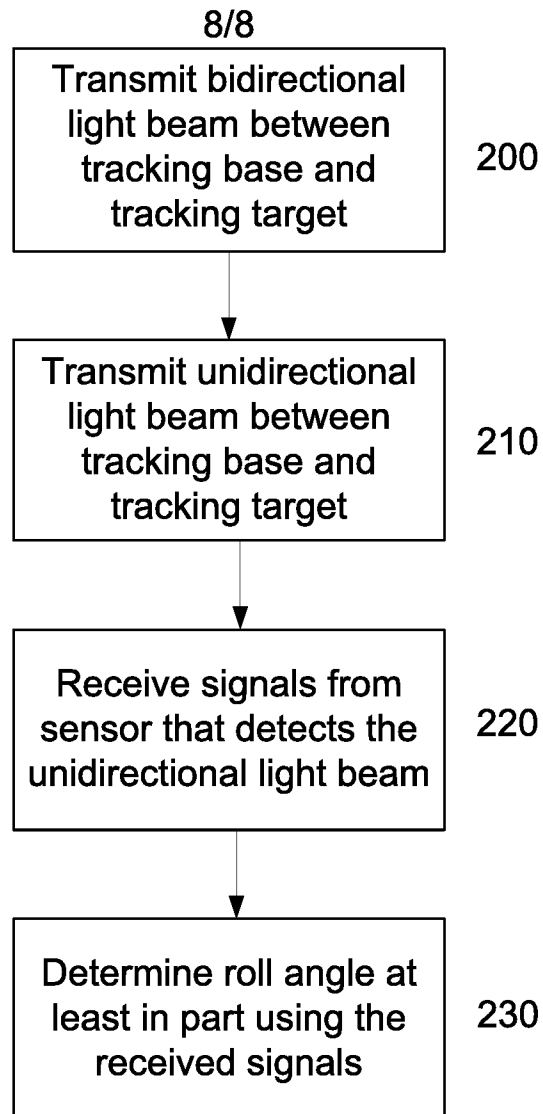


FIG. 7

**FIG. 8**

INTERNATIONAL SEARCH REPORT

 International application No.
PCT/AU2018/050873

A. CLASSIFICATION OF SUBJECT MATTER

G01B 11/26 (2006.01) B25J 13/08 (2006.01) G01B 9/02 (2006.01) G01S 17/66 (2006.01) G01S 17/42 (2006.01)

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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

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

Databases: PATENW = (EPODOC, WPIAP, Full text)

Keywords: laser, tracking, orientation, position, roll, multiple degrees of freedom, parallel, beam, roll angle, bidirectional, unidirectional, position displacement and similar terms, IPC/CPC marks: G01B11, B25J, G01S17, G01C21

Databases: Google, Google Patents, Google Scholar, Espacenet

Keywords: roll angle, laser tracking, 6DOF, Orientation, parallel, beam, bidirectional, unidirectional, position sensitive and like terms, IPC/CPC marks in Espacenet: G01B11/26, B25J13/089, G01S17/66, G01S17/42, G01B9/02, G01C3/00, G01C22/00

Applicant(s)/Inventor(s) name search in Google Patents, Espacenet and Auspat: Keywords: Fastbrick, Mark Pivac

Applicant(s)/Inventor(s) name searched in internal databases provided by IP Australia

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 29 October 2018	Date of mailing of the international search report 29 October 2018
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au	Authorised officer Susan Bellm AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. +61262832751

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2018/050873
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013/0250285 A1 (FARO Technologies, Inc.) 26 September 2013 abstract; figure 1, figure 4; paragraphs [0017], [0040], [0076], [0087]	1-3, 17-19, 20-21
X	US 2006/0215179 A1 (MCMURTRY et al.) 28 September 2006 figure 7; paragraphs [0001]-[0002], [0031], [0051], [0056], [0060], [0124]-[0125], [0127]-[0128]	1-22
<div>Form PCT/ISA/210 (fifth sheet) (January 2015)</div>		

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 2013/0250285 A1	26 September 2013	US 2013250285 A1	26 Sep 2013
		US 8670114 B2	11 Mar 2014
		BR 112013020380 A2	06 Jun 2017
		CA 2826229 A1	16 Aug 2012
		CN 101995577 A	30 Mar 2011
		CN 102216803 A	12 Oct 2011
		CN 102906594 A	30 Jan 2013
		CN 102906594 B	08 Apr 2015
		CN 103380350 A	30 Oct 2013
		CN 103403575 A	20 Nov 2013
		CN 103403575 B	16 Sep 2015
		CN 103459601 A	18 Dec 2013
		CN 103477184 A	25 Dec 2013
		CN 103477188 A	25 Dec 2013
		CN 103477245 A	25 Dec 2013
		CN 103492870 A	01 Jan 2014
		CN 103492870 B	25 Nov 2015
		CN 103502842 A	08 Jan 2014
		CN 103608642 A	26 Feb 2014
		CN 103608642 B	24 Feb 2016
		CN 103649673 A	19 Mar 2014
		CN 103649676 A	19 Mar 2014
		CN 103688132 A	26 Mar 2014
		CN 103698769 A	02 Apr 2014
		CN 103703363 A	02 Apr 2014
		CN 103703389 A	02 Apr 2014
		CN 103703389 B	22 Jul 2015
		CN 103765238 A	30 Apr 2014
		CN 104094080 A	08 Oct 2014
		CN 104136880 A	05 Nov 2014
		CN 104246535 A	24 Dec 2014
		CN 104251663 A	31 Dec 2014
		CN 104251696 A	31 Dec 2014
		CN 105051488 A	11 Nov 2015
CN 105102925 A	25 Nov 2015		
CN 105102926 A	25 Nov 2015		
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		CN 105190232 A	23 Dec 2015
		DE 102010038955 A1	24 Feb 2011
		DE 102016108587 A1	24 Nov 2016
		EP 2545396 A1	16 Jan 2013
		EP 2545396 B1	12 Feb 2014
		GB 2472514 A	09 Feb 2011
		GB 2472514 B	03 Aug 2011
		GB 2477902 A	17 Aug 2011
		GB 2477902 B	18 Sep 2013
		GB 2493481 A	06 Feb 2013
		GB 2493481 B	05 Mar 2014
		GB 2498670 A	24 Jul 2013
		GB 2498670 B	23 Oct 2013
		GB 2498671 A	24 Jul 2013
		GB 2498671 B	25 Dec 2013
		GB 2502197 A	20 Nov 2013
		GB 2502197 B	01 Jan 2014
		GB 2503153 A	18 Dec 2013
		GB 2503153 B	25 Mar 2015
		GB 2503179 A	18 Dec 2013
		GB 2503179 B	18 Nov 2015
		GB 2503390 A	25 Dec 2013
		GB 2503390 B	29 Oct 2014
		GB 2504431 A	29 Jan 2014
		GB 2504431 B	27 Jan 2016
		GB 2504432 A	29 Jan 2014
		GB 2504432 B	09 Dec 2015
		GB 2504433 A	29 Jan 2014
		GB 2504639 A	05 Feb 2014
		GB 2504639 B	28 Oct 2015
		GB 2504890 A	12 Feb 2014
		GB 2504891 A	12 Feb 2014
		GB 2504891 B	20 Aug 2014
		GB 2504892 A	12 Feb 2014
		GB 2504892 B	02 Mar 2016
		GB 2505353 A	26 Feb 2014
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
Form PCT/ISA/210 (Family Annex)(January 2015)			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		GB 2505353 B	06 May 2015
		GB 2505354 A	26 Feb 2014
		GB 2505354 B	04 Nov 2015
		GB 2506535 A	02 Apr 2014
		GB 2506535 B	09 Mar 2016
		GB 2510510 A	06 Aug 2014
		GB 2510510 B	07 Oct 2015
		GB 2511236 A	27 Aug 2014
		GB 2511236 B	28 Jan 2015
		GB 2512250 A	24 Sep 2014
		GB 2512250 B	28 Jan 2015
		GB 2512554 A	01 Oct 2014
		GB 2513806 A	05 Nov 2014
		GB 2513806 B	20 Jul 2016
		GB 2515211 A	17 Dec 2014
		GB 2515211 B	22 Jul 2015
		GB 2516528 A	28 Jan 2015
		GB 2516528 B	21 Oct 2015
		GB 2518543 A	25 Mar 2015
		GB 2518544 A	25 Mar 2015
		GB 2518769 A	01 Apr 2015
		GB 2518998 A	08 Apr 2015
		GB 2524931 A	07 Oct 2015
		GB 2524931 B	27 Jan 2016
		GB 2527424 A	23 Dec 2015
		GB 2527424 B	03 Feb 2016
		GB 2527991 A	06 Jan 2016
		GB 2527991 B	15 Aug 2018
		GB 2527992 A	06 Jan 2016
		GB 2527992 B	27 Jun 2018
		GB 2527993 A	06 Jan 2016
		GB 2527993 B	27 Jun 2018
		GB 2528024 A	13 Jan 2016
		GB 2528024 B	02 Mar 2016
		GB 2534812 A	03 Aug 2016
		JP 2013534636 A	05 Sep 2013
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		JP 5398936 B2	29 Jan 2014
		JP 2011039052 A	24 Feb 2011
		JP 5401412 B2	29 Jan 2014
		JP 2013145240 A	25 Jul 2013
		JP 5544032 B2	09 Jul 2014
		JP 2013525787 A	20 Jun 2013
		JP 5544042 B2	09 Jul 2014
		JP 2014517262 A	17 Jul 2014
		JP 5554459 B2	23 Jul 2014
		JP 2014508931 A	10 Apr 2014
		JP 5599524 B2	01 Oct 2014
		JP 2014016354 A	30 Jan 2014
		JP 5615416 B2	29 Oct 2014
		JP 2014514564 A	19 Jun 2014
		JP 5723059 B2	27 May 2015
		JP 2014508293 A	03 Apr 2014
		JP 5758014 B2	05 Aug 2015
		JP 2014511493 A	15 May 2014
		JP 5797282 B2	21 Oct 2015
		JP 2015510115 A	02 Apr 2015
		JP 5797346 B2	21 Oct 2015
		JP 2014514561 A	19 Jun 2014
		JP 5868488 B2	24 Feb 2016
		JP 2015507744 A	12 Mar 2015
		JP 6013505 B2	25 Oct 2016
		JP 2016517513 A	16 Jun 2016
		JP 6291562 B2	14 Mar 2018
		JP 2016514271 A	19 May 2016
		JP 6355710 B2	11 Jul 2018
		JP 2012509464 A	19 Apr 2012
		JP 2013538331 A	10 Oct 2013
		JP 2014066728 A	17 Apr 2014
		JP 2014232113 A	11 Dec 2014
		JP 2014240837 A	25 Dec 2014
		JP 2014514563 A	19 Jun 2014
		JP 2014515107 A	26 Jun 2014
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
Form PCT/ISA/210 (Family Annex)(January 2015)			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		JP 2014515826 A	03 Jul 2014
		JP 2014515827 A	03 Jul 2014
		JP 2014516409 A	10 Jul 2014
		JP 2014516410 A	10 Jul 2014
		JP 2015534055 A	26 Nov 2015
		JP 2016516993 A	09 Jun 2016
		JP 2016519757 A	07 Jul 2016
		MX 2013009092 A	17 Oct 2013
		US 2011260033 A1	27 Oct 2011
		US 8422034 B2	16 Apr 2013
		US 2013009035 A1	10 Jan 2013
		US 8437011 B2	07 May 2013
		US 2013128284 A1	23 May 2013
		US 8467071 B2	18 Jun 2013
		US 2012206716 A1	16 Aug 2012
		US 8467072 B2	18 Jun 2013
		US 2010128259 A1	27 May 2010
		US 8525983 B2	03 Sep 2013
		US 2012120415 A1	17 May 2012
		US 8537371 B2	17 Sep 2013
		US 2013214122 A1	22 Aug 2013
		US 8537375 B2	17 Sep 2013
		US 2012262730 A1	18 Oct 2012
		US 8537376 B2	17 Sep 2013
		US 2012262699 A1	18 Oct 2012
		US 8558992 B2	15 Oct 2013
		US 2012262693 A1	18 Oct 2012
		US 8570493 B2	29 Oct 2013
		US 2013010308 A1	10 Jan 2013
		US 8576380 B2	05 Nov 2013
		US 2013201470 A1	08 Aug 2013
		US 8593648 B2	26 Nov 2013
		US 2012236320 A1	20 Sep 2012
		US 8619265 B2	31 Dec 2013
		US 2013037694 A1	14 Feb 2013
		US 8654354 B2	18 Feb 2014
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
Form PCT/ISA/210 (Family Annex)(January 2015)			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		US 2013208128 A1	15 Aug 2013
		US 8654355 B2	18 Feb 2014
		US 2011032509 A1	10 Feb 2011
		US 8659749 B2	25 Feb 2014
		US 2012262698 A1	18 Oct 2012
		US 8681320 B2	25 Mar 2014
		US 2013229512 A1	05 Sep 2013
		US 8724119 B2	13 May 2014
		US 2013222791 A1	29 Aug 2013
		US 8724120 B2	13 May 2014
		US 2012206808 A1	16 Aug 2012
		US 8740396 B2	03 Jun 2014
		US 2012262694 A1	18 Oct 2012
		US 8842259 B2	23 Sep 2014
		US 2012262728 A1	18 Oct 2012
		US 8848203 B2	30 Sep 2014
		US 2014158860 A1	12 Jun 2014
		US 8896848 B2	25 Nov 2014
		US 2013155386 A1	20 Jun 2013
		US 8902408 B2	02 Dec 2014
		US 2012262692 A1	18 Oct 2012
		US 8908154 B2	09 Dec 2014
		US 2014185059 A1	03 Jul 2014
		US 9007601 B2	14 Apr 2015
		US 2014268093 A1	18 Sep 2014
		US 9041914 B2	26 May 2015
		US 2012210462 A1	16 Aug 2012
		US 9109231 B2	18 Aug 2015
		US 2015092199 A1	02 Apr 2015
		US 9146094 B2	29 Sep 2015
		US 2012262550 A1	18 Oct 2012
		US 9151830 B2	06 Oct 2015
		US 2012262697 A1	18 Oct 2012
		US 9157987 B2	13 Oct 2015
		US 2015160344 A1	11 Jun 2015
		US 9164173 B2	20 Oct 2015
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		US 2012262573 A1	18 Oct 2012
		US 9207309 B2	08 Dec 2015
		US 2015049329 A1	19 Feb 2015
		US 9377885 B2	28 Jun 2016
		US 2015377605 A1	31 Dec 2015
		US 9395174 B2	19 Jul 2016
		US 2015253124 A1	10 Sep 2015
		US 9400170 B2	26 Jul 2016
		US 2014267623 A1	18 Sep 2014
		US 9448059 B2	20 Sep 2016
		US 2014267619 A1	18 Sep 2014
		US 9453717 B2	27 Sep 2016
		US 2013202010 A1	08 Aug 2013
		US 9453913 B2	27 Sep 2016
		US 2014267620 A1	18 Sep 2014
		US 9482514 B2	01 Nov 2016
		US 2013293684 A1	07 Nov 2013
		US 9482529 B2	01 Nov 2016
		US 2012265479 A1	18 Oct 2012
		US 9482746 B2	01 Nov 2016
		US 2015022826 A1	22 Jan 2015
		US 9482755 B2	01 Nov 2016
		US 2014267629 A1	18 Sep 2014
		US 9494412 B2	15 Nov 2016
		US 2014028805 A1	30 Jan 2014
		US 9686532 B2	20 Jun 2017
		US 2016178348 A1	23 Jun 2016
		US 9772394 B2	26 Sep 2017
		US 2017176169 A1	22 Jun 2017
		US 9885559 B2	06 Feb 2018
		US 2017285127 A1	05 Oct 2017
		US 9885771 B2	06 Feb 2018
		US 2017280132 A1	28 Sep 2017
		US 9967545 B2	08 May 2018
		US 2014340750 A1	20 Nov 2014
		US 2015070712 A1	12 Mar 2015
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			
Form PCT/ISA/210 (Family Annex)(January 2015)			

INTERNATIONAL SEARCH REPORT		International application No.	
Information on patent family members		PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
		US 2015331159 A1	19 Nov 2015
		US 2016364874 A1	15 Dec 2016
		US 2016370171 A1	22 Dec 2016
		US 2016377410 A1	29 Dec 2016
		US 2017030705 A1	02 Feb 2017
		US 2018120089 A1	03 May 2018
		WO 2010057169 A2	20 May 2010
		WO 2011133731 A2	27 Oct 2011
		WO 2012109515 A1	16 Aug 2012
		WO 2012112388 A1	23 Aug 2012
		WO 2012125671 A1	20 Sep 2012
		WO 2012141810 A1	18 Oct 2012
		WO 2012141868 A1	18 Oct 2012
		WO 2012141888 A1	18 Oct 2012
		WO 2012142062 A2	18 Oct 2012
		WO 2012142063 A2	18 Oct 2012
		WO 2012142064 A2	18 Oct 2012
		WO 2012142074 A2	18 Oct 2012
		WO 2012142356 A1	18 Oct 2012
		WO 2012142384 A1	18 Oct 2012
		WO 2012142554 A1	18 Oct 2012
		WO 2012154322 A1	15 Nov 2012
		WO 2012154356 A1	15 Nov 2012
		WO 2013101542 A1	04 Jul 2013
		WO 2013115836 A1	08 Aug 2013
		WO 2014046968 A1	27 Mar 2014
		WO 2014143644 A1	18 Sep 2014
		WO 2014149701 A1	25 Sep 2014
		WO 2014149702 A1	25 Sep 2014
		WO 2014149704 A1	25 Sep 2014
		WO 2014149705 A1	25 Sep 2014
		WO 2014149706 A1	25 Sep 2014
		WO 2015102786 A1	09 Jul 2015
		WO 2015200746 A1	30 Dec 2015
		WO 2015200747 A1	30 Dec 2015
		WO 2016073208 A1	12 May 2016
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.			

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2018/050873	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
US 2006/0215179 A1	28 September 2006	WO 2017151196 A1	08 Sep 2017
		US 2006215179 A1	28 Sep 2006
		AU 2003242862 A1	23 Jan 2004
		CN 1666084 A	07 Sep 2005
		CN 101476883 A	08 Jul 2009
		EP 1540273 A1	15 Jun 2005
		JP 2005532544 A	27 Oct 2005
		WO 2004005848 A1	15 Jan 2004
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(January 2015)			